MÉMOIRE DE RECHERCHE

Cross-domain priming: quantifying the mathematical priming effect.

Mémoire préparé sous la direction de Mme Barbara HEMFORTH

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Cross-domain priming: quantifying the mathematical priming effect.

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Abstract

The role of common representations or operations between language and mathematics still remains under debate to this day. An approach first proposed by (Scheepers et al., 2011) was to apply the priming paradigm and use mathematical equations as a prime and attachment ambiguities as a target, the only common similarity being the structure. Priming effects have been shown based on this method (e.g. see Scheepers, Galkina, Shtyrov, and Myachykov (2019)), but reproducibility issues are regularly raised by researchers (unfortunately usually not published). We report analyses for three mathematical to language priming experiments including post-hoc analyses where prime exposition lead to a more detailed pattern of results. Taken together, these experiments highlight problems with current paradigms: participants have to be skillful in mathematics but not too high-performing because otherwise they will solve equations too rapidly, thus reducing their exposure to the prime. Also, the equations traditionally used in the literature to represent low relative clause attachments may not be fully adequate. This suggests that for mathematics to language priming, the order of operations carried out by the participants should be taken into account.

Acknowledgements

I would like to thank Céline Pozniak for the great insights she gave during this exploratory work and for advice on the designs of our experiments.

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Contents

1 Introduction

Human speakers repeat themselves and re-utilize what has been previously said, even in experimental settings. A trivial example is the response to a question, it often reuses most of the lexical content of the question (Levelt & Kelter, 1982). To go a little bit further, we can also mention cooperative maze games (Garrod & Anderson, 1987) where participants have to interact between them to escape a maze and they quickly settle on common terms such as ”row”, ”line” or ”column” to describe positions and they stick to them until the game ends. Another example are interactive trading card games (Brennan & Clark, 1996; Branigan, Pickering, Stewart, & McLean, 2000) where participants have to describe pictures to successfully finish the game and they quickly use the same words or chunk of words in their descriptions, as for example, referring to a dog by its breed or just say ”dog”, or referring to a car by adding its color or just say ”car”. Still in the card games paradigm, it has been found that participants not only reuse previous words, but also the structure of previous complex nouns: when participants heard a complex NP containing a relative clause (RC), e.g. “the square that's red”, they were more likely to produce a similar structure than a NP with a pronominal adjective (”the red square”) (Cleland & Pickering, 2003). Haywood, Pickering, and Branigan (2005) found that re-utilization of structure is that frequent that it can encroach upon referential context. For ease of production, participants sometimes prefer to reuse previous content rather than contextually more felicitous new explicit content, thus disadvantaging the ease of comprehension.

The phenomenon of reusing previous structure has also been observed to work across languages. In a study led by Hartsuiker, Pickering, and Veltkamp (2004), Spanish-English bilingual participants described cards in the context of a game. They found that the participants who had just heard a sentence in Spanish tended to use the same type of sentence in English, in particular the passive ones. English and Spanish passive have in common their word order and syntactic structure. The fact that this re-utilization phenomenon works across different languages when structures are similar highlights the role of syntax for word-sequence re-utilization. These data can be interpreted as evidence that this phenomenon targets more abstract syntactic representations.

Parallel to the study of words and structures, phenomena of repetitions have also been found in many linguistic sub-domains such as phonology, morphology or semantics. All these effects came with the same term: priming. From these observations, Pickering and Garrod (2006) (see also Pickering and Ferreira (2008)) established a framework that theorizes why priming takes place at every linguistic level. Their main point is that priming is essential to a successful communication because it helps to align speakers' linguistic representations and construct a common situation model.

1.1 Syntactic Priming

From now on, we use terms defined as follows (different from some of the literature) to facilitate the comprehension of this master's thesis. Syntactic priming will be used as priming specific to the syntactic domain, Structural priming includes all cross-domain priming effects and Mathematical priming will be specific to priming effects from the mathematical domain to the language domain.

A more detailed analysis on syntactic repetition led by Bock and Griffin (2000) states that syntactic priming is a long-lasting effect which may rely on an implicit-learning phenomenon (contrary to semantics where the effect is short and may rely on a memory-based phenomenon (Joordens & Becker, 1997)). To support this claim, they conducted two priming experiments. In general, in a priming experiment, the element supposed to impact the processing or representation of another element is called the "prime", the impacted element is called the "target". To test the persistence of priming, they used various distractors between the prime and the target, called "lags". At each trial, the participant had to produce an utterance, either repeating a sentence (the prime) or describing a picture (the target, see Figure 1). Primes using passives or prepositional datives yielded more utilization of the respective structure in the target. Importantly, they found priming effects in language production up the maximum amount of 10 lags included in their experiment.

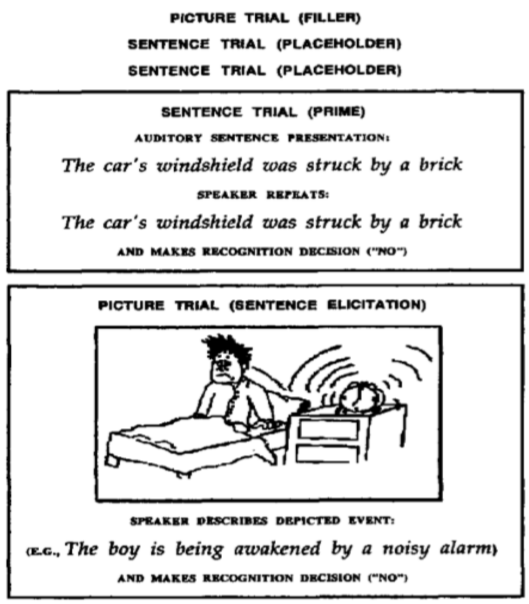

Figure 1: Design used in Bock and Griffin (2000)

In a follow-up article, Bock, Dell, Chang, and Onishi (2007) used the same paradigm (as in Bock and Griffin (2000)) but modified the procedure for the prime: instead of repeating a sentence, participants only listened to it. They observed priming effects from comprehension to production and, again, this effect persisted across to all lags (up to 10 in the experiment).

Moreover, this priming effect is observed from a language to another as demonstrated by Loebell and Bock (2003). Fluent German-English bilinguals, after producing a prime sentence in one of their language, had to describe an unrelated pictured event in the other language

(Figure 2, using the same design as in Bock and Griffin (2000)). The primed sentences were either datives (prepositional and double-object datives) or transitives (actives and passives). The results showed that the production of datives in one language primed the use of datives in the other language. In contrast, the use of passives in a language did not prime the use of passives in the other language, presumably because German and English passives have different word orders structures for passives (German being a verb-final language).

Figure 2: Design used in Loebell and Bock (2003)

The fact that syntactic priming occurs from comprehension to production and from one language to another highlights the fact that this phenomenon is happening at a very abstract level.

The syntactic priming effect has also been observed through brain-imagery (fMRI) with the help of the repetition suppression effect (RS). (Noppeney & Price, 2004) The RS describes the phenomenon that less brain activity is produced when the same or a similar stimulus is shown twice or more (Auksztulewicz & Friston, 2016).

All previous works on syntactic priming was based on preferences between different structures which were, however, similar down to the level of constituent labels. On the other hand, if syntactic priming relies on abstract representation of syntax, it should depend on more abstract syntactic structure and not on the nature of the constituents (labels). Loncke, Van Laere, and Desmet (2011) tried to manipulate attachment preferences for two different attachment processes that can be represented as the same abstract syntactic structure. They conducted a sentence completion priming experiment in Dutch: the prime stimuli were incomplete sentence starting with a complex noun had to be completed with a prepositional phrase (PP) with forced high or low attachment (they distinguished the attachment of the PP via the gender of a possessive pronoun). The target stimuli were incomplete sentences starting with a complex noun ending with "die" (equivalent of that/who), forcing the production of a RC (they distinguished the intended attachment of the RC via number marking on the verb). The description of the attachment is described by its position in the syntactic representation: if the PP or RC is attached to the first NP, it is a high attachment (Figure 3[1]); if it is attached to the second NP, it is a low attachment (Figure 4). They successfully primed RC attachment preference with the help of PP attachment, these results emphasize the need of abstract syntactic structure similarity instead of structures of the same nature down to constituent labels.

[1]Every syntactic representation in this master thesis are simplified for ease of interpretation

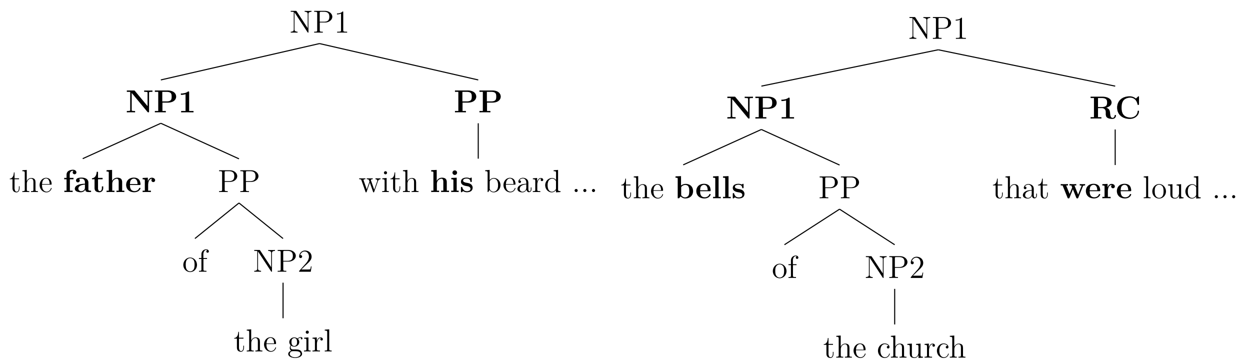

Figure 3: High attachment structure for PP and RC (Loncke et al., 2011)

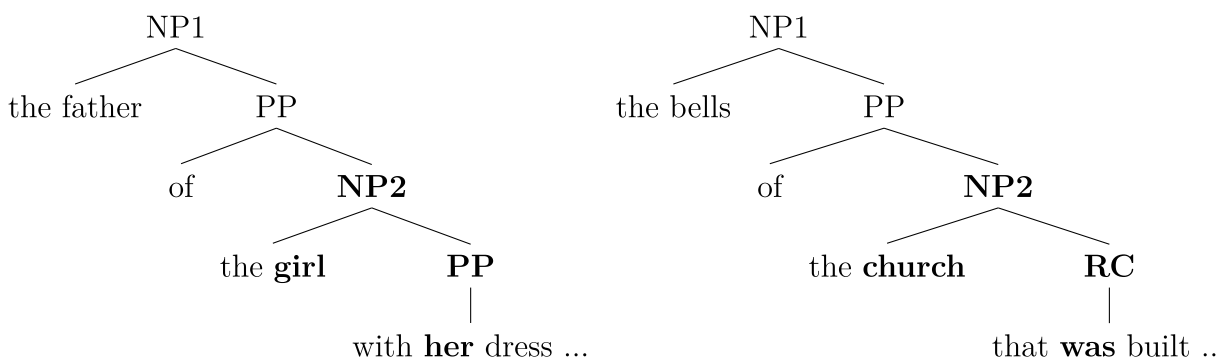

Figure 4: Low attachment structure for PP and RC (Loncke et al., 2011)

The research question of this master thesis, investigate how far these abstract representations can be pushed, whether they can even cross cognitive domains. However, to discuss this question, we have to first talk about the role of common representations and processing between language and mathematics.

1.2 Sharing of structure building resources theory

The work on mathematical priming is a central part of an ongoing debate on whether cross-domain structural interactions are based on common representation: *Sharing of structure build-*

ing resources theory; or common cognitive processors: *Sharing of structure processing capacity* theory. For the *Sharing of structure building resources* theory, the focus is on common structural representation and shared working memory resources across domains.

Before introducing frameworks, a key element of this theory and frameworks is that those domains are indeed ruled by structural processing. Van de Cavey and Hartsuiker (2016) gave evidence that what appears as a linear sequence in surface in some but not all domains are in fact treated as a structure, sequential information has to be organized into an integrated structure for music but not for sequences of colored dots. Similar to previous experiments described before, the completion experiment in this paper has for target an incomplete ambiguous sentence structure ”I saw the knives in the kitchen that...” which could either be continued as a low attachment ”was dirty” or a high attachment ”were sharp” (note the word ”that” which forces a RC continuation). The primes were melodies composed of 8 notes grouped in 3 chunks (Figure 5). Chunks could follow either of two harmonic patterns, creating two separations for the high attachment condition and one separation for the low attachment condition. The two first chunks, supposed to represent the first NP (the knives) and the second NP (the kitchen), always showed two different harmonic patterns which were consistent across conditions. Only the last chunk (representing the RC) differed across conditions and could either be harmonically consistent with the first or the second chunk.

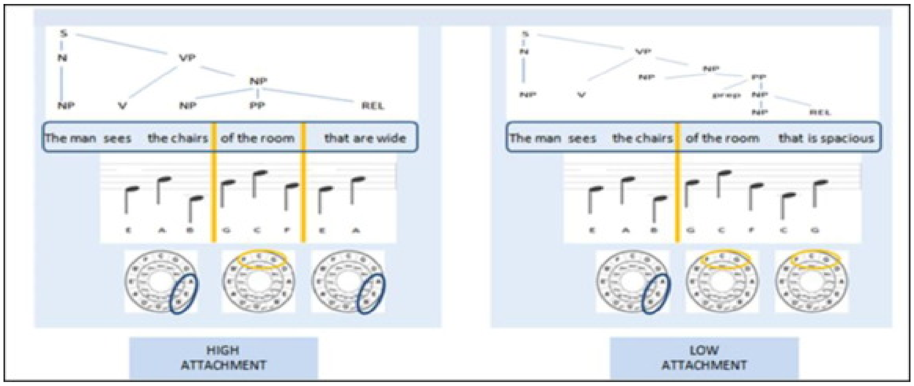

Figure 5: Prime differences between the High and Low attachment condition (Van de Cavey & Hartsuiker, 2016)

Van de Cavey and Hartsuiker found significant priming effects but one possible interpretation of the experiment was that the melodies could be interpreted as a linear sequence "ABA" or "ABB" and therefore the difference observed was not the result of a structural priming (but possibly some kind of linear priming independent of structure). To counter this interpretation, they conducted the same experiment but replaced melodies with series of colored patches in order to reproduce these "ABA" or "ABB" patterns. The hypothesis here is that colored patches do not trigger any abstract structural representations. The authors did not find priming effects in this case, which highlights the need of a structural interpretation to have a structural priming effect. In a follow-up experiment, they replicated this experiment using mathematical stimuli as prime and still found priming effects.

Patel (2003) proposed the *Shared syntactic resource hypothesis*: the idea that both music and language need to integrate smaller and distinct units within a higher structure, they both demand syntactic rules for processing. Those rules may be specific to their domain, but their underlying foundation might rely on the same representation. Patel (2010) later sharpens his theory by saying that representation (long term memory) between language and music are separated but the active syntactic processing of those two can overlap in the resource networks (short-term memory involved in the parsing) (Figure 6).

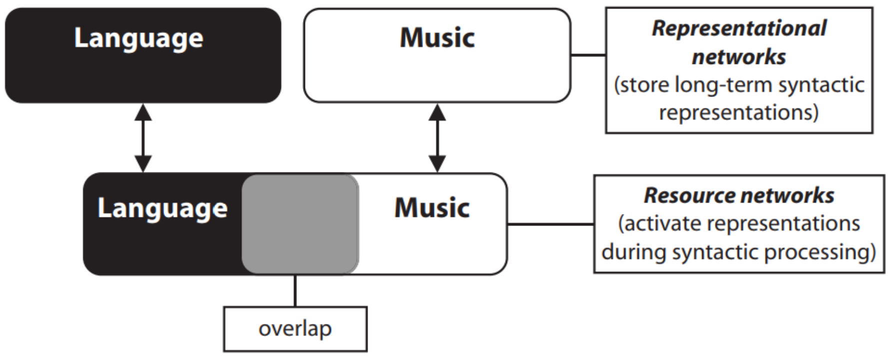

Figure 6: Interactions between music and language (Patel, 2010)

Kljajević et al. (2010) suggests that different cognitive domains like language, mathematics or music might share the same syntactic working memory resources (processing relevant integration within sequences of structurally dependent elements). Separate processes may be activated for each domain, but all these domains may rely on the same working memory, which means that interactions and priming across domains are simply structural interference.

More specific to mathematical priming, Scheepers (2019) proposes a reuniting view analyzing equations with Lexicalized Tree Adjoining Grammar (LTAG). The main goal and principle of LTAG is to combine Treelets (representations of syntactic sub-structures) to form a bigger structure. The two operations used in LTAG that combine elements are *Substitution* and *Adjunction* (Figure 7). *Substitution* allows the addition of a new incoming element and *Adjunction* allows the addition of an element between two previous elements. Scheepers shows that this framework may be applied to the treatment of both language and arithmetic, which suggest that mental syntactic representations might share these two essentials operations.

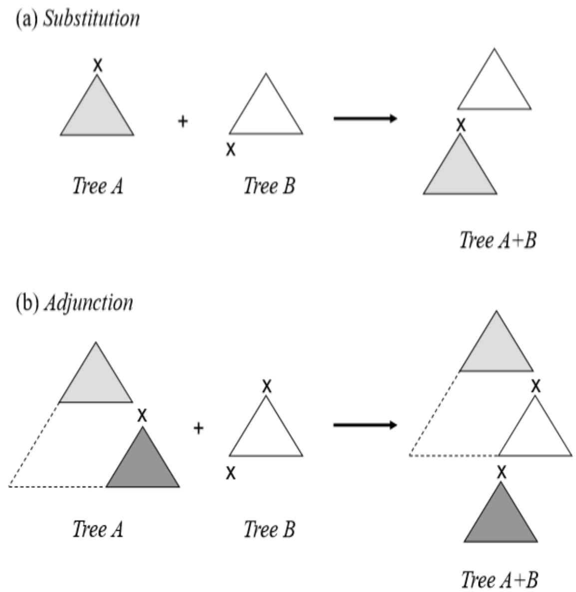

Figure 7: Substitution and Adjunction in the LTAG framework (Scheepers, 2019)

In addition to the work directly testing structure sharing across cognitive domains, data from EEG experiments may shed light on cross-domain interaction. The P600, an Event-related potential (ERP), is a positive electric wave found approximately 600 milliseconds after the onset of a critical event. The P600 has been greatly investigated and is modulated after some kind of violation or a comprehension failure due to complexity at the syntactic level in sentence comprehension (oral or written). This ERP component, initially thought to be proper to the language processing, has been shown to be modulated in experiments using mathematical materials using paradigms similar to the (psycho-)linguistic studies.

Martín-Loeches, Casado, Gonzalo, De Heras, and Fernández-Frías (2006) showed participants equations and their results. Some equations presented arithmetic violations, an operator was present instead of a number (5/- = 9), and some equations presented order-relevant violations (5-1 = -4). Another condition was the presence of parentheses to complexify and lengthen the equation (8-(5*1) = 3). Arithmetic violations, order-relevant violations and the only presence of parentheses yielded P600 effects. This can be interpreted such that sentence and mathematical processing share similarities because the same ERP component is modulated by the same type of violations.

Núñez-Peña and Honrubia-Serrano (2004) presented participants with a series of seven numbers, the first six were the result of an addition or subtraction of the same number, and the seventh number was either a correct or an incorrect continuation of the series (4 - 7 - 10 - 13 - 16 - 19 - 23 - *). Incorrect continuations led to a P600 effect. More interestingly, the stronger the incorrect continuations were (farther from the correct answer), the stronger the amplitude of the P600 was. This goes in line with the linguistic literature stating that the P600 effect is an ERP component that reflects complexity of the task through its amplitude (?, ?).

This specific ERP component has also been modulated in experiments with out-of-key music violations (Patel, Gibson, Ratner, Besson, & Holcomb, 1998) and patterns within string of characters (Lelekov-Boissard & Dominey, 2002).

The P600 is now thought to reflect not only violation (or complexity) in linguistic structures, but in any rule-governed sequence: "In fact, taking into account the results reported in other studies, the P600 could be considered not as a specific index of breaking linguistic rules, but as a more general index of violation in any rule-governed sequence" (Núñez-Peña and Honrubia-Serrano (2004), p. 139) The fact that this ERP component is found in different structural domains may suggest that some common syntactic processes are used for every structural treatment, regardless of the domain. In other words, although every domain may rely on their specific rules, all these domains are treated using some amount of common underlying structural operations, thus shifting the view from multiple domains using the same syntactic working memory to a global syntactic treatment process for every domain.

Moreover, the N400 ERP initially thought to be specific to semantics have also been modulated with mathematical materials (Jost, Hennighausen, & Rösler, 2004) and with non-linguistic materials (McPherson & Holcomb, 1999; Castle, Van Toller, & Milligan, 2000), contradicting the hermetic view of language processing that has sometimes been proposed.

1.3 Sharing of processing capacity theory

As for the *Sharing of processing capacity* theory, instead of focusing on how and whether interactions between structural domains may take place, the focal point is whether language and mathematics are produced and treated by the same processors, or, more precisely, which brain areas may be common for structural treatment. Although we agree with a vast majority of studies that concludes that brain areas used in language processing and mathematical processing are at least partially different, the claims proposed by many articles seem to overshoot and propose a clear distinction between these two domains, contradicting what has been observed in the mathematical priming literature. Also, most studies do no investigate working memory, one of the central points in the *Sharing of structure building resources* theory. It is also important to mention that the most used method in brain imagery, Functional magnetic resonance imaging (fMRI), lacks a good temporal resolution which means that fine grained temporal distinctions can be overlooked.

Beginning with those who support a clear distinction between language and mathematics, Amalric and Dehaene (2016) compared the cognitive processes of experts in mathematics while evaluating the truth values of mathematical (in four domains relative to mathematics: analysis, algebra, topology and geometry) and non-mathematical statement (as in examples 1 and 2).

(1) a. A finite left-invariant measure over a compact group is bi-invariant.

b. In finite measure, the series expansion of the roots of a holomorphic map is reflexive.

(2) a. In ancient Greece, a citizen who could not pay his debts was made a slave.

b. The Greek mythology is the smallest alcohol derived from the VAT.

Using fMRIs, they found no brain activation in areas related to language and concluded that their results suggest that "high-level mathematics recruits the same brain circuit as basic arithmetic" (Amalric and Dehaene (2016), p. 4913). However, using this experimental design, it mainly calls out representation and storage of mathematical knowledge compared to general knowledge (encyclopedic knowledge), thus mostly about possible shared relations on the semantic level. This work did not discuss possible overlap between language and arithmetic processing, the claim that this experiment shows that mathematics and language are independent may be overstated taking into account the tasks used here.

Fedorenko, Behr, and Kanwisher (2011) used fMRI with non-linguistic tasks (arithmetic, working memory, cognitive control and music) and found little or no response in language specific regions. In order to designate which brain areas are specific to language, they used language localizer sessions to target brain areas used while processing language and this individually for every participant. This series of experiments provides therefore more rigorous data, they do not base their claims on brain regions traditionally associated with language in the literature. Their design for the arithmetic task was a forced-choice equation (the participant had to calculate and choose the right answer) composed of consecutive addition of different numbers ($21 + 7 + 8 + 6 = 44/42$). Contrary to Martín-Loeches et al. (2006), the numbers had no relation with one another and the correct result was always proposed. The task consisted of multiple linear additions with no sense of structure involved. These multiple rather simple additions can be ordered and grouped as the participant wishes and it might thus not recruit the kind of structural reasoning that may be common for both language and mathematics.

Monti, Parsons, and Osherson (2012), using fMRI data, say that processing of syntax-like operations of algebra does not rely on language neural mechanisms. Again, we believe that the claim proposed by this article is too large. Their approach was to oppose language stimuli (Z was paid X by Y) to algebraic stimuli (X minus Y is greater than Z). Those algebraic stimuli are composed of unknown numbers and do not need any structure or order-based operations, thus ruling-out a major aspect in equation processing that may be related to language.

Varley, Klessinger, Romanowski, and Siegal (2005) tested three men with large left-hemisphere perisylvian lesions with severe grammatical impairment (and some difficulty in processing phonological and orthographic number words) on mathematical calculations, with one of the conditions having order relevant parentheses. They all passed the test with considerably high success including the equations with parentheses, indicating for the authors a "remarkable independence of mathematical calculations from language grammar in the mature cognitive system" (Varley et al. (2005), p.3519). We think that language syntax is more complex than mathematical syntax and what may be common between these two domains may lie at a very basic level of language processing (order, grouping and hierarchical structure). Mathematical syntax surely has no long-distance dependencies or movement within the syntactic tree, nobody would claim that every syntactic operation in language processing can be found in mathematical reasoning. Moreover, without detailed information on the severe agrammatic aphasia present in the patients, we cannot be sure that this is evidence for a split in the cognitive system: if they can produce very basic utterances, the threshold may already be high enough for mathematical reasoning. If they can't produce very basic utterances, we believe that order of operations and parentheses priority can be interpreted without a thorough understanding of all levels of syntax; they may also use a different cognitive process to correctly solve equations such as their symbol system to understand priorities (operations and parentheses).

More in line with the question of this master's thesis, Makuuchi, Bahlmann, and Friederici (2012) also investigated differences between language and mathematics in the brain but focused on hierarchical structure building. Their set stimuli were created following the pattern of b in Figure 8. The idea is to separate first level structure building (the build-up of hierarchical structure with new elements) and second structure level building (the build-up of hierarchical structure with elements treated by the first level building). They used basic Japanese sentence (c), equations (d, using Reverse Polish notation, the operator is presented after the two operands) and a working memory control task (e).

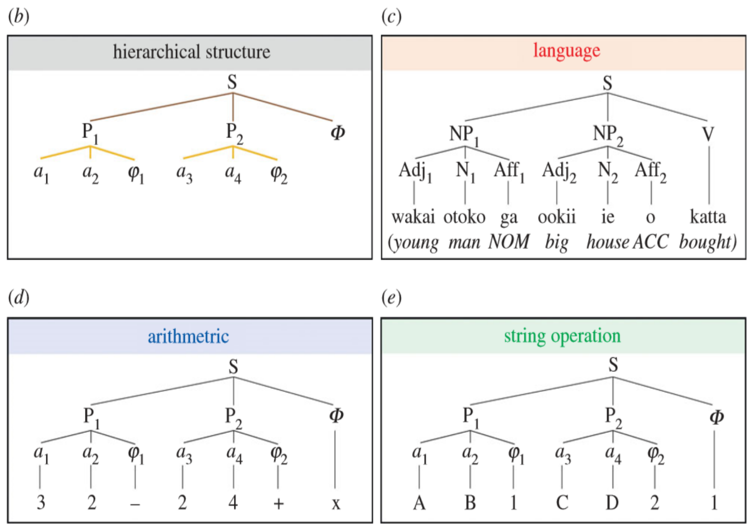

Figure 8: Stimuli used in Makuuchi et al. (2012)

Using fMRI data, they found anterior-to-posterior functional organization in the prefrontal cortex according to the level of structure building. For all three domains, they found that the ventral pre-motor cortex supports first level structure building whereas the dorsal pars opercularis is used for second level structure building (with lower activation for the language task). These results provide evidence for common processors across cognitive domains involving hierarchical structure building, even though the dorsal pars opercularis seems to be uniquely involved in language treatment.

Finally, Nakai and Okanoya (2018) used fMRIs to investigate the priming effect of mathematics to language and vice-versa. They used small phrases and equations, either right or left-branching (Figure 9), as both primes and targets. The conducted experiment had two conditions: the similarity of structure (Incongruent or Congruent) and the direction of the priming (from language to arithmetic vs. from arithmetic to language). They also used localizer sessions using tasks exclusively targeting language or mathematics regions.

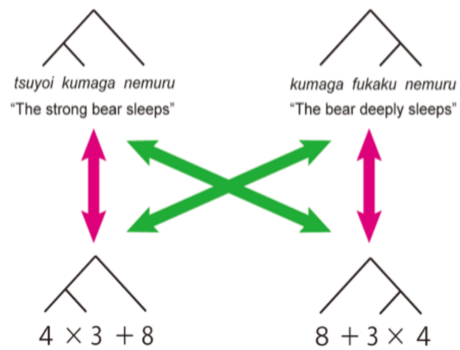

Figure 9: Stimuli used in Nakai and Okanoya (2018)

Using these localizer sessions, they were able to identify brain areas used specifically for language and mathematics, which include large brain regions and the bilateral inferior frontal gyrus (IFG). Then, using the experimental data, they examined the contrast between Incongruent and Congruent conditions, they found that bilaterally, IFG was more active for the incongruent condition, suggesting a repetition suppression effect (the RS describes a phenomenon where less brain activity is produced when the same or a similar stimulus is shown twice or more). Importantly, the RS was bidirectional (from language to arithmetic as well as from arithmetic to language). To confirm that this bilateral IFG activation is involved in both, language and arithmetic processing, they applied the localizer sessions as an inclusive mask on the experimental data, and the bilateral IFG activation was still found for the incongruent condition in both directions (Figure 10). To sum up, they observed the RS across domains in both directions if the prime and target share the same structural representation.

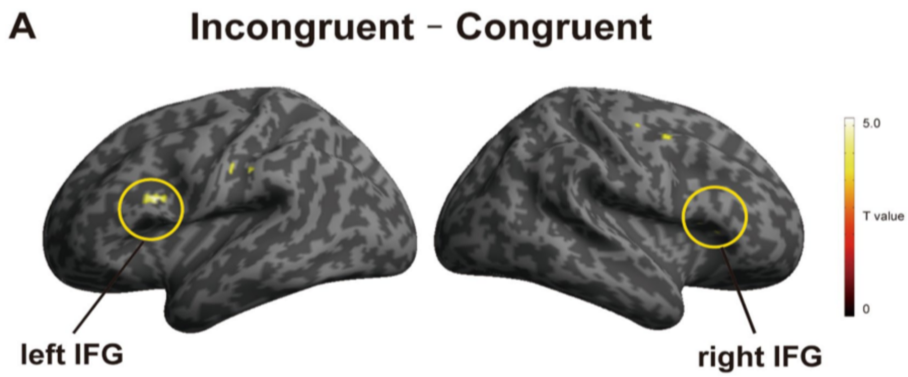

Figure 10: common bilateral IFG activation in Nakai and Okanoya (2018)

This experiment directs us to the main topic of this Master's thesis which will be addressed in the next section.

1.4 Mathematical Priming

As we have shown earlier, syntactic priming concerns structural similarities beyond the nature of constituents. It even works across languages. This has been taken as an argument that this phenomenon taps into abstract representations of language. If the human brain uses underlying joint processes or processors for every structural domain (meaning domains building structure out of sequences) and uses abstract representations as a basis for structure building, this means it should be possible to use priming to influence the structural representations of one domain using representations in another domain. Indeed, the goal of mathematical priming, is twofold: In addition to explore common cognitive processes across domains, it can possibly also be used to understand the mental representation of syntax using structural similarities in other cognitive domains.

Scheepers et al. (2011) showed evidence for mathematics to language influences in that they successfully primed RC attachment preferences with mathematical equations. The order and/or combination of operations needed to correctly solve an equation can share structural similarities with a syntactic tree (Figure 11 & 12), and may thus be calling out common syntactic working memory resources or structure building. Using a sentence completion priming paradigm, the authors used an equation as a prime and an incomplete sentence as a target. Equations were made to either resemble a low or a high attachment. The incomplete sentences were composed of a complex NP follow by the word ”who” or ”that”, forcing the production of a RC. This RC could either refer to the first or the second NP of the complex NP. The goal of the experiment was to test whether this attachment preference can be biased by the previous equation. They actually found more high attachments after high attachment primes and more low attachments after low attachment primes. They also asked several groups of students from different disciplines to participate in their experiments, and found that the more the field required mathematical knowledge, the more pronounced were the results. In a second experiment, the authors simplified equations with redundant parentheses to facilitate the equation (the order of operations to be applied) and this led to more pronounced results also with less mathematically-skilled participants.

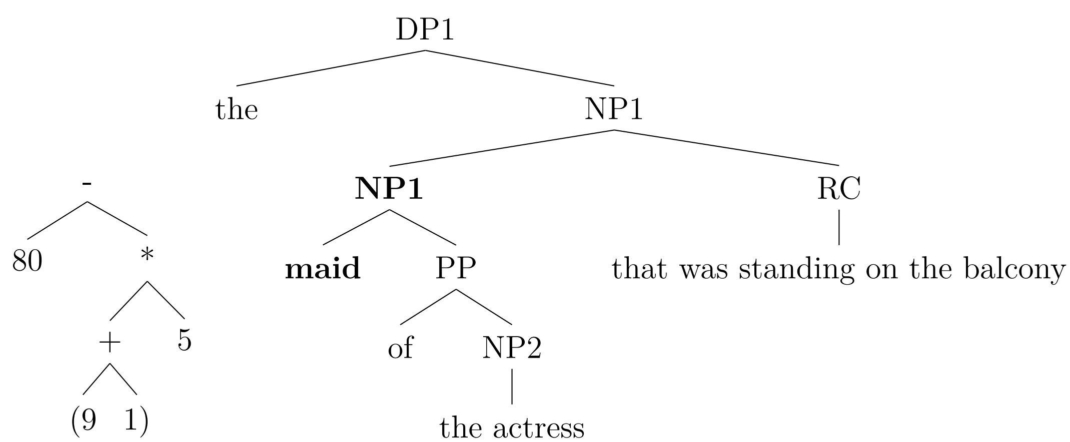

Figure 11: High attachment common representation for arithmetic and language following Scheepers et al. (2011)

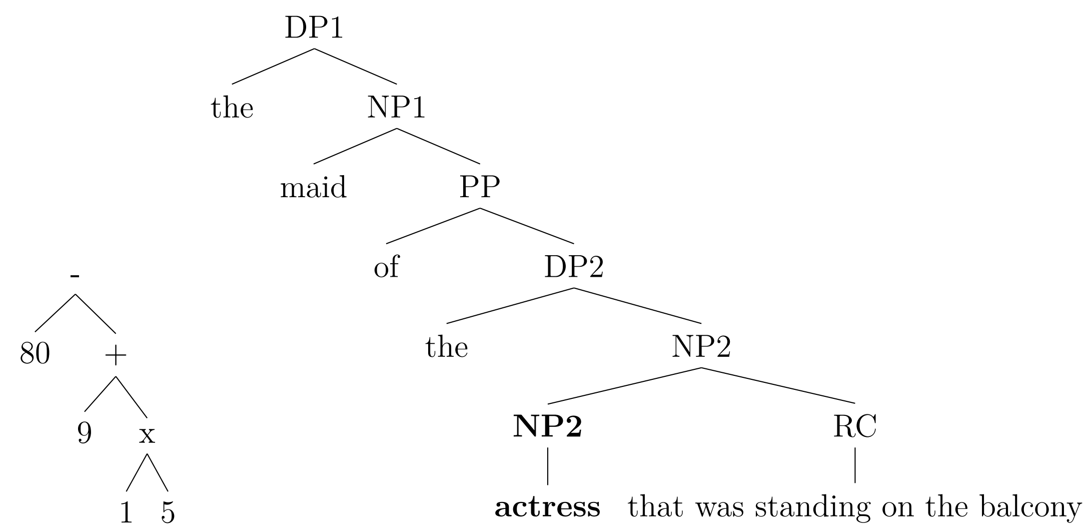

Figure 12: Low attachment common representation for arithmetic and language following Scheepers et al. (2011)

Scheepers and Sturt (2014) used a sensicality judgment task instead of a sentence completion task to investigate the influence of left or right branching equations ($5 \times 2 + 7$ vs. $5 + 2 \times 7$) as primes on structurally left-or-right branching adjective-noun-noun compounds (*alien-monster movie* vs. *lengthy monster-movie*) as targets (Figure 13 & 14). Participants had to calculate the equation then provide judgments for a phrase using an adjective-noun-noun compounds. Given the fact that the equation ”5 + 2 x 7” must be started by ”2 x 7” to correctly calculate the result, this right branching equation structure is supposed to prime a right branching compound in language and vice versa for left branching structures. The mathematical formula influenced sensicality judgments of the linguistic structures. In a second parallel experiment, they switched the order of prime and target, making the language stimuli the primes and the mathematical stimuli the targets. In this experiment, they also found evidence for language to mathematics priming. It is important to note that this second version of the experiment is only possible and can therefore only performed by participants with below average mathematical knowledge. Indeed, compared to language, equations are not ambiguous, they have to be calculated using a precise order (except series of additions or subtraction) and are not subject to multiple interpretations, requiring participants to be unaware of operator priority rules.

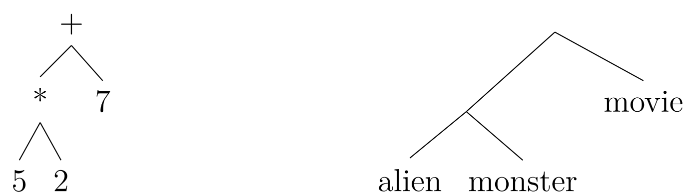

Figure 13: Left branching structure similarities between equations and adjective-noun-noun compounds (Scheepers & Sturt, 2014)

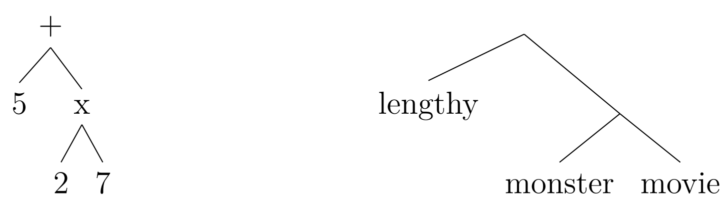

Figure 14: Right branching structure similarities between equations and adjective-noun-noun compounds (Scheepers & Sturt, 2014)

Zeng, Mao, and Liu (2018) conducted a mathematical priming experiment in Chinese mandarin. They used ambiguous Chinese sequences (example 3) NP1+NP2+AP (simplified representation) where the AP can refer to NP1 (example 3a) or to NP2 (example 3b), this structure is similar to a relative clause in English.

(3) Xiaoli you ke zuanjie hen ...
Xiaoli have a diamond very ...

a. Xiaoli you ke zuanjie hen kaixin.
Xiaoli have a diamond very happy

(Xiaoli is very happy because she has a diamond)

b. Xiaoli you ke zuanjie hen shanyao.
Xiaoli have a diamond very shiny
(Xiaoli has a diamond that is very shiny)

They asked to participants to resolve an equation like (example 4a) or (example 4b) and then decide which NP the AP referred to in examples like (example 3a) or (example 3b). The equations used as primes were either ordered from left to a right to be similar to a high attachment structure (example 4a), or ordered from right to left to be similar to a low attachment structure (example 4b).

(4) a. (5+1+2)x3
b. 5+(1+2x3)

For this experiment, they recruited two populations, children and adults. They found mathematical priming in both groups but priming was more consequent with children. Their explanation was that children are less efficient in mathematics thus increasing their calculation time and thus their exposure to the prime. They are also less experimented with language and thus less settled with respect to their preferences.

Pozniak, Hemforth, and Scheepers (2018) provided the first online data on mathematical priming. In a visual world eye-tracking experiment, they used Scheepers et al. (2011) format equations as prime (to have high and low attachment primes) and sentences like "the daughter of the teacher who lived in Paris" (that have a complex NP composed of two NPs and RC) as target. They measured eye-fixation for the prediction of the attachment of the RC and they confirmed that the mathematical priming effect is more prominent and long-lasting with participants familiar with mathematics (Figure 15).

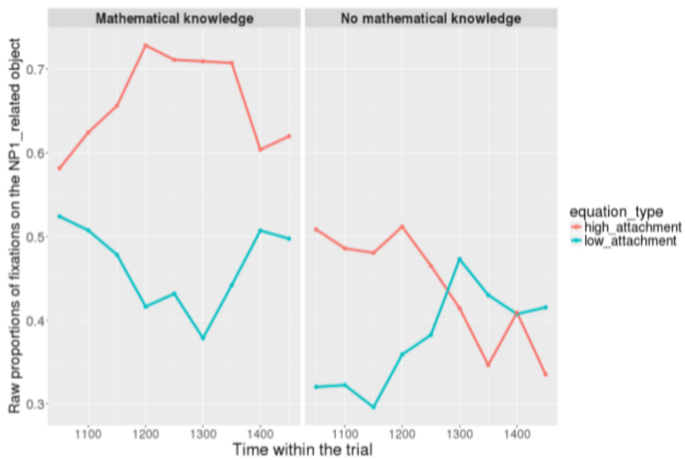

Figure 15: Eye-fixations differences between participants with mathematical knowledge and participants without mathematical knowledge (Pozniak et al., 2018)

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2 Aim of experiments

In spite of the studies cited in the previous section, mathematical priming is not a robust phenomenon. The presence of so few articles since Scheepers et al. (2011) is a strong indicator about this, in addition, the amplitude of priming effects presented in the literature are often very small. Mostly unpublished studies witness the inconsistency and replication problems of this phenomenon. The goal of this master's thesis is to further understand what is really happening by manipulating various settings. Therefore, much of the work presented here is broadly exploratory and much of the data presented is the result of post-hoc analyses.

We conducted three experiments for this master's thesis. The first one was run on an internet-based platform at participants' location of choice and used simpler priming structures that were not previously used for the attachment of RCs. Despite having a high success rate for correct equation results, we did not find systematic mathematical priming effects. In particular, younger participants did not show any effects at all for any of our conditions. We attributed these lacks of effects to lack of concentration on younger participants. Priming effects (different from expected ones) only showed up in analyses taking age and calculation time into account. In order to remedy this situation, we passed the other two experiments in a controlled environment at the university and we used equations previously used as primes in published experiments. Notwithstanding a low success rates for equation results, we still found priming effects in trials where the time used to calculate exceeded the median within participants that responded correctly to at least two thirds of the equations. Controlling the amount of correctly calculated equations was taken as a measure of the level of mathematical knowledge of the participants and analyzing the time required to answer the equation allows to control the exposure to the prime (similar to Zeng et al. (2018) for children). In our third experiment, using smaller numbers and redundant brackets to facilitate the comprehension of the order of operations, we increased success rates for equation results. We had more participants that responded correctly to two thirds of the equation.

With the results of these experiments, we think that we now understand more why mathematical priming is so inconsistent in different experiments. We suggest that participants have to be familiar with mathematics to share common representations across domains (by having the right equation structure) but not too efficient because it reduces the exposure to prime. But details of the mathematical equations also play an important role. These finding will permit better designs in order to stress and manipulate the exposure to prime (more on this in Future work).

3 First Experiment

This experiment was designed in order to compare the effect of mathematical priming on two French structures with NP1+NP2+RC sequences, standard relative clauses (RC) and so-called pseudo relative clauses (PR; Pozniak, Hemforth, Haendler, Santi, and Grillo (2019)), through the use of two classes of verbs, stative and perception verbs. Indeed, in French, stative verbs exhibit a NP2 attachment bias for the RC and prohibit PR while perception verbs exhibit a NP1 bias and allow PR (the nature of the bias). The nature of the bias of perception verbs is due to the PR-fist hypothesis, which facilitates the interpretation of PR (more on this in materials).

Unlike other mathematical priming experiments, we measured the time used to solve an equation (the exposure to the prime) in all our experiments. This exposure time seems to be crucial for an efficient cross-domain priming (as Zeng et al. (2018) suggested). In the linguistics literature, there is no consensus on whether or not exposure time of prime increases priming on target. In the psychology literature, there is some evidence that more exposure to a prime can lead to a more prominent effect (Dijksterhuis & Van Knippenberg, 1998). However, as soon as the participant becomes aware that the prime is indeed a prime, priming effects are no longer observed (Murphy & Zajonc, 1993). Fortunately, in our experiments, participants had generally no idea about the relation between the equations and the linguistic stimuli in the experiment. No participant seemed to be aware that we were conducting an experiment on the structural similarities between mathematics and language.

We are aware that measuring prime exposure via the time used to solve equations is not controlling prime exposure and therefore not optimal. Many cognitive processes are active while calculating and calculation time may be due to different strategies or acquisition of cognitive resources. As previously said this work is broadly exploratory. We will present effects of exposure as post-hoc analyses to treat them with adequate caution.

3.1 Participants

Results from 100 French participants were analyzed for the experiment. Of all participants, one was dropped for not having French as their native language, one for not responding correctly to equations, one discovered what the experiment was about, one was helped by someone else for calculation and one had not the required legal age. They were recruited using the RISC (https://www.risc.cnrs.fr) and social networks. The mean age of our participants was 35.81 and the oldest participants was 74 while the youngest was 18. 51 men and 49 women participated.

3.2 Material

3.2.1 Pseudo-Relatives

Different from previous experiments, we added Pseudo-relatives (PR) to our experimental design. These structures, as described in Pozniak et al. (2019), are introduced in a syntactic environment with perception verbs and are always ambiguous with a RC reading. As can be shown in Figure 16, the RC is embedded within the DP and directly modifies it, it relates to the entity described by the DP. The PR is in a sisterhood relationship with the DP (Figure 17), it gives a perceptual report of an event. For this very reason, perception verbs, when preceding complex NP, are inducing an attachment bias of the relative towards NP1. For processing reasons, the PR reading is preferred over the RC reading, but this preference decreases over time in experimental settings (Pozniak et al., 2019). Since PRs are structurally different from RCs, our intent was to use them as controls, our material was only composed of primes designed towards RCs. We did therefore not expect priming affects for PRs.

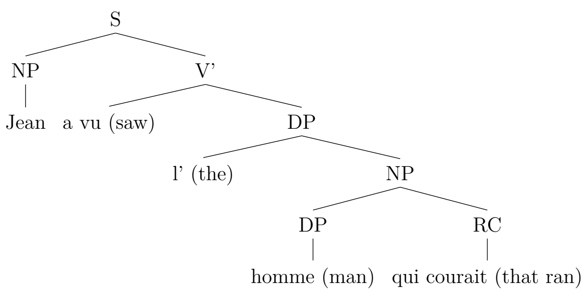

Figure 16: Relative Clause

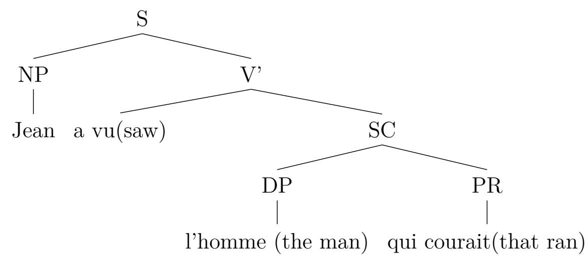

Figure 17: Pseudo Relative

3.2.2 Materials

This experiment has a two by two design with 20 items using Verb Type (stative vs. perception verbs) and Prime (low vs high priming) as experimental factors. Participants were asked to complete a sentence containing a complex DP (one NP embedded within a NP) in object position followed by "qui" (who) thus enforcing the participants to produce a RC (table 1). Half of the items had a plural NP1 and a singular NP2 while the other half had a singular NP1 and the plural NP2. This difference of number between the two nouns allows to define the attachment of the RC as intended by the participants.

Stative verbs	high priming: (8+5)*3	Carl a connu l'agent des chanteurs qui ...
Stative verbs	low priming: 8*(5+3)	Carl a connu l'agent des chanteurs qui ...
Perception verbs	high priming: (8+5)*3	Carl a vu l'agent des chanteurs qui ...
Perception verbs	low priming: 8*(5+3)	Carl a vu l'agent des chanteurs qui ...

Table 1: Experiment 1 Design

Each sentence completion was preceded by an equation that was supposed to prime the completion. We used equations from Scheepers and Sturt (2014), they were used successfully for mathematics to language priming for adjective-noun-noun branching ambiguities. These calculations are simpler compared to Pozniak et al. (2018) and Scheepers et al. (2011). Participants only had to carry out two operations (three numbers) and the order of operations was indicated by parentheses. We hoped to have a better score of correct calculations compared to what has been found in previous experiments. Our view to choose this equation format was to prime only the attachment ambiguity of the sentence. The first type of equation shares common structural properties with non-local RC attachment (high attachment) while the second equation shares common structural properties with local RC attachment (low attachment) (Figure 18).

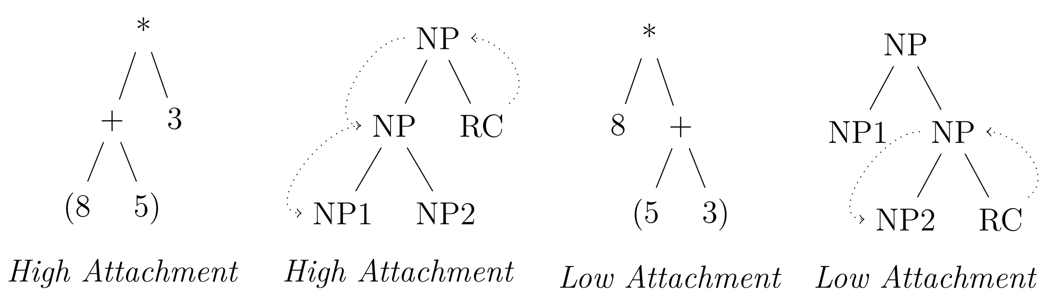

Figure 18: Attachment similarities between syntax and arithmetic.
(We chose to name our nodes NP for simplicity reasons, we are completely aware that they could be named DP.)

Numbers of equations were randomly generated with LibreOffice Calc. 20 fillers were added, one half consisted of unrelated equations and the other half were unrelated uncompleted sentences. These two types of fillers were not paired unlike critical trials.

3.3 Procedure

The experiment was hosted on a website called Ibex farm (Drummond, 2013). Participants had access to the website from their own computers. They were asked for their consent and a small survey was conducted before the experiment: their age, nationality, genre, last diploma obtained, field of study or professional activity, region of birth and native language were requested (see appendix). Participants were advised that they could withdraw their consent to provide their data and were asked to enter a unique code, used for an eventual withdrawal. During a short training, 3 sentences and 5 equations, they were asked for each item to fill a text-box placed at the end of a non-finished sentence or enter the result of an equation. They were asked to imagine a logical and natural continuation for every sentence. The experiment took roughly 15 to 20 minutes to complete. Latin-squared lists were generated automatically by Ibex farm.

3.4 Prediction

We expect perception verbs (NP1 biased because of the PR-first hypothesis) to yield more high attachments in completions than stative verbs (NP2 biased).

We also expect that equations sharing structural properties with non-local RCs yields more high-attachment than equation sharing properties with low-attachment, but only with stative verbs. These equations we used in this experiment are supposed to share structural properties with a RC, not a PR.

3.5 Results

For the analysis of data throughout this master thesis, we used Bayesian analysis (Bürkner et al., 2017): models are systematically maximal which take into account random effects (items and participants) as well as individual random slopes and outputs a probability of effects that suits better a rather exploratory work (frequentist analyses only return binary outputs: either significative or not). Bayesian analyses always allow for maximal models while frequentist maximal models often do not converge.

3.5.1 Main Results

Participants responded correctly to 91,11% of the equation so we did not removed trials with incorrect equations. Overall results of high attachment proportions in the different conditions are shown in Figure 19 and Table 2.

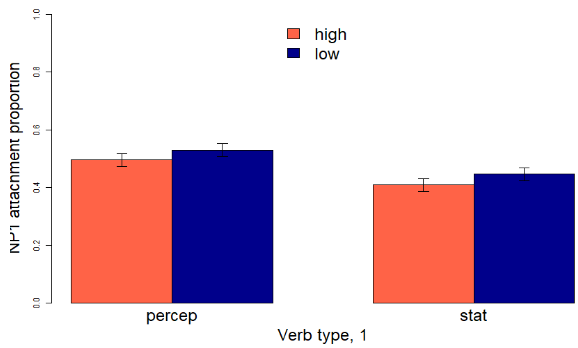

Figure 19: Verb Type, Overall. (Experiment 1)

Perception - High	Perception - Low	Stative - High	Stative - Low
49,49%	52,94%	40,93%	44,60%

(Percentage values are adapted from proportions)

Table 2: Verb Type, Overall. (Experiment 1)

According to our hypothesis on prime exposure, we split our data by median of the time used to solve the equation (6,95 seconds), Figure 20 and Table 3 show proportion of high attachments in the different conditions.

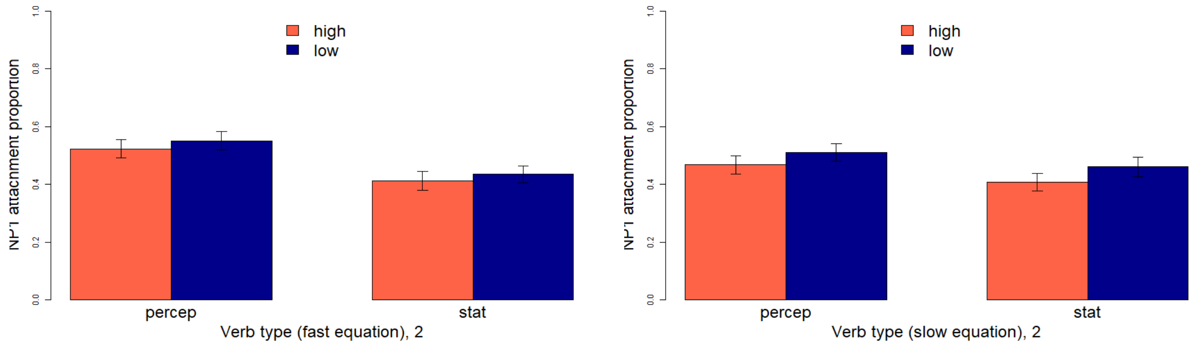

Figure 20: Verb Type, Overall, split by speed of equation. (Experiment 1)

	Perception - High	Perception - Low	Stative - High	Stative - Low
Fast equation	52,23%	55,08%	41,15%	43,43%
Slow equation	46,72%	50,97%	40,75%	46,08%

(Percentage values are adapted from proportions)

Table 3: Verb Type, Overall, split by speed of equation. (Experiment 1)

For the Bayesian analysis of the main results, the dependent variable being the attachment of the RC (NP1 coded as 1, NP2 attachment as 0), we centered predictors: we coded the verb type condition as "-1" for the stative verbs and "1" for the perception verbs; prime condition as "-1" for the high priming condition and "1" for the low priming condition; exposure condition as "-1" for the fast equation and "1" for the slow equation. We used weakly informative priors with 4 chains of 3000 iterations using the *brms* package (Bürkner et al., 2017). Here is the formula used:

```
fit <- brm(comp.graph ~ 1+vt*pr*slow + (1+vt*pr*slow|id) +
(1+vt*pr*slow|Item), data=data, family=bernoulli,
prior=prior, chains=4, iter=3000)
```

We here only report effects and interactions that are at least 80% probable (Figure 21 & Table

4): the verb type effect is 98,9% probable with more high attachments for perception verbs and the prime effect is 93.5% probable with more low attachments after low attachment primes.

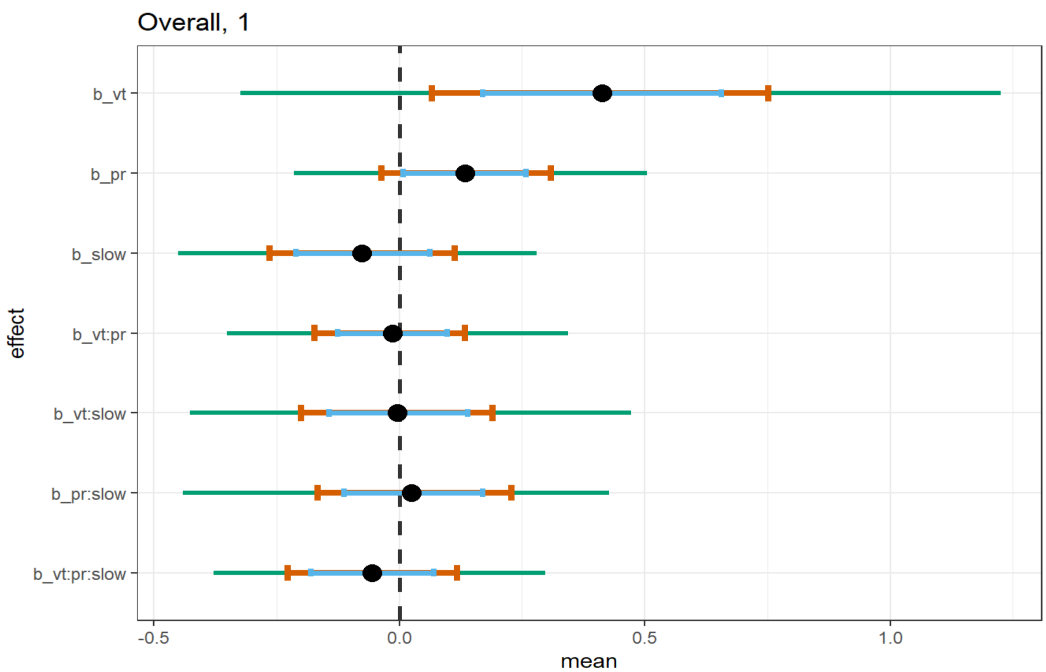

Figure 21: Effects and interactions, Overall. (Experiment 1)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	0.412456703827448	0.9895	0.0105	0.0667350066678774	0.752317287374329
pr	0.133479041323973	0.935	0.065	-0.036819017573957	0.308933450082838
slow	-0.0761342037772634	0.209	0.791	-0.264048038707947	0.112817231117552
vt:pr	-0.0144363037144668	0.419	0.581	-0.172885459127711	0.134254686496873
vt:slow	-0.00387872370143283	0.482333333333333	0.517666666666667	-0.20030006324668	0.190207561134303
pr:slow	0.0252062642563267	0.593166666666667	0.406833333333333	-0.16649686216601	0.229375439955236
vt:pr:slow	-0.0561278312595939	0.2515	0.7485	-0.227308192809156	0.118662013818052

Table 4: Effects and interactions, Overall. (Experiment 1)

3.5.2 Post-hoc analysis

After exploring the data in more detail, we found that the age of the participants seemed to play a crucial role in the results. We used the same model as previously described but added a new variable according to the median age, 27, coding participants below median as "-1" and participants above median as "1". Here is the formula used:

```
fit <- brm(comp.graph ~ 1+vt*pr*slow*ag + (1+vt*pr*slow*ag|id) +
(1+vt*pr*slow*ag|Item), data=data, family=bernoulli,
prior=prior, chains=4, iter=3000)
```

We only report effects and interactions that are at least 80% probable. The verb type effect is 98,8% probable as before. The prime attachment effect is 92% probable again with more high attachments after low attaching primes. The age effect is 99,8% probable. The interaction of verb type and age interaction is 99,8% probable (Figure: 22 & Table 5) with a stronger effect of Verb Type for the above median group.

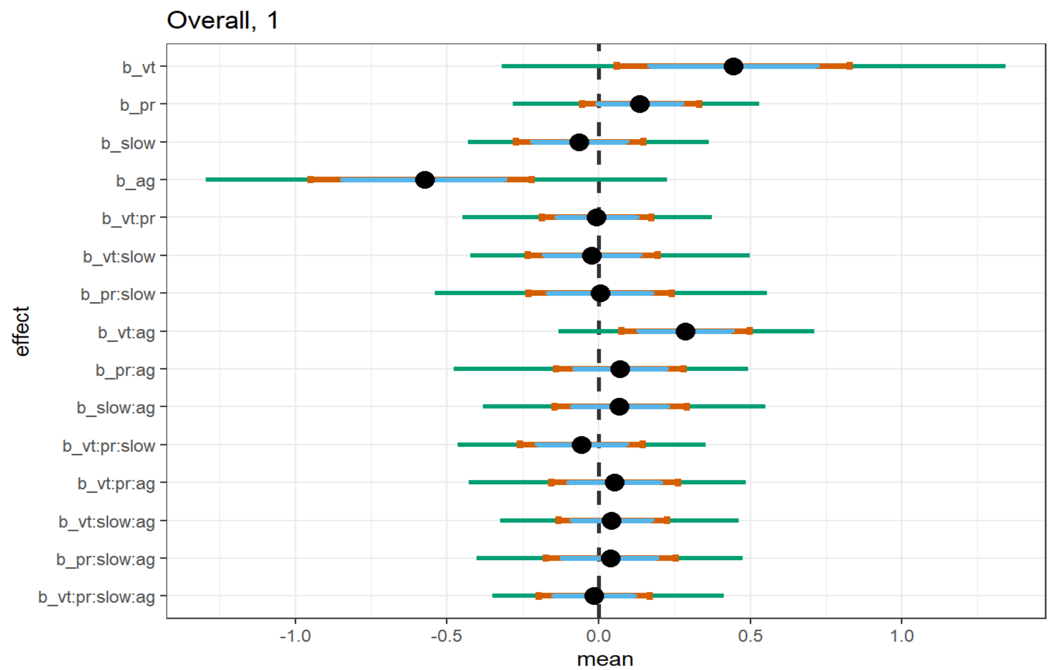

Figure 22: Effects and interactions, Overall with age implemented. (Experiment 1)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	0.443501842677769	0.988	0.012	0.0588759569533817	0.827441040235589
pr	0.13477289116078	0.921333333333333	0.0786666666666667	-0.0536507431933255	0.332521831129462
slow	-0.0635929554388605	0.276	0.724	-0.273033386109544	0.147678328528675
ag	-0.574259940013111	0.000833333333333333	0.999166666666667	-0.950956444785176	-0.220144672063278
vt:pr	-0.00664319763187981	0.471166666666667	0.528833333333333	-0.18753939345914	0.174587345823277
vt:slow	-0.0224532303484061	0.417	0.583	-0.234009574858421	0.194936583404124
pr:slow	0.00423952670348825	0.510166666666667	0.489833333333333	-0.229872358029009	0.242103412262977
vt:ag	0.285896713881795	0.996333333333333	0.00366666666666667	0.0758939748365759	0.497917068325658
pr:ag	0.0693392052099379	0.7385	0.2615	-0.140967581462242	0.280800160605132
slow:ag	0.0688554911151619	0.737666666666667	0.262333333333333	-0.144407826984996	0.290403970160688
vt:pr:slow	-0.0569626015105826	0.279833333333333	0.720166666666667	-0.258808450295291	0.145593603396467
vt:pr:ag	0.052719176276649	0.701333333333333	0.298666666666667	-0.155901253066995	0.261916193479161
vt:slow:ag	0.0426441116714944	0.677166666666667	0.322833333333333	-0.133284487302201	0.225456263157164
pr:slow:ag	0.0383672962903373	0.639333333333333	0.360666666666667	-0.17453181594016	0.254783143131273
vt:pr:slow:ag	-0.0142238234174476	0.433	0.567	-0.198182255927275	0.169545570975465

Table 5: Effects and interactions, Overall with age implemented. (Experiment 1)

Because age had a strong probability effect and the interaction of age with Verb Type, we divided our data in two groups, below and above median age groups (27), to go further in the analyses. Results for the below median age group are shown in Figure 23 and Table 6 Differences for fast and slow equations are shown in Figure 24 and Table 7. The median for the time used to solve equations is 6,61 seconds for the below median age group.

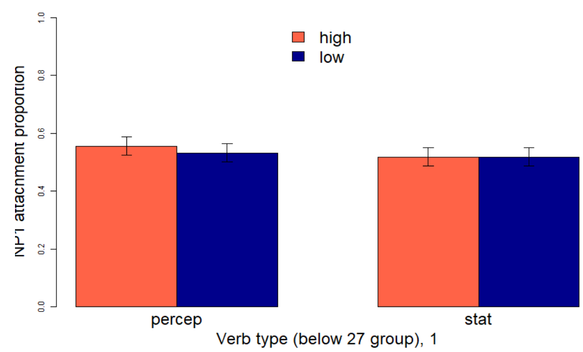

Figure 23: Verb Type, age below 27. (Experiment 1)

Perception - High	Perception - Low	Stative - High	Stative - Low
55,55%	53,2%	51,81%	51,81%

(Percentage values are adapted from proportions)

Table 6: Verb Type, age below 27. (Experiment 1)

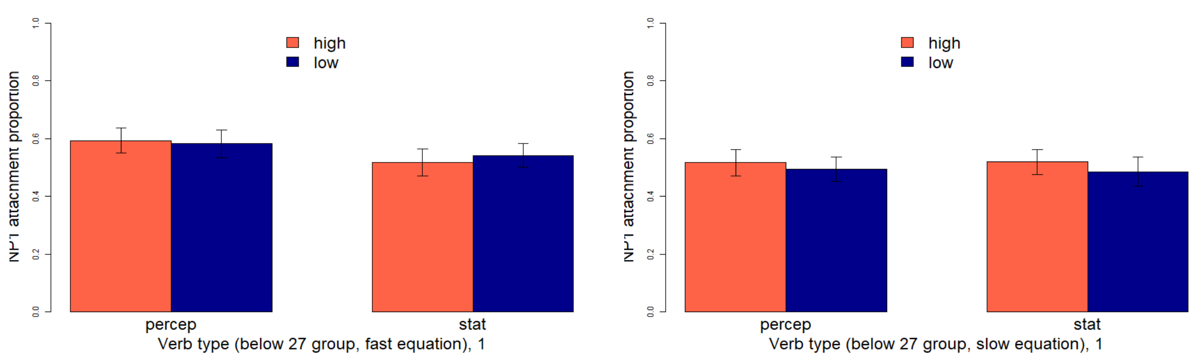

Figure 24: Verb Type, age below 27, split by speed of equation (Experiment 1)

	Perception - High	Perception - Low	Stative - High	Stative - Low
Fast equation	59,23%	58,18%	51,75%	54,11%
Slow equation	51,63%	49,29%	51,85%	48,54%

(Percentage values are adapted from proportions)

Table 7: Verb Type, age below 27, split by speed of equation (Experiment 1)

For the Bayesian analysis, we used the same model as previously described minus the age variable. We used this formula:

```
fit <- brm(comp.graph ~ 1+vt*pr*slow + (1+vt*pr*slow|id) +
(1+vt*pr*slow|Item), data=data, family=bernoulli,
prior=prior, chains=4, iter=3000)
```

The Bayesian analysis of the below median age group returned a probable effect for the verb type at 86,51%; for the prime attachment at 82,35% and for the speed of equation at 84,87% (Figure 25 & Table 8).

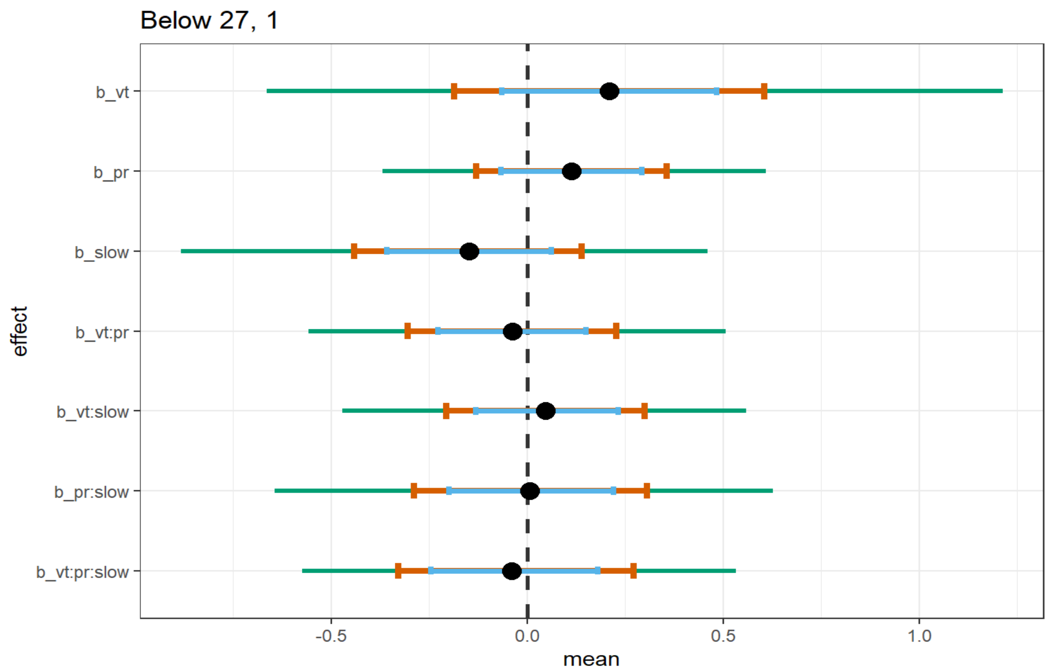

Figure 25: Effects and interactions, age below 27. (Experiment 1)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	0.208973575999622	0.865166666666667	0.134833333333333	-0.185691591505606	0.605006257206991
pr	0.112944178029635	0.8235	0.1765	-0.129810466705748	0.355108396673614
slow	-0.147782110217314	0.151333333333333	0.848666666666667	-0.440623417171968	0.139930411759136
vt:pr	-0.0380655043626806	0.388166666666667	0.611833333333333	-0.30452998254804	0.226462439674221
vt:slow	0.0474662046390556	0.650166666666667	0.349833333333333	-0.207306887270409	0.298933928498104
pr:slow	0.00737161535103116	0.511333333333333	0.488666666666667	-0.288019763416188	0.30483655901951
vt:pr:slow	-0.0404756238327904	0.373833333333333	0.626166666666667	-0.3284983849725 02	0.271249298052534

Table 8: Effects and interactions, age below 27. (Experiment 1)

Results for the above median age group are shown in Figure 26 and Table 9 Differences for fast and slow equations within this group are shown in Figure 27 and Table 10. The median for the time used to solve equations is 7,33 seconds for the above median age group.

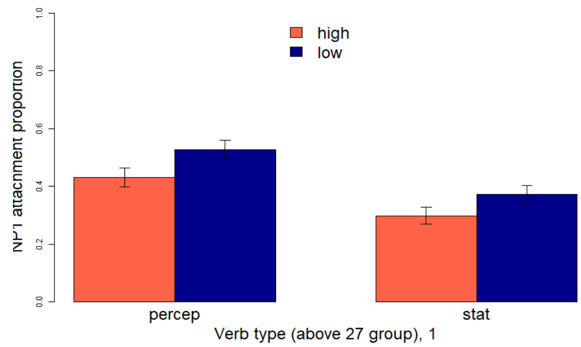

Figure 26: Verb Type, age above 27. (Experiment 1)

Perception - High	Perception - Low	Stative - High	Stative - Low
43,1%	52,67%	29,75%	37,19%

(Percentage values are adapted from proportions)

Table 9: Verb Type, age above 27. (Experiment 1)

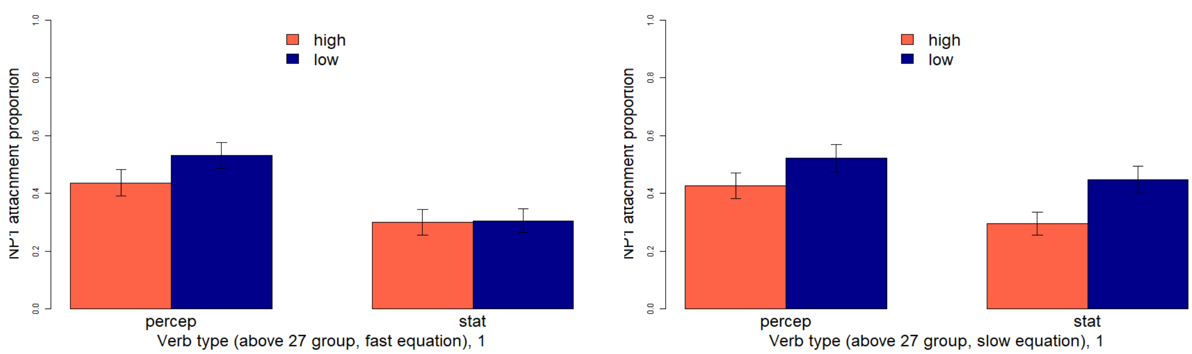

Figure 27: Verb Type, age above 27, split by speed of equation. (Experiment 1)

	Perception - High	Perception - Low	Stative - High	Stative - Low
Fast equation	43,58%	53,12%	30%	30,46%
Slow equation	42,62%	52,17%	29,54%	44,73%

(Percentage values are adapted from proportions)

Table 10: Verb Type, age below 27, split by speed of equation (Experiment 1)

The Bayesian analysis of the above median age group, using the same parameters as previously described, returned a probable effect for the verb type at 99,8% with more high attachments for perception verbs; for the prime attachment 94,6% with more high attachments for low attachment primes; for the verb type and prime interaction 80,1% and for the verb type, prime attachment and speed of equation interaction 83,2% with a priming effect only for perception verbs for fast equations and priming effects for both verb types for slow equations (Figure 28 & Table 11).

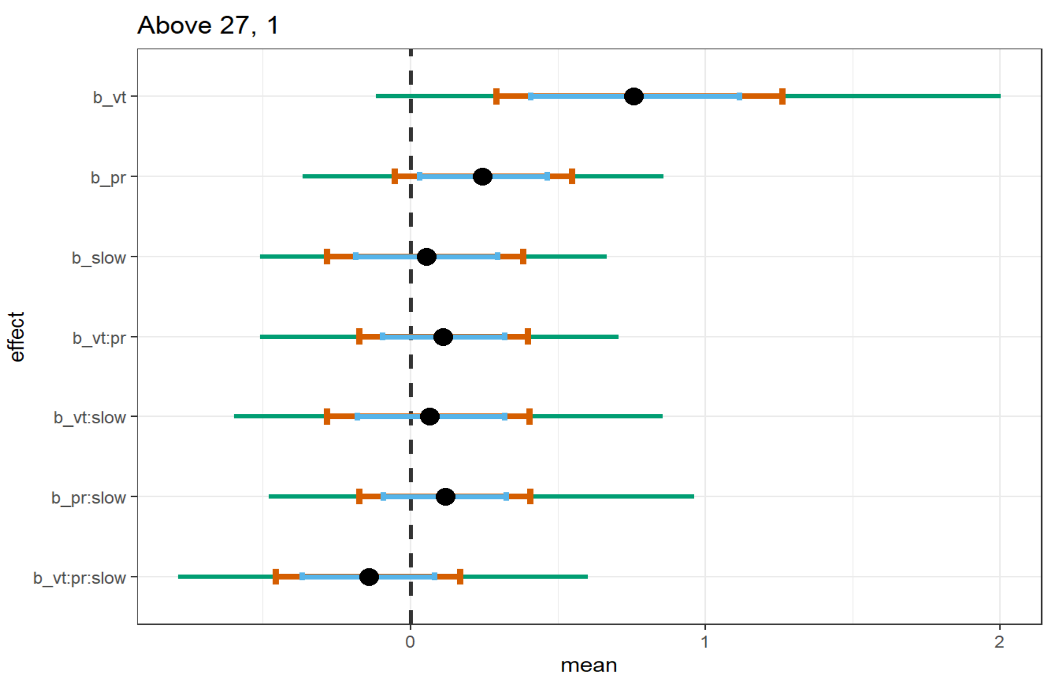

Figure 28: Interaction and effects, age above 27. (Experiment 1)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	0.757293199776373	0.999666666666667	0.000333333333333333	0.291488927937219	1.2614835084114
pr	0.243758770665985	0.953	0.047	-0.0537447872983177	0.549464876422164
slow	0.0542943517691886	0.626166666666667	0.373833333333333	-0.282623634090306	0.382589387484055
vt:pr	0.111262852878649	0.778	0.222	-0.173442944001571	0.398019787299132
vt:slow	0.0646215021611068	0.65	0.35	-0.281660689411661	0.405530427436726
pr:slow	0.118247310142375	0.796666666666667	0.203333333333333	-0.173423764978095	0.405954371772161
vt:pr:slow	-0.141652151903412	0.179833333333333	0.820166666666667	-0.455871255152371	0.169155712227157

Table 11: Interaction and effects, age above 27. (Experiment 1)

3.6 Discussion

In this experiment, we replicated the difference in attachments preferences between perception and stative verbs. We also observed a possible priming effect. However, this effect was the opposite of our prediction: The low attachment condition had a higher proportion of high attachments than the high attachment condition. This effect showed up in particular in the >27 group. Finally, still for the >27 group, exposure time (defined as the time participants needed to calculate the result of the mathematical formula) to the prime yielded a more prominent priming effect.

The fact that perception verbs yield more high attachments adds more evidence to the current PR literature. Why did we only find clear preferences for the >27 group? We think that the lack of a controlled (laboratory) setting for this experiment contributed to distraction in particular for the lower-aged group while the >27 group remained focused on the task, this may be why we observe smaller to no effects for the lower-aged group. For this reason, we consider the lower-aged group as not reliable and we will not include it in our discussion. The priming effect being more prominent when the length of prime exposure is compatible with evidence from the priming literature as long as participants are not aware of the prime (which generally was the case in our experiments). However, this priming effect goes in the wrong direction compared to our predictions, the proportion of high-attachments is higher in the low priming condition. Although this is obviously very speculative, we suggest that what is primed in the low priming condition is the closure of the complex NP instead of the attachment preference. As in Figure 29 and Figure 30 show, the parenthesis after the "3" marks the right edge and the end of the structure, and may thus prime the prohibition of the continuation of the NP, indirectly resulting in a high attachment priming for the incoming RC.

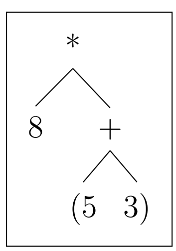

Figure 29: Low attachment prime

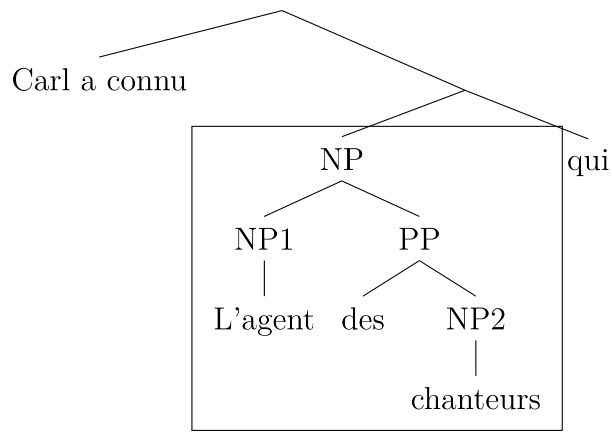

Figure 30: Low attachment prime resemblance with a closed NP

As previously discussed in the Introduction, parenthesis seem to play an important role in the processing of mathematical structure: for example, the appearance of the opening parenthesis in mathematics elicits a P600 (Martín-Loeches et al., 2006). In this experiment, the closing parenthesis in the mathematical formula may have primed a closed complex NP.

This rejoins the disambiguation and early closure literature, but we think that prosody may play an important role here. If the prosodic realization of a structure NP1-NP2-RC ("Someone shot the servant of the actress who was on the balcony") has a pause between the NP2 and the RC, a high attachment preference of the RC has been found (Jun, 2003) (See also (Jun & Bishop, 2015; Kuang, 2010). The closing parenthesis may be interpreted either has a closure of a given structure or a ”prosodic comma” and thus result in the pattern we found here: it primes the parser to close the complex NP and attach the incoming RC high.

To address the multiple problems in this, we decided to pass further experiments directly at the laboratory to have a more controlled experimental setting and we used the equation format previously applied for the RC attachment ambiguity to make sure that we prime structure similarities. Our hypotheses on the prosodic priming by parentheses certainly merit more attention but will have to be part of future research.

4 Second Experiment

Because we had such small probabilities of effects, priming going the opposite of our predictions and problems of attention in the younger group, we decided to no longer run the experiment in an uncontrolled environment but in more reliable experimental settings in the lab at the Unversity of Paris. We also used equations previously utilized to prime RC attachment ambiguity.

4.1 Participants

We had 36 participants, all native French speakers, only one was excluded for not having French as a native language. They were recruited using the RISC site (`https://www.risc.cnrs.fr`) and University's social networks. The mean age of the participants was 38.08 and the oldest participants was 75 while the youngest was 18. They were 10 men and 25 women.

4.2 Material

Like the first experiment, this was also a two by two experiment with now 28 items using stative vs. perception verbs and low vs high priming as experimental factors (table 12). Participants were asked to finish a sentence containing a complex NP in object position followed by "who", which forces them to produce a RC. As before, half of the items had a plural NP1 and a singular NP2 while the other half had a singular NP1 and the plural NP2. This difference of number between the two NPs allows to define the attachment of the RC as intended by the participants. Each critical sentence, the target, was preceded by an equation, the prime. The structural priming, either high or low, caused by the equation is supposed to impact on the attachment preference of the produced RC. This priming effect should only be observed only in the stative condition of the factor Verb Type. The major difference with the first experiment is the format of the equations, we used the same equation format as Scheepers et al. and Pozniak et al. did (Figure 12 & Figure 11).

Stative verbs	high priming: 80-(9+1)*5	Carl a connu l'agent des chanteurs qui ...
Stative verbs	low priming: 80-9+1*5	Carl a connu l'agent des chanteurs qui ...
Perception verbs	high priming: 80-(9+1)*5	Carl a vu l'agent des chanteurs qui ...
Perception verbs	low priming: 80-9+1*5	Carl a vu l'agent des chanteurs qui ...

Table 12: Experiment 2 Design

4.3 Procedure

The experiment was hosted on the website Ibex farm (Drummond, 2013) but participants were asked to come to the university to pass the experiment. They were asked for their consent and a small survey was conducted before the experiment: their age, nationality, genre, last diploma obtained, field of study or professional activity, region of birth and native language were requested (see appendix). Participants were asked to enter a unique code, used for an eventual withdrawal of their data. They completed a brief practice session before the experiment with 3 sentences and 5 equations. For each trial, they had to either fill a text-box of a non-finished sentence or enter the result of an equation. Participants were authorized to solve equations with the use of a blank paper. The experiment was designed to last approximately 30 minutes and paid 5€, but due to high variation between participants, it took between 20 and 50 minutes. Participants were paid accordingly to the time they spent on the experiment. Latin-squared lists were generated automatically by Ibex farm.

4.4 Predictions

Predictions are the same as in Experiment 1, we expect more high attachments with perception than stative verbs. We also expect the high-priming condition to return more high attachments than the low-priming condition, but only within the stative condition.

4.5 Results

4.5.1 Main results

Figure 31 and table 13 show proportion of high attachments in the different conditions.

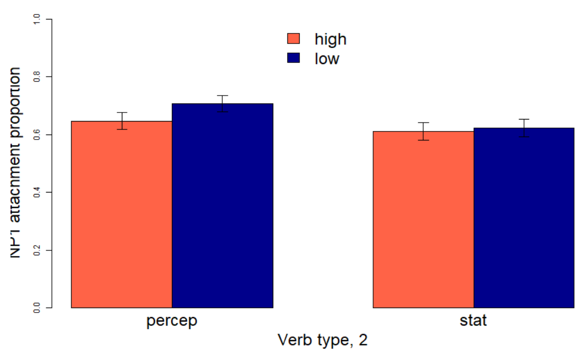

Figure 31: Verb Type, overall. (Experiment 2)

Perception - High	Perception - Low	Stative - High	Stative - Low
64,68%	70,63%	61,11%	62,30%

(Percentage values are adapted from proportions)

Table 13: Verb Type, overall. (Experiment 2))

Figure 32 and table 14 show proportions of high attachments for the fast and slow equations determined by the median of time passed for the equation, 24,64 seconds.

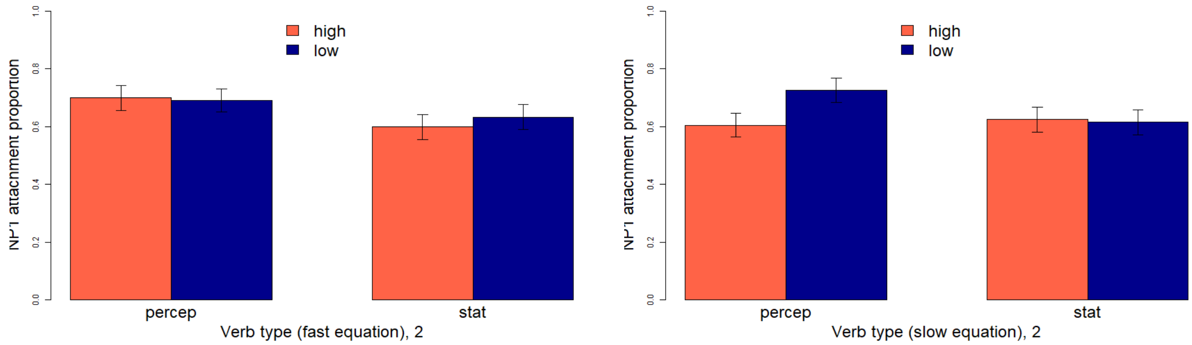

Figure 32: Verb Type, overall, median-split by speed. (Experiment 2)

	Perception - High	Perception - Low	Stative - High	Stative - Low
Fast equation	69,91%	69,04%	59,84%	63,2%
Slow equation	60,43%	72,57%	62,4%	61,41%

(Percentage values are adapted from proportions)

Table 14: Verb Type, overall, median-split by speed. (Experiment 2)

For the Bayesian analysis of the main results, the dependent variable being the attachment of the RC (NP1 coded as 1, NP2 coded as 0), we centered predictors: we coded the verb type predictor as "1" for the stative verbs and "-1" for the perception verbs, the prime predictor as "-1" for the high priming condition and "1" for the low priming condition, exposure as "-1" for fast equations and "1" for slow equations. We also added the a predictor correctness of equation (mathematical skill of the participant) as "-1" for below two third correct equations and as "1" for above the two third. We will talk about these results in more detail in the following section. We used weakly informative priors with 4 chains of 3000 iterations using the *brms* package (Bürkner et al., 2017). Here is the formula used:

```
fit <- brm(attachment ~ 1+vt*pr*slow*cor + (1+vt*pr*slow*cor|id) +
(1+vt*pr*slow*cor|Item), data=data, family=bernoulli,
prior=prior, chains=4, iter=3000)
```

We only report effects with at least 80% probability (Figure 33 & Table ??). The verb type effect is at 95,6% with more high attachments for perception verbs. The prime effect is at 87% with more high attachments after low attachment primes. The speed of equation effect is at 90% with more high attachments for fast equations. The verb type and prime interaction is at 81% with a stronger priming effect for perception verbs. The prime and speed for equation interaction is at 89,2% with a stronger priming effect for slow equations. The verb type, prime and speed for equation interaction is at 87,4% with a priming effect only for perception verbs in the slow equation condition. The verb type, prime and correctness for equation is at 81,6% (see next section for details).

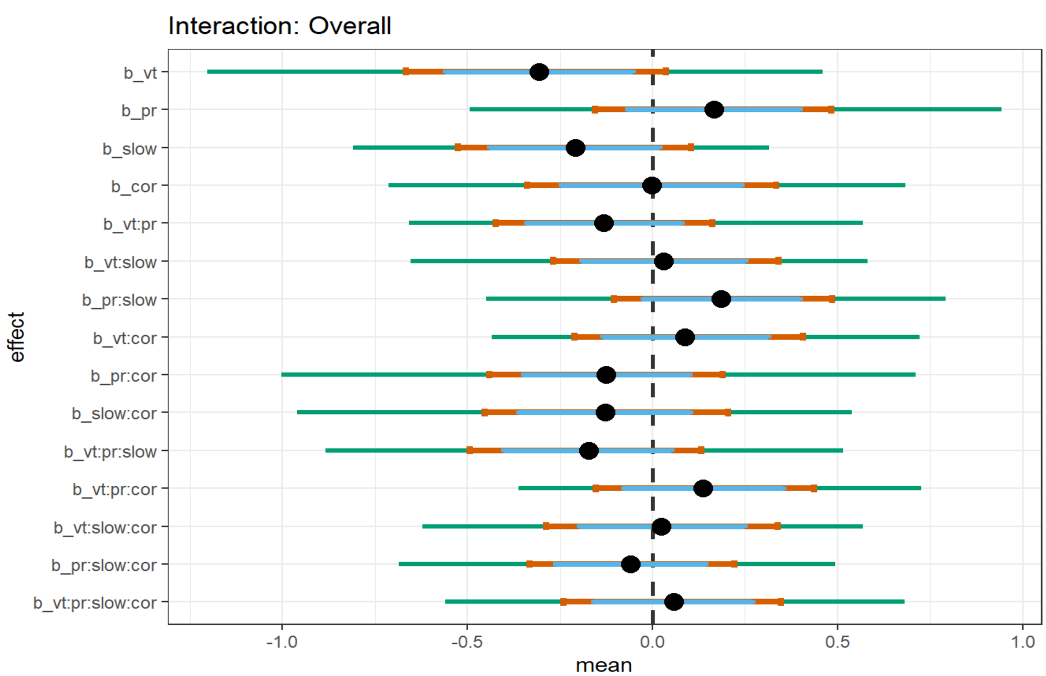

Figure 33: Interaction and effects, overall. (Experiment 2)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	-0.305855621901149	0.0385	0.9615	-0.666705185840254	0.0366872272062441
pr	0.167000328613684	0.850833333333333	0.149166666666667	-0.156169126575488	0.483087595104826
slow	-0.20831122017414	0.0948333333333333	0.905166666666667	-0.526135108668358	0.104206716269077
cor	-0.00168145730567843	0.492833333333333	0.507166666666667	-0.338058178873434	0.334633078530574
vt:pr	-0.132182850544436	0.178333333333333	0.821666666666667	-0.42453004338882	0.161169904445873
vt:slow	0.0307522350842401	0.579833333333333	0.420166666666667	-0.267796404398078	0.341115985843905
pr:slow	0.184469551392253	0.8975	0.1025	-0.103788000143094	0.486520698163199
vt:cor	0.0871386900621526	0.710166666666667	0.289833333333333	-0.210957451511905	0.407722843815853
pr:cor	-0.125070215102502	0.211166666666667	0.788833333333333	-0.44165142770766	0.188483719685458
slow:cor	-0.12705886745938	0.203666666666667	0.796333333333333	-0.454118794589209	0.205163181522679
vt:pr:slow	-0.172442607095698	0.129	0.871	-0.492936207831746	0.131791440753009
vt:pr:cor	0.13647375432265	0.816833333333333	0.183166666666667	-0.153193595502703	0.436072452964983
vt:slow:cor	0.0242323863263487	0.560833333333333	0.439166666666667	-0.286969641802292	0.338468269957884
pr:slow:cor	-0.058584332245543	0.336166666666667	0.663833333333333	-0.332752689572563	0.221112349592048
vt:pr:slow:cor	0.0564950327532732	0.653833333333333	0.346166666666667	-0.241524961529221	0.34813112932111

Table 15: Interaction and effects, overall. (Experiment 2)

4.5.2 Post-hoc analysis

To shed more light on the interaction with mathematical skill, we then analyzed mathematically non-skilled and skilled participants separately (Mathematical priming effects seems to be more prominent with participants which are more at ease with mathematics (Scheepers et al., 2011; Pozniak et al., 2018)). In order to determine which participants were skilled, we divided them in two groups, those who correctly responded to at least two thirds of the equations (14) (at least 19 correct responses) and those who did not (22).

Figure 34 and table 16 show proportion of high attachment in the different conditions for the mathematically non-skillful group.

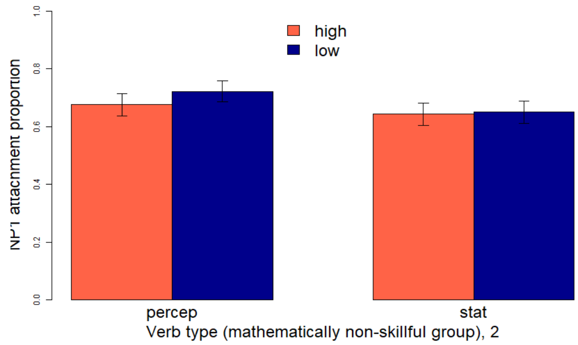

Figure 34: Verb Type, mathematically non-skillful group. (Experiment 2)

Perception - High	Perception - Low	Stative - High	Stative - Low
67,53%	72,08%	64,28%	64,93%

(Percentage value are adapted from proportion)

Table 16: Verb Type, mathematically non-skillful group. (Experiment 2)

Figure 35 and table 17 show proportion of high attachments for the fast and slow equation (determined by the median: 29,32 seconds) within the mathematically non-skillful group.

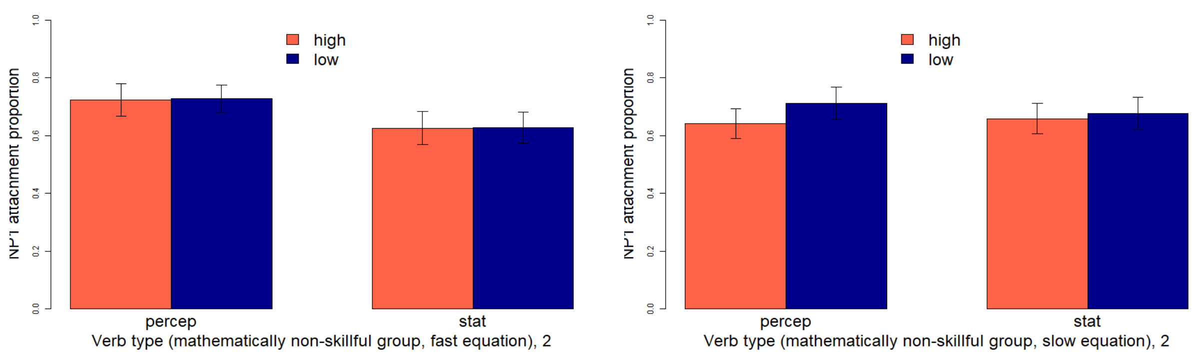

Figure 35: Verb Type, mathematically non-skillful group, split by speed of equation. (Experiment 2)

	Perception - High	Perception - Low	Stative - High	Stative - Low
Fast equation	72,31%	72,73%	62,5%	62,65%
Slow equation	64,04%	71,21%	65,85%	67,61%

(Percentage values are adapted from proportions)

Table 17: Verb Type, mathematically non-skillful group, split by speed of equation. (Experiment 2)

For the analysis of the mathematically non skillful group, we use the same model as described in the Main Results, minus the correctness of equation variable, returning a probable effect of verb type of 86,4%, a probable effect of speed of equation at 85,8% and a probable interaction of verb type and speed of equation at 90% (Figure 36 & Table 18). Directions of effects were the same as in the main results but with smaller probabilities.

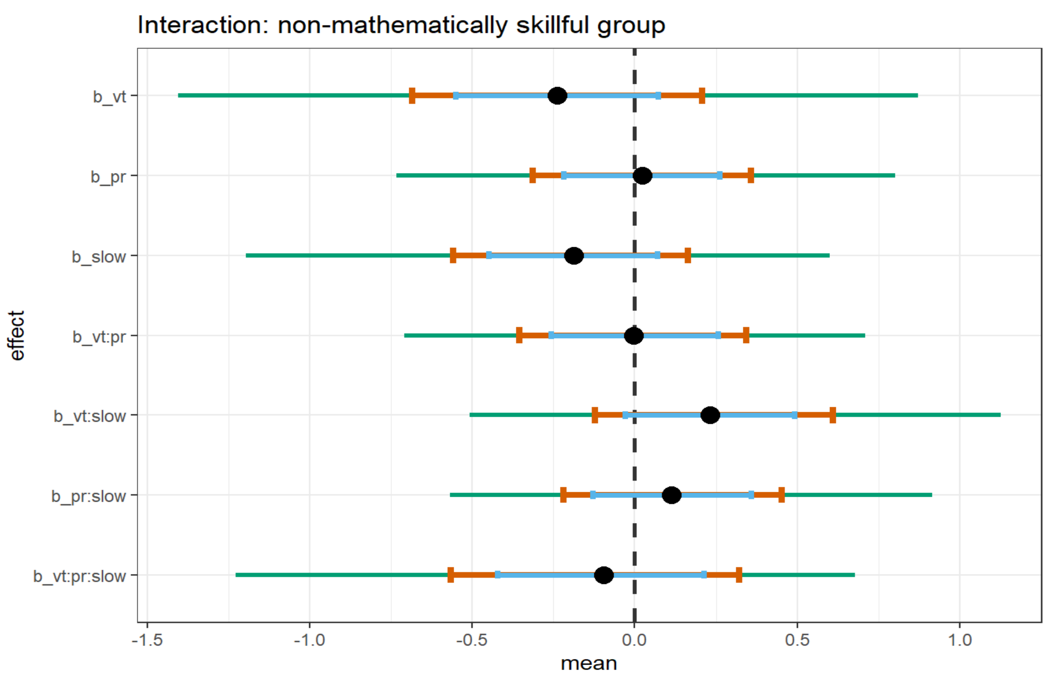

Figure 36: Effects and interactions, mathematically non-skillful group. (Experiment 2)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	-0.239194637201739	0.136166666666667	0.863833333333333	-0.684150959457583	0.20763187745128
pr	0.022870636367156	0.565	0.435	-0.313938058505759	0.356938110555139
slow	-0.188658660434889	0.141666666666667	0.858333333333333	-0.558665289915747	0.164198879389498
vt:pr	-0.00444604154707136	0.485833333333333	0.514166666666667	-0.354989041516219	0.342220323647246
vt:slow	0.231641953433894	0.899833333333333	0.100166666666667	-0.122938212504027	0.609680818692575
pr:slow	0.113319097088942	0.754	0.246	-0.219856057107105	0.451652193081657
vt:pr:slow	-0.0958008964157777	0.3355	0.6645	-0.565802585978775	0.320590899254337

Table 18: Effects and interactions, mathematically non-skillful group. (Experiment 2)

Figure 37 and table 19 show proportion of high attachments in the mathematically skilled group for the different conditions.

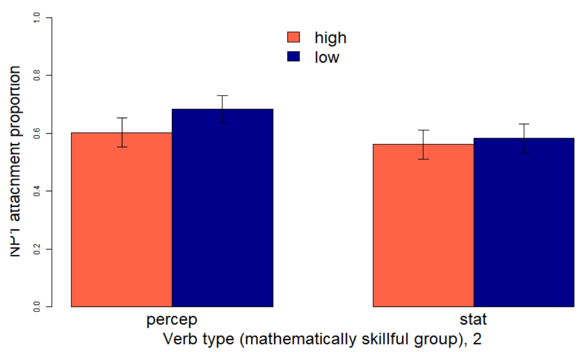

Figure 37: Verb Type, mathematically skilled group. (Experiment 2)

Perception - High	Perception - Low	Stative - High	Stative - Low
60,2%	68,37%	56,12%	58,16%

(Percentage values are adapted from proportions)

Table 19: Verb Type, mathematically non-skillful group. (Experiment 2)

Figure 38 and table 20 show proportion of high attachments for the fast and slow equation (determined by the median: 17,92 seconds) within the mathematically skilled group.

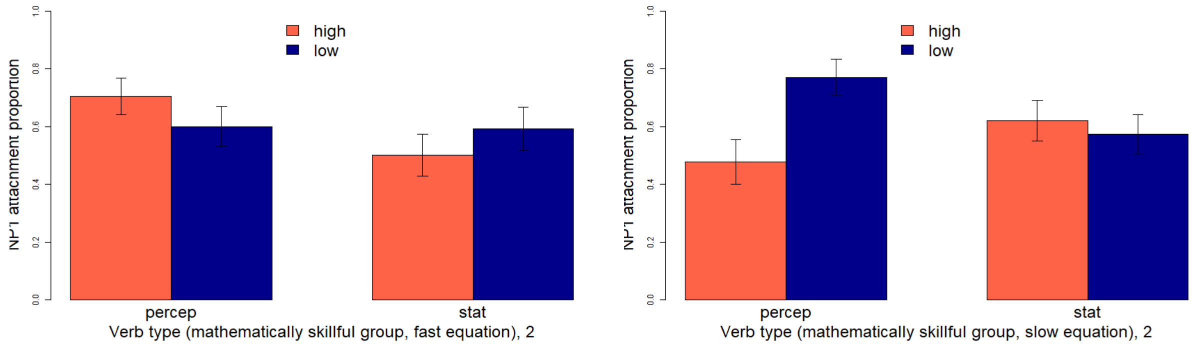

Figure 38: Verb Type, median-split by speed in equations within the mathematically skilled group. (Experiment 2)

	Perception - High	Perception - Low	Stative - High	Stative - Low
Fast equation	70,37%	60%	50%	59,09%
Slow equation	47,73%	77,08%	62%	57,41%

(Percentage values are adapted from proportions)

Table 20: Verb Type, mathematically non-skillful group, split by speed of equation. (Experiment 2)

We then fitted the same Bayesian model (as for the non-mathematically skillful group) to data from the mathematically skillful group. We only report effects higher than 80% (Figure 39 & Table 21). The verb type effect is at 89,23%. The speed of equation effect is at 80,46%. The verb type, prime and speed of equation interaction effect is at 98,02% with more high attachments for perception verbs after low attachment primes only for for slow equations.

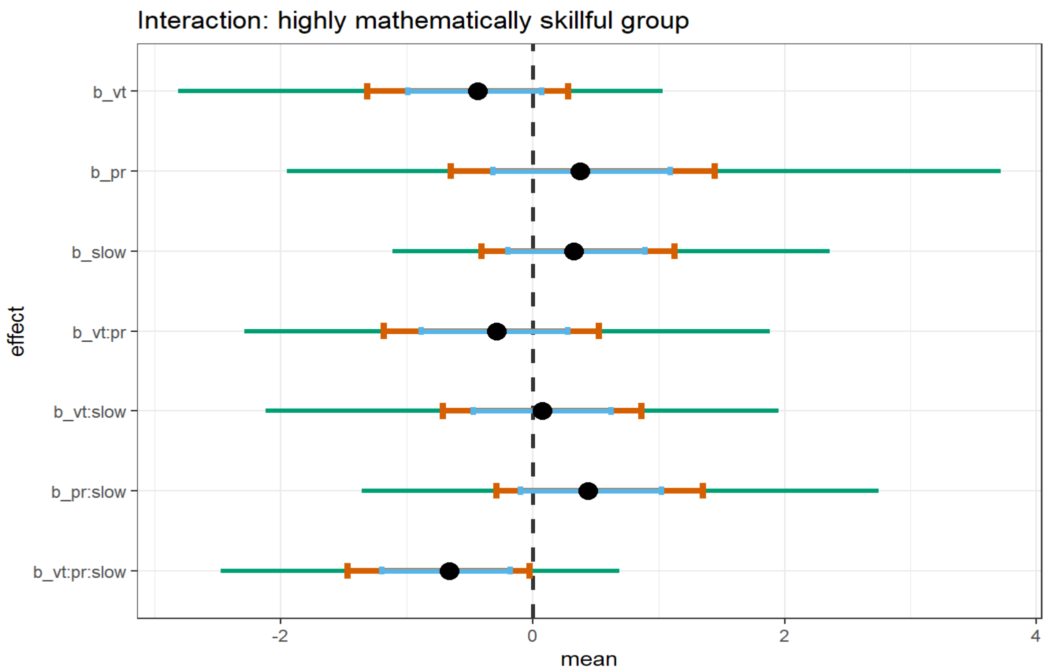

Figure 39: Interaction and effects, mathematically skilled group. (Experiment 2)

effect	mean	prob_greater	prob_smaller	l95	h95
vt	-0.440350862080358	0.107666666666667	0.892333333333333	-1.31364182299026	0.279073881623822
pr	0.374482889647566	0.791	0.209	-0.653423862318165	1.44407967599555
slow	0.322693888669397	0.804666666666667	0.195333333333333	-0.408734039160594	1.12573566673305
vt:pr	-0.284618204252473	0.235666666666667	0.764333333333333	-1.18364584633892	0.526522309483625
vt:slow	0.0761815652038037	0.595166666666667	0.404833333333333	-0.712080749145235	0.864312693013139
pr:slow	0.436810093350964	0.8825	0.1175	-0.290256517261496	1.35480060872084
vt:pr:slow	-0.66102346964689	0.0198333333333333	0.980166666666667	-1.47255429745413	-0.0264087204749731

Table 21: Interaction and effects, mathematically skilled group. (Experiment 2)

4.6 Discussion

Before discussing the main results of this experiment, we would like to point out a major misleading and wrong structure in the mathematical priming literature. In the paper of Scheepers et al., the authors propose a structural representation of the mathematical formula that is supposed to resemble a low-attachment syntactic structure (Figure 40). However, we think that there is one critical error in this representation. The representation of the equation "$80 - 9 + 1 \times 5$", suggests a combinatory sequence where the first operation is to multiply "1 x 5", then add 9 to the result and finally subtract this result from 80. However, this is not how people calculate (and arrive at the expected result. They rather start with "80-9", then calculate "1*5" or the other way around and subtract the latter result from the first leading to a different representation (Figure 41). To have an equation that correctly resemble a low-attachment structure, we should use "$80 - (9 + 1 \times 5)$" (Figure 42).

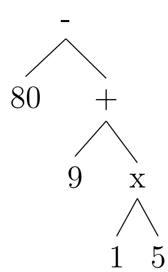

Figure 40: Wrong structure representation for a low attachment priming

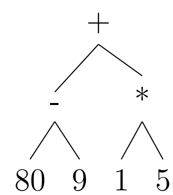

Figure 41: Actual structure representation for a low attachment priming

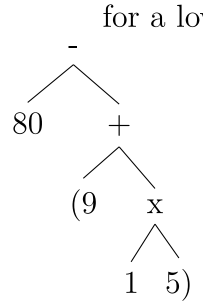

Figure 42: Correct structure representation for a low attachment priming

We believe that starting an operation at the right edge still may have a priming effect as observed in previous publications (and Experiment 3), but this effect might not be due to structural priming but a sequence of operations. Unfortunately, we realized this after the third experiment so it still has the equation we now consider as inadequate.

The most unexpected pattern we found in this experiment was the increased number of high attachments for sentences with perception verbs (pseudo relative environments) in the case of longer calculation time and skillful participants. This may be explained by the actual structure of the low attachment prime: this structure being parallel in many ways greatly resembles a PR, hence the major increase of high-attachments. For the static low-priming condition, we observe almost no difference (from 59% to 57%) because this structure does not resemble a low-priming attachment. For the static and high-priming condition, the rise of high-attachments (from 50% to 62%) may be due to a mathematical structural priming effect, but the difference being too close with the stative and high-priming condition, we don't interpret this result as a successful priming effect.

5 Third Experiment

One of the differences between our experiments and previous ones was that we added Perception verbs. This may have an experimental context effect that has the lack of priming on statives as a consequence. Therefore, in the third experiment, we followed what has been previously done in the literature, that is to say to have less conditions: we removed Perception verbs. To have less variation in the duration of the experiment, we used smaller numbers in the equations and reduced the number of items. We also changed the equation format as in the second experiment of Scheepers et al., adding redundant parentheses to correctly indicate the order of operations. This has led to greater priming effects in a less mathematically skilled group in earlier work.

5.1 Participants

We had 34 participants, all native French speakers (2 additional participants were excluded for not having French as their native language). They were recruited using the RISC (https://

www.risc.cnrs.fr) and University's social networks. Mean age was at 31.67 and the oldest participants was 76 while the youngest was 18. They were 11 men and 23 women.

5.2 Material

This experiment had only two-conditions (high and low attachment primes) to fall in line with most priming experiments in the literature. It used the same target stimuli as Experiment 2 for sentences minus 8 items making it a 20 items experiment. Targets were incomplete sentences containing a complex DP (one NP embedded within a NP) in object position followed by "qui" (who) thus enforcing the participants to produce a RC. In these sentences, half of the items had a plural NP1 and a singular NP2 while the other half had a singular NP1 and the plural NP2. This difference in number between the two NPs allows to define the attachment of the RC as intended by the participants. As for the primes, we changed the format of the equation using redundant parentheses (Scheepers et al., 2011). Those parentheses indicate the correct order of calculation for addition, subtraction and multiplication priority, which makes them redundant in this case. They showed better accuracy levels for mathematically less skilled participant in previous experiments. We used smaller numbers, from 2 to 5, for equations as well (except the very high number at the beginning) to reduce variation between participants. Following evidence from psychology, we also made sure to not have operations using the same number because they have a processing advantage (Blankenberger, 2001; Campbell & Graham, 1985; Miller, Perlmutter, & Keating, 1984) and not use multiplication with 1 because they appear to be solved by using a separate rule (Sokol, McCloskey, Cohen, & Aliminosa, 1991).

high priming: 80-((2+3)*4)	Carl a connu l'agent des chanteurs qui ...
low priming: 80-2+(3*4)	Carl a connu l'agent des chanteurs qui ...

Table 22: Experiment 3 Design

5.3 Procedure

The experiment was hosted on the website Ibex farm (Drummond, 2013) but participants had to come to the university to pass the experiment. They were asked for their consent and a small survey was conducted before the experiment: their age, nationality, genre, last diploma obtained, [U+FB01]eld of study or professional activity, region of birth and native language were requested (see appendix). Participants were asked to enter a unique code, used for an eventual withdrawal of their data. They completed a brief practice session before the experiment, 3 sentences and 5 calculations. For each trial, they had to either fill a text-box of a non-finished sentence or enter the result of a given equation. Participants were no longer authorized to use a paper to solve equations. The experiment took approximately 25 minutes. Participants were paid 5€ when they completed the experiment. Latin-squared lists were generated automatically by Ibex farm.

5.4 Prediction

We expect more high attachments with the high-attachment prime than with the low-attachment prime.

5.5 Results

5.5.1 Main Results

Overall, the percentage of high attachment for the low and high priming condition is at 55,59% (Figure 43).

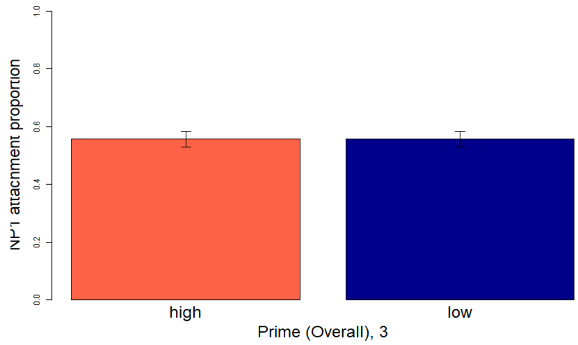

Figure 43: Prime, overall. (Experiment 3)

Figure 44 and Table 23 show the differences of high attachments for fast and slow equation (determined by the median of time passed to solve the equation: 16,31 seconds).

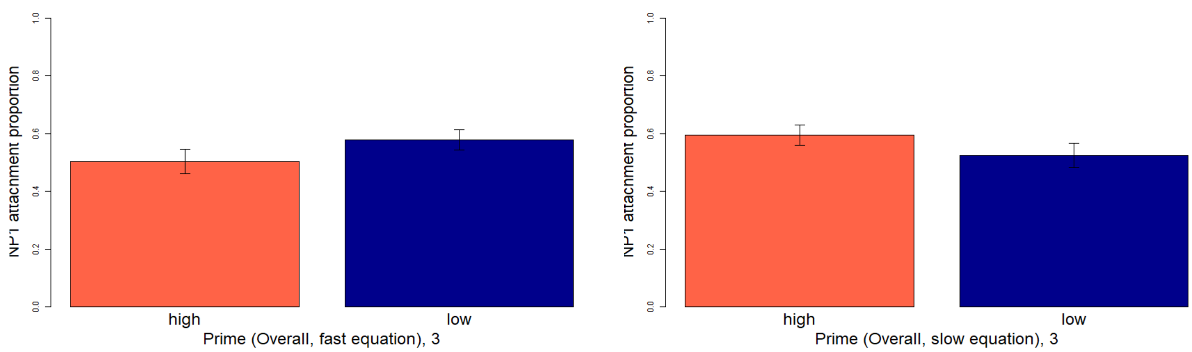

Figure 44: Prime, overall, median-split by speed of equations. (Experiment 3)

	High	Low
Fast equation	50,35%	57,87
Slow equation	59,39%	52,45%

(Percentage values are adapted from proportions)

Table 23: Prime, overall, median-split by speed of equations. (Experiment 3)

For the Bayesian analysis of the main results, the dependent variable being the RC attachment (coded as 1 for NP1 and 0 for NP2), we centered predictors: prime condition as "-1" for the high priming condition and "1" for the low priming condition; exposure condition as "-1" for the fast equation and "1" for the slow equation and correctness of equation as "-1" for below two thirds of correct equations and as "1" for above the two thirds. We used weakly informative priors with 4 chains of 3000 iterations using the *brms* package (Bürkner et al., 2017). Here is the formula used:

```
fit <- brm(attachment ~ 1+pr*slow*cor + (1+pr*slow*cor|id) +
(1+pr*slow*cor|Item), data=data, family=bernoulli,
prior=prior, chains=4, iter=3000)
```

The model returned a probable effect of speed of equation at 89,3% probable (Figure 45 & Table 24).

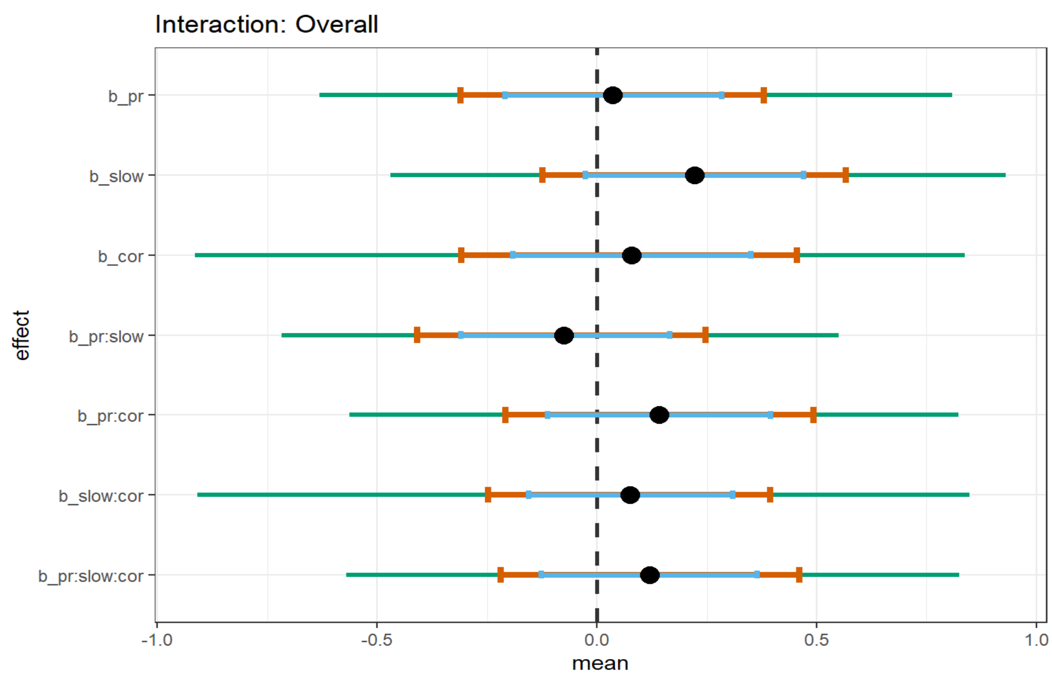

Figure 45: Interaction and effects, overall. (Experiment 3)

effect	mean	prob_greater	prob_smaller	l95	h95
pr	0.0357612372923316	0.585	0.415	-0.312424733779682	0.383879377435383
slow	0.217293222323171	0.893333333333333	0.106666666666667	-0.122586722132742	0.561703873408837
cor	0.0838412981902095	0.673	0.327	-0.292733210589759	0.468105080704131
pr:slow	-0.0740139900842867	0.322	0.678	-0.408051284225128	0.261032419317988
pr:cor	0.14241803067528	0.794333333333333	0.205666666666667	-0.192533960993216	0.504747109307098
slow:cor	0.075538051894372	0.679666666666667	0.320333333333333	-0.239083600692659	0.400569957490939
pr:slow:cor	0.123267457668448	0.755333333333333	0.244666666666667	-0.215078506710808	0.460799493928961

Table 24: Interaction and effects, overall. (Experiment 3)

5.5.2 Post-hoc analysis

We analyzed the 11 participants that had less than two thirds of correct equations (not more than 13). The percentage of high attachments for the mathematically non-skilled group is at 59,17% for the high condition and 65,33% for the low condition.

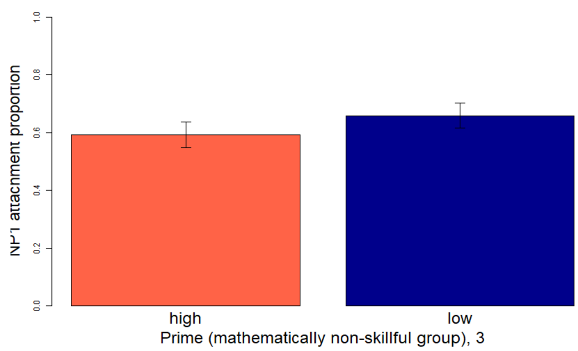

Figure 46: Prime, mathematically non-skilled group. (Experiment 3)

Figure 47 and Table 25 show the proportion of high attachment in the two conditions for fast and slow equations (by median: 17,74 seconds).

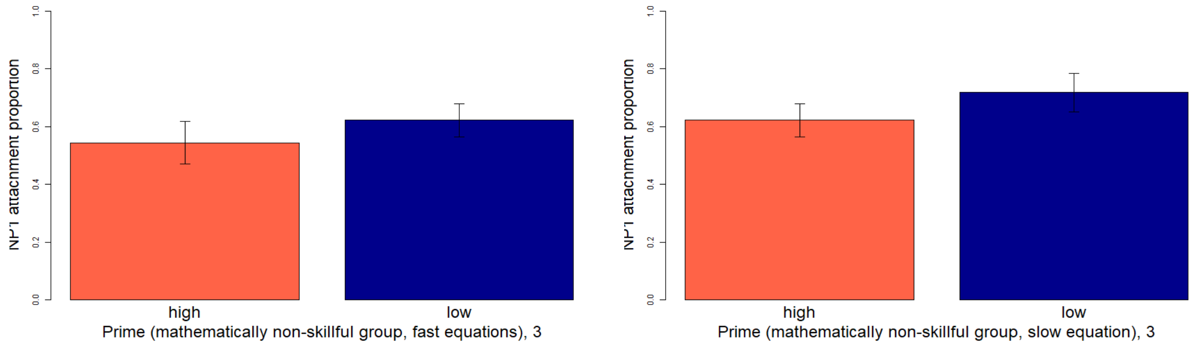

Figure 47: Prime, mathematically non-skilled group, median-split by speed of equations. (Experiment 3)

	High	Low
Fast equation	54,35%	62,16
Slow equation	62,16%	72,14%

(Percentage values are adapted from proportions)

Table 25: Prime, mathematically non-skilled group, median-split by speed of equations. (Experiment 3)

The same model as previously described in the main results minus the correctness of equation variable returned a probable effect of prime at 83% (with more high attachments after low attachment primes) and a probable effect of speed of equation at 91,1% (with more high attachments for slow equations), (Figure 48 & Table 26).

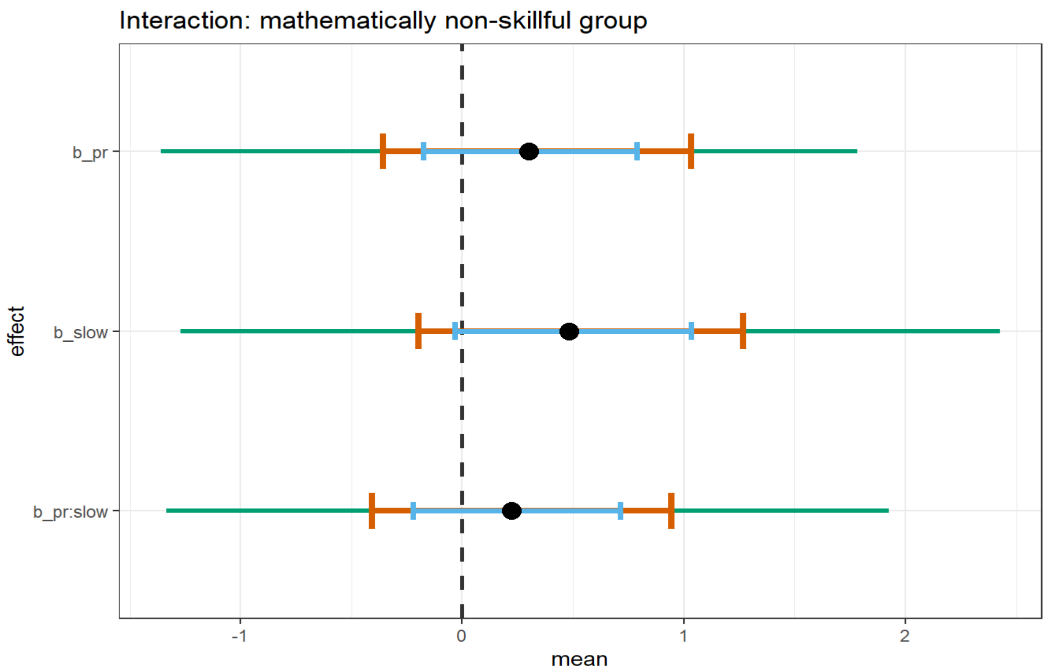

Figure 48: Interaction and effects, mathematically non-skilled group. (Experiment 3)

effect	mean	prob_greater	prob_smaller	l95	h95
pr	0.300431767294434	0.829833333333333	0.170166666666667	-0.358602440077768	1.03215303504252
slow	0.482812280267847	0.910666666666667	0.0893333333333333	-0.196680823600391	1.26626983622684
pr:slow	0.222128009798934	0.753666666666667	0.246333333333333	-0.405707777897741	0.945265925835942

Table 26: Interaction and effects, mathematically non-skilled group. (Experiment 3)

We then only kept participants (22) that had at least two thirds of equations correct (at least 14). For the mathematically skilled group, the high priming condition return 53,64% of NP1 attachments and 50% for the low priming condition (Figure 49).

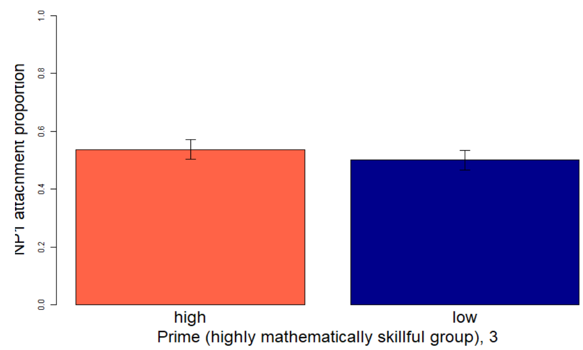

Figure 49: Prime, mathematically skilled group (Experiment 3)

Figure 50 and Table 27 show the proportion of high attachment in the two conditions for fast and slow equation (determined by median: 15,78 seconds) in the mathematically skilled group.

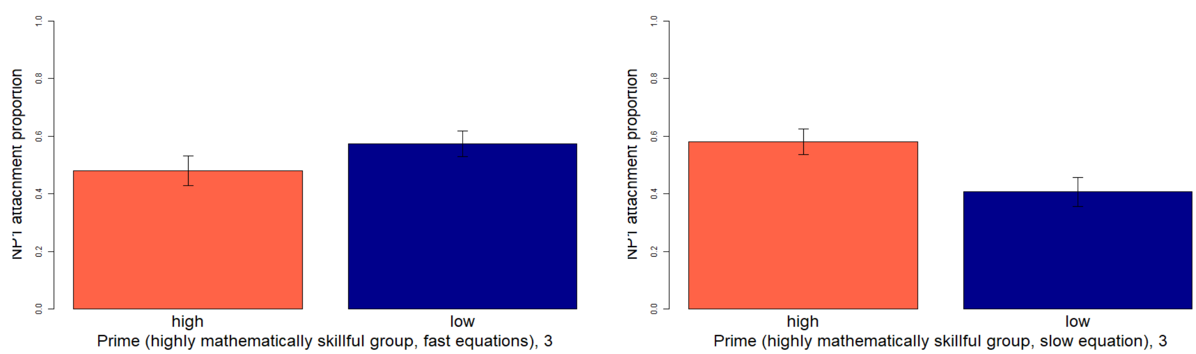

Figure 50: Prime, mathematically skilled group, median-splitted by speed of equations. (Experiment 3)

	High	Low
Fast equation	47,42%	57,26
Slow equation	58,06%	40,62%

(Percentage values are adapted from proportions)

Table 27: Prime, mathematically non-skilled group, median-split by speed of equations. (Experiment 3)

We ran the same model as previously described on the mathematically skilled group and found an probability of 83.3% for an effect of prime type with more high attachments after high attachment primes. There also is an interaction at 93,3% for prime type and speed of equations (Figure 51 & Table 28) with more high attachments for high attachment primes for slow equations but slightly more high attachments for low attachment primes for fast equations.

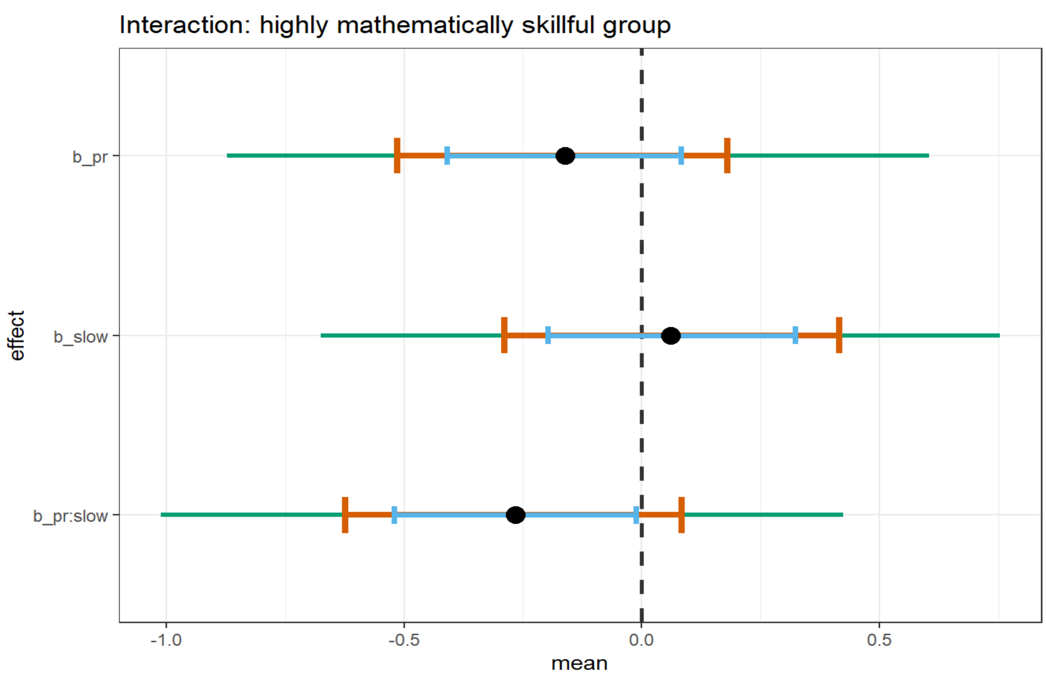

Figure 51: Interaction and effects, mathematically skilled group. (Experiment 3)

effect	mean	prob_greater	prob_smaller	l95	h95
pr	-0.161781404719751	0.167333333333333	0.832666666666667	-0.513731870319097	0.180997051979635
slow	0.0607160345039468	0.6315	0.3685	-0.289484700530322	0.415489912010115
pr:slow	-0.265239150172388	0.0671666666666667	0.932833333333333	-0.62365940600273	0.0833038145199251

Table 28: Interaction and effects, mathematically skilled group. (Experiment 3)

5.6 Discussion

As shown previously in Experiment 1 & 2, exposure to prime (meaning time for calculation here) seems to be a key component for cross-domain structural priming. For the mathematically skilled group, we observe the expected priming effect for the attachment of a RC only if their exposure to prime is long enough (for fast equations it even slightly goes in the opposite sense and the is a weak effect of the same kind for the mathematically non-skilled group across exposure times). The format of the equation is not optimal for the low priming condition (see the discussion of Experiment 2) and we may have here an effect of order of operations rather than a structural priming effect (more on this in the general discussion, *Incremental Procedural Account* (Scheepers et al., 2011)). Indeed, as can be seen in Figure 52, starting the equation at the right edge may prime the attachment between the second NP and the RC.

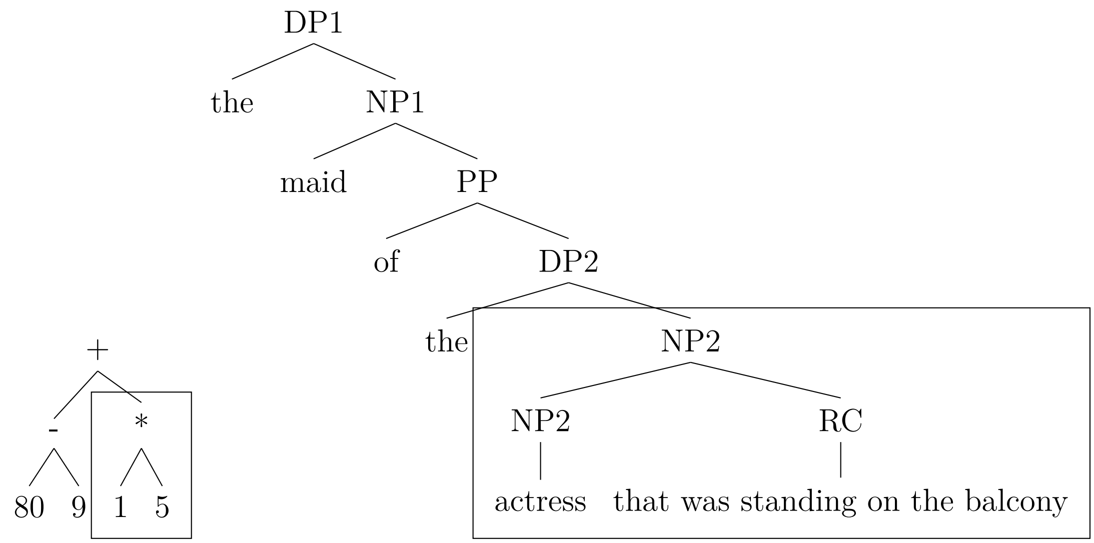

Figure 52: Common right edge association between mathematics and language.

6 General discussion

Before coming to more general conclusions, we will summarize what we found in the three experiments. Across experiments, priming effects were not as straightforward as we may have hoped.

Experiment 1: We Used mathematical primes (either high ”(8+5)*3” or low ”8*(5+3)”) that we thought similar to RC attachment in the target sentences that contained either a perception or a stative verb. Both primes had no effect whatsoever on perception verbs. For stative verbs, we found differences between low and high primes only in the older (>27) group and when the time used to calculate the equation was long enough. However, this difference was opposite from what was predicted. What we thought to be low attachment primes resulted in more high attachments in the target sentences. So it seems that the mathematical formula may have had some effect. We explained this effect in the following way: Because the equation of the low priming condition ended with a parenthesis, we think that this structure with the addition of a closed parenthesis at the right edge primes a closed complex NP structure. The second NP being closed, the incoming element, the RC, has to be attached higher, resulting in an attachment to the first NP (high attachment). However, we observed this only when the exposure to prime (calculation time) was above median. The effects we found may be explained when looking at RC attachment through the prism of prosody. If a prosodic pause is placed between a complex NP and a RC, the attachment preference of the RC will be biased towards the first NP of the complex NP (Jun, 2003; Jun & Bishop, 2015). The closed parenthesis could have been interpreted has a prosodic comma, and because primes seem to be similar to a closed complex noun, this prosodic comma could have been primed between the NP2 and the RC. Although a numerical difference is shown in Figure 26 for the perception verb condition, the probability of effect is rather low. Plus, this difference shown in Figure 26 did not increase with the above median prime length exposure. Nonetheless, this experiment suggests that exposure length to prime led to greater priming effect.

Experiment 2: We changed mathematical primes and used previously used equations (high "80-(9+1)*5" and low "80-9+1*5"). We did observe mathematical priming for skillful participants and longer calculation times, but still not the one expected. The stative verb condition, the one supposed to be subject to priming, did not show differences between fast and slow calculation times and no clear priming effect. We think that the absence of priming effect is the result of unsuited materials, the low primes were not similar to a sentence with a low attached RC. The reason for the lack of an effect could also be a too dense paradigm for a priming experiment, too complex equations or a low amount of mathematically skilled participants. For the perception verb condition, beyond the typical increase of high attachments, we only found differences in the mathematically skillful group due to priming in that low attachment primes gave rise to more high attachments. We argued that there is a major issue with our priming materials: the actual low priming equation greatly resemble a PR structure so that these primes structurally primed high attachments. Once more, this priming effect is only present when the prime exposure is rather long (Figure 38).

Experiment 3: We removed the perception verb condition and used the same primes as in the second experiment but we added redundant parentheses ("80-((2+3)*4)" and low "80-2+(3*4)"). In this experiment, we found the expected differences between high and low priming conditions but again only in the mathematically skillful group and when equations were slowly calculated. More high attachments were found after high attachment primes than after low attachment primes. Given our previous discussion on the representation of the low attachment prime, it is unclear whether we observed mathematical priming (in the sense of structural priming) within slow equations. We only discovered the problem while conducting the third experiment so we did not correct that. Primes used for the low condition were not strictly similar to a relative clause with low attachment. This challenges our view because we adopted the point of view that mathematical priming is the result of structural similarities. However, it has been suggested that mathematical priming is in fact the result of order of operations (the *Incremental Procedural* account proposed by Scheepers et al. (2011) and supported by Zeng et al. (2018)) The very action of starting the equation at the right edge prime may be sufficient to successfully prime a low attachment, but this would be not the result of a structural priming. However, since we did not have a baseline condition, it is also possible that only the high attachment prime was effective here. This will have to be tested in future experiments.

Our experiments show one major problem in the mathematical priming literature: The equation format in mathematical priming experiments have to be systematically tested in pilot experiments before conducting a more thorough experiment. For Experiment 1, we used equation that were thought to reflect only on the ambiguity of the sentence but our results were contradicting our prediction. For Experiment 2 and 3, in the low condition, we use an equation format that did not really share structural similarities with low RC attachment, resulting in unexpected results for the second experiment and other possible explanations for the third experiment. Because we still need to find out what really is behind mathematical priming, we have to meticulously choose format equation and consider every possible interpretation of an experiment.

The role of parentheses has been suggested to be the indicator of apparent syntactic embedding, indicating a syntactic complexity resulting in a P600 (Martín-Loeches et al., 2006). Our first experiment suggests that a closed parenthesis can be interpreted as a prosodic comma. If an opening parenthesis can also be interpreted as prosodic comma or bridge, this would mean that, in a mathematical equation similar to a prosodic structure, parentheses can be used as prosodic frontiers and reflect prosodic groups of a sentence. In this case, maybe prosodic priming adds to the structural priming that has been assumed here.

Throughout these three experiments, we highlighted one important point that was previously not controlled or measured, the prime exposure. What we used as exposure time is the time used to solve equations. One important point to note is that the exposure time is measured in our experiments as the time taken for each equation (post-hoc analysis), not controlled as an experimental factor (taken into account in the design). This temporal window is not a pure reflection of prime exposure, other cognitive processes are in effect during the treatment of an equation. For example, participants using more time to calculate may use different strategies. Nevertheless, our results give evidence that exposure length to the prime have a direct impact on mathematical priming. This rejoins previous literature in psychology where exposure to prime has a direct impact on the priming effect towards the target (Dijksterhuis & Van Knippenberg, 1998). This priming effect is no longer present as soon as the participant is aware of the prime's intent (Murphy & Zajonc, 1993) but luckily, participants in our experiments indicated that they were not aware of possible joint mental syntactic representations between equations and linguistic structure, syntactic knowledge is implicit knowledge and therefore not consciously accessible.

We think that our results explain why mathematical priming has been so inconsistent in previous articles and in (unfortunately) unpublished research. Participants have to be familiar with mathematics but not too efficient: their exposition to prime is reduced when they calculate the equation too quickly and it may then be less effective. Although the question whether mathematical priming can only be modulated within these specific participants remains, Pozniak et al. (2018) found little mathematical priming effect with participants that were categorized has having *no mathematical knowledge*, so paradigms and designs might have a critical role in a successful priming experiment.

Another possible interpretation of this exposure time is that long calculation time may recruit more brain regions that share cognitive resources between mathematics and language. Long calculation time may also call out different strategies to solve the equation which has the effect of producing other representations that can be primed. Such questions have not be treated in major theories of structural domain interactions (such as the *Sharing of structure building resources* and *Sharing of processing capacity*) but also most known frameworks (Patel, 2003; Kljajević et al., 2010) did not include aspects of processing time and its importance even though this question has been treated in the cognitive psychology literature (Dijksterhuis & Van Knippenberg, 1998; Murphy & Zajonc, 1993).

This mathematical priming tool can be used to further explore the structural mental representation of language. Because the phenomenon seems to operate at a very high-level of abstraction, theoretically, as long as the equation shares structural similarities with a syntactic representation, it can be primed. Many more detailed aspects will have to be worked out first, but this tool can be applied to other questions such as the presence of ternary trees (for coordination) or provide more information on the chunking of elements in the global hierarchical representation of expressions (Swets, Desmet, Hambrick, & Ferreira, 2007). Some of the effects found in our experiments (for example the weak effects of low attachment primes leading to more high attachments for non-mathematically skilled participants and for fast exposure times with mathematically skilled participants in Experiment 3) still call for an explanation.

6.1 Future Work

Now that we have evidence suggesting that exposure to prime plays an important role, future experiments will need to be adapted accordingly. To control prime exposure, using more complex equation may not be the best solution: Experiment 2, which had more difficult equations, had fewer participants able to correctly calculate compared to Experiment 3. Forcing the participant to calculate an equation in a given period of time (with the help of a timer) may also not be the best solution because this could generate attention problems. One possible solution that can be considered is to increase the number of primes before the target. Multiple equations of the same structure would be presented in order to increase the priming effect. This might give rise to some awareness of the observed phenomenon by the participants, but this seems unlikely and can be controlled with additional questions at the end of the experiment to find out if they are aware of the priming effect (none of our participants were aware so far). We have to also be more meticulous towards the choice of the equation format. We should actually test equations that really share structural similarities with a RC attachment, as discussed in the second experiment (Figure 42).

Because Experiment 1 has a possible prosodic interpretation, it could be interesting to test whether we could prime prosodic sentence pattern with the help of parentheses in equations. Parentheses would be used as a chunking tool, they would mark prosodic frontiers reflecting prosodic grouping. This could be tested in attachment ambiguities where prosodic information plays a major role.

To find out whether participants resort to other strategies in long calculations, eye-tracking or fMRI studies could be used as an exploratory tool to investigate such phenomenon. Eye-tracking would give indices on how precisely participants calculate equations and fMRI would give information whether long calculations increase brain activities in previously known areas or whether long calculations recruit other brain areas common to language. Exploratory eye-tracking data could help investigate the question whether mathematical representation are result of a *Representational* or an *Incremental Procedural* account (Scheepers et al., 2011).

More work needs to be done first, but the open question of how much mathematical primes have an impact on language ambiguity still remains. For example, can a mathematical prime may be substantial enough to modulate a Garden-Path effect, both in an on-line experiment (Frazier & Rayner, 1982) and in EEG experiments (Friederici, Mecklinger, Spencer, Steinhauer, & Donchin, 2001). Since P600s are the result of structural violations or complexities, finding relevant ERP components in cross-domain priming experiments would further advance the understanding of this phenomenon. Modulating such ERP components in an EEG experiment would provide more evidence towards common structural operations across rule governed domains building structure out of sequential input (Van de Cavey & Hartsuiker, 2016; Núñez-Peña & Honrubia-Serrano, 2004; Makuuchi et al., 2012; Nakai & Okanoya, 2018).

We think that this work may be only the beginning of a more ambitious Ph.D. project. Indeed, this subject requires more exploratory work to understand what is really happening in mathematical priming and more generally in cross-domain priming.

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7 Appendix

-Instruction and survey common to all three experiments.

-Items for the first experiment.

-Items for the second experiment.

-Items for the third experiment.

Dans cette expérience, il vous est demandé de compléter des phrases (par exemple, "Marie parle à Jean parce qu'...") et résoudre des équations (par exemple, "3+4/9").

L'ensemble devrait vous prendre environ 20 minutes.

Merci de votre participation !

Les données collectées durant cette expérience le sont à des fins de la recherche fondamentale. Aucune donnée personnelle d'identification ne sera stockée ou transmise à des tiers.

Vous pouvez arrèter l'expérience à tout moment. Dans ce cas, vos données ne seront pas transmises.

Votre âge :

Votre nationalité :

Votre genre : ○ Homme ○ Femme ○ Autre ○ Je ne veux pas répondre à cette question

Votre dernier diplôme obtenu :
- ○ Avant le baccalauréat
- ○ Baccalauréat ou équivalent
- ○ Bac+2 ou équivalent
- ○ Bac+3 ou équivalent
- ○ Bac+5 ou équivalent
- ○ Bac+8 ou équivalent

Votre domaine d'études ou d'activité professionnelle :

Votre région de naissance :

Votre langue maternelle :

Choisissez svp un code unique que vous pouvez utiliser pour une retraction éventuelle de vos données:

☐ Je suis majeur.e et j'accepte les termes et conditions de cette expérience.

→ Click here to continue

Figure 53: Instructions and survey common for all three experiments

Verb	Prime	Items	Equation	Sentence
stative	low	1	(3+4)*5	Carl a été ami avec l'agent des chanteurs qui ...
perception	low	1	(9+2)*4	Carl a rencontré l'agent des chanteurs qui ...
stative	high	1	9*(6+8)	Carl a été ami avec l'agent des chanteurs qui ...
perception	high	1	5*(2+2)	Carl a rencontré l'agent des chanteurs qui ...
stative	low	2	(1+7)*5	Grégoire a été employé par les avocats de l'acteur qui ...
perception	low	2	(9+3)*7	Grégoire a épié les avocats de l'acteur qui ...
stative	high	2	3*(1+4)	Grégoire a été employé par les avocats de l'acteur qui ...
perception	high	2	3*(4+9)	Grégoire a épié les avocats de l'acteur qui ...
stative	low	3	(3+8)*6	Pierre a couru avec les amis de l'athlète qui ...
perception	low	3	(7+6)*8	Pierre a enregistré les amis de l'athlète qui ...
stative	high	3	4*(2+4)	Pierre a couru avec les amis de l'athlète qui ...
perception	high	3	8*(1+7)	Pierre a enregistré les amis de l'athlète qui ...
stative	low	4	(4+7)*2	Franck a logé chez les invités de la mariée qui ...
perception	low	4	(9+9)*2	Franck a photographié les invités de la mariée qui ...
stative	high	4	1*(3+1)	Franck a logé chez les invités de la mariée qui ...
perception	high	4	2*(8+7)	Franck a photographié les invités de la mariée qui
stative	low	5	(2+9)*4	Brice a été marié avec le professeur des étudiants qui ...
perception	low	5	(1+8)*7	Brice a écouté le professeur des étudiants qui ...
stative	high	5	2*(9+3)	Brice a été marié avec le professeur des étudiants qui ...
perception	high	5	9*(6+1)	Brice a écouté le professeur des étudiants qui ...
stative	low	6	(1+2)*9	Béatrice va à l'université avec les enfants du musicien qui ...
perception	low	6	(8+7)*7	Béatrice a imaginé les enfants du musicien qui ...
stative	high	6	4*(7+2)	Béatrice va à l'université avec les enfants du musicien qui ...
perception	high	6	9*(9+4)	Béatrice a imaginé les enfants du musicien qui ...
stative	low	7	(9+9)*4	Christian a fait la fête avec le père des étudiants qui ...
perception	low	7	(3+4)*7	Christian a vu le père des étudiants qui ...
stative	high	7	2*(3+5)	Christian a fait la fête avec le père des étudiants qui ...
perception	high	7	7*(3+5)	Christian a vu le père des étudiants qui ...
stative	low	8	(4+8)*8	Melissa a été hebergé par les filles du voisin qui ...
perception	low	8	(1+6)*8	Melissa a aperçu les filles du voisin qui ...
stative	high	8	3*(3+4)	Melissa a été hebergé par les filles du voisin qui ...
perception	high	8	9*(5+3)	Melissa a aperçu les filles du voisin qui ...
stative	low	9	(5+9)*4	Sandra est voisin des jardiniers du millionnaire qui ...
perception	low	9	(4+2)*9	Sandra s'est représenté les jardiniers du millionaire qui ...
stative	high	9	1*(1+5)	Sandra est voisin des jardiniers du millionnaire qui ...
perception	high	9	7*(5+9)	Sandra s'est représenté les jardiniers du millionaire qui ...
stative	low	10	(6+8)*9	Rayan a vécu avec le capitaine des marins qui ...

perception	low	10	(1+7)*9	Rayan a regardé le capitaine des marins qui ...
stative	high	10	9*(3+2)	Rayan a vécu avec le capitaine des marins qui ...
perception	high	10	8*(5+3)	Rayan a regardé le capitaine des marins qui ...
stative	high	11	8*(5+9)	Joel travaille avec les stylistes de la célébrité qui ...
perception	high	11	2*(4+9)	Joel a filmé les stylistes de la célébrité qui ...
stative	low	11	(5+6)*1	Joel travaille avec les stylistes de la célébrité qui ...
perception	low	11	(8+9)*8	Joel a filmé les stylistes de la célébrité qui ...
stative	high	12	1*(4+6)	Adrien s'entraîne avec avec les assistants du PDG qui ...
perception	high	12	5*(9+3)	Adrien a observé les assistants du PDG qui ...
stative	low	12	(6+9)*1	Adrien s'entraîne avec avec les assistants du PDG qui ...
perception	low	12	(5+2)*5	Adrien a observé les assistants du PDG qui ...
stative	high	13	9*(7+4)	Alban est lié aux comptables du ministre qui ...
perception	high	13	3*(4+9)	Alban a espionné les comptables du ministre qui ...
stative	low	13	(9+8)*2	Alban est lié aux comptables du ministre qui ...
perception	low	13	(6+1)*1	Alban a espionné les comptables du ministre qui ...
stative	high	14	2*(4+4)	Tina étudie avec les médecins du mannequin qui ...
perception	high	14	1*(6+9)	Tina a surveillé les médecins du mannequin qui ...
stative	low	14	(7+8)*7	Tina étudie avec les médecins du mannequin qui ...
perception	low	14	(1+2)*3	Tina a surveillé les médecins du mannequin qui ...
stative	high	15	4*(9+9)	Louis est employé par le manager des acteurs qui ...
perception	high	15	7*(4+6)	Louis a surpris le manager des acteurs qui ...
stative	low	15	(4+3)*9	Louis est employé par le manager des acteurs qui ...
perception	low	15	(7+7)*4	Louis a surpris le manager des acteurs qui ...
stative	high	16	8*(5+2)	Christophe a pardonné les sbires du dictateur qui ...
perception	high	16	8*(3+6)	Christophe a entendu les sbires du dictateur qui ...
stative	low	16	(1+6)*8	Christophe a pardonné les sbires du dictateur qui ...
perception	low	16	(4+4)*5	Christophe a entendu les sbires du dictateur qui ...
stative	high	17	2*(1+2)	Stéphane passe du temps avec les fans du chanteur qui ...
perception	high	17	1*(6+6)	Stéphane a dessiné les fans du chanteur qui ...
stative	low	17	(9+1)*6	Stéphane passe du temps avec les fans du chanteur qui ...
perception	low	17	(7+5)*3	Stéphane a dessiné les fans du chanteur qui ...
stative	high	18	7*(8+7)	George a divorcé du représentant des employés qui ...
perception	high	18	9*(4+5)	George a distingué le représentant des employés qui ...
stative	low	18	(8+3)*6	George a divorcé du représentant des employés qui ...
perception	low	18	(1+4)*5	George a distingué le représentant des employés qui ...
stative	high	19	8*(3+9)	Alice a été fiancé au chirurgien des soldats qui ...
perception	high	19	6*(5+5)	Alice a peint le chirurgien des soldats qui ...
stative	low	19	(2+4)*8	Alice a été fiancé au chirurgien des soldats qui ...

perception	low	19	(5+5)*5	Alice a peint le chirurgien des soldats qui ...
stative	high	20	4*(5+2)	Paul est sorti avec le coach des cheerleaders qui ...
perception	high	20	5*(5+8)	Paul a repéré le coach des cheerleaders qui ...
stative	low	20	(7+6)*9	Paul est sorti avec le coach des cheerleaders qui ...
perception	low	20	(8+4)*2	Paul a repéré le coach des cheerleaders qui ...

Table 29: Items for the first experiment.

Verb	Prime	Items	Equation	Sentence
stative	low	1	94-5+(8*5)	Grégoire a collaboré avec les avocats de l'acteur qui ...
stative	high	1	94-((5+8)*5)	Grégoire a collaboré avec les avocats de l'acteur qui ...
perception	low	1	94-5+8*5	Grégoire a épié les avocats de l'acteur qui ...
perception	high	1	94-(5+8)*5	Grégoire a épié les avocats de l'acteur qui ...
stative	low	2	98-7+(2*9)	Pierre a couru avec les amis de l'athlète qui ...
stative	high	2	98-((7+2)*9)	Pierre a couru avec les amis de l'athlète qui ...
perception	low	2	98-7+2*9	Pierre a enregistré les amis de l'athlète qui ...
perception	high	2	98-(7+2)*9	Pierre a enregistré les amis de l'athlète qui ...
stative	low	3	94-1+(8*9)	Sandra a bavardé avec les jardiniers du millionnaire qui ...
stative	high	3	94-((1+8)*9)	Sandra a bavardé avec les jardiniers du millionnaire qui ...
perception	low	3	94-1+8*9	Sandra s'est représenté les jardiniers du millionaire qui ...
perception	high	3	94-(1+8)*9	Sandra s'est représenté les jardiniers du millionaire qui ...
stative	low	4	80-3+(1*3)	Joel a travaillé avec les stylistes de la célébrité qui ...
stative	high	4	80-((3+1)*3)	Joel a travaillé avec les stylistes de la célébrité qui ...
perception	low	4	80-3+1*3	Joel a filmé les stylistes de la célébrité qui ...
perception	high	4	80-(3+1)*3	Joel a filmé les stylistes de la célébrité qui ...
stative	low	5	97-6+(9*5)	Tina a étudié avec les médecins du mannequin qui ...
stative	high	5	97-((6+9)*5)	Tina a étudié avec les médecins du mannequin qui ...
perception	low	5	97-6+9*5	Tina a surveillé les médecins du mannequin qui ...
perception	high	5	97-(6+9)*5	Tina a surveillé les médecins du mannequin qui ...
stative	low	6	98-6+(9*8)	Christophe a pardonné les sbires du dictateur qui ...
stative	high	6	98-((6+9)*8)	Christophe a pardonné les sbires du dictateur qui ...
perception	low	6	98-6+9*8	Christophe a entendu les sbires du dictateur qui ...
perception	high	6	98-(6+9)*8	Christophe a entendu les sbires du dictateur qui ...
stative	low	7	97-1+(8*7)	Stéphane a dansé avec les fans du chanteur qui ...
stative	high	7	97-((1+8)*7)	Stéphane a dansé avec les fans du chanteur qui ...
perception	low	7	97-1+8*7	Stéphane a dessiné les fans du chanteur qui ...
perception	high	7	97-(1+8)*7	Stéphane a dessiné les fans du chanteur qui ...
stative	low	8	87-8+(7*9)	Brice a marié le professeur des étudiants qui ...
stative	high	8	87-((8+7)*9)	Brice a marié le professeur des étudiants qui ...
perception	low	8	87-8+7*9	Brice a écouté le professeur des étudiants qui ...
perception	high	8	87-(8+7)*9	Brice a écouté le professeur des étudiants qui ...
stative	low	9	90-9+(9*8)	Christian a partagé avec le père des étudiants qui ...
stative	high	9	90-((9+9)*8)	Christian a partagé avec le père des étudiants qui ...
perception	low	9	90-9+9*8	Christian a vu le père des étudiants qui ...
perception	high	9	90-(9+9)*8	Christian a vu le père des étudiants qui ...
stative	low	10	84-7+(5*7)	George a divorcé du représentant des employés qui ...

stative	high	10	84-((7+5)*7)	George a divorcé du représentant des employés qui ...
perception	low	10	84-7+5*7	George a distingué le représentant des employés qui ...
perception	high	10	84-(7+5)*7	George a distingué le représentant des employés qui ...
stative	low	11	81-6+(7*6)	Alice a fiancé le chirurgien des soldats qui ...
stative	high	11	81-((6+7)*6)	Alice a fiancé le chirurgien des soldats qui ...
perception	low	11	81-6+7*6	Alice a peint le chirurgien des soldats qui ...
perception	high	11	81-(6+7)*6	Alice a peint le chirurgien des soldats qui ...
stative	low	12	82-7+(2*9)	Paul est sorti avec le coach des cheerleaders qui ...
stative	high	12	82-((7+2)*9)	Paul est sorti avec le coach des cheerleaders qui ...
perception	low	12	82-7+2*9	Paul a repéré le coach des cheerleaders qui ...
perception	high	12	82-(7+2)*9	Paul a repéré le coach des cheerleaders qui ...
stative	low	13	80-9+(8*7)	Franck a logé chez les invités de la mariée qui ...
stative	high	13	80-((9+8)*7)	Franck a logé chez les invités de la mariée qui ...
perception	low	13	80-9+8*7	Franck a photographié les invités de la mariée qui ...
perception	high	13	80-(9+8)*7	Franck a photographié les invités de la mariée qui ...
stative	low	14	87-8+(9*3)	Sarah a aimé le promoteur des musiciens qui ...
stative	high	14	87-((8+9)*3)	Sarah a aimé le promoteur des musiciens qui ...
perception	low	14	87-8+9*3	Sarah a photographié le promoteur des musiciens qui ...
perception	high	14	87-(8+9)*3	Sarah a photographié le promoteur des musiciens qui ...
stative	low	15	94-1+(8*2)	Béatrice a joué avec les enfants du musicien qui ...
stative	high	15	94-((1+8)*2)	Béatrice a joué avec les enfants du musicien qui ...
perception	low	15	94-1+8*2	Béatrice a imaginé les enfants du musicien qui ...
perception	high	15	94-(1+8)*2	Béatrice a imaginé les enfants du musicien qui ...
stative	low	16	90-9+(3*4)	Lucie a dîné avec le maître des élèves qui ...
stative	high	16	90-((9+3)*4)	Lucie a dîné avec le maître des élèves qui ...
perception	low	16	90-9+3*4	Lucie a imaginé le maître des élèves qui ...
perception	high	16	90-(9+3)*4	Lucie a imaginé le maître des élèves qui ...
stative	low	17	98-4+(2*5)	Jeanne a marché avec le meneur des manifestants qui ...
stative	high	17	98-((4+2)*5)	Jeanne a marché avec le meneur des manifestants qui ...
perception	low	17	98-4+2*5	Jeanne a aperçu le meneur des manifestants qui ...
perception	high	17	98-(4+2)*5	Jeanne a aperçu le meneur des manifestants qui ...
stative	low	18	93-9+(5*6)	Melissa a hebergé les filles du voisin qui ...
stative	high	18	93-((9+5)*6)	Melissa a hebergé les filles du voisin qui ...
perception	low	18	93-9+5*6	Melissa a aperçu les filles du voisin qui ...
perception	high	18	93-(9+5)*6	Melissa a aperçu les filles du voisin qui ...
stative	low	19	90-7+(4*4)	Adrien a entraîné les assistants du PDG qui ...
stative	high	19	90-((7+4)*4)	Adrien a entraîné les assistants du PDG qui ...
perception	low	19	90-7+4*4	Adrien a observé les assistants du PDG qui ...

perception	high	19	90-(7+4)*4	Adrien a observé les assistants du PDG qui ...
stative	low	20	80-4+(2*5)	Clément a consulté le supérieur des techniciens qui ...
stative	high	20	80-((4+2)*5)	Clément a consulté le supérieur des techniciens qui ...
perception	low	20	80-4+2*5	Clément a observé le supérieur des techniciens qui ...
perception	high	20	80-(4+2)*5	Clément a observé le supérieur des techniciens qui ...
stative	low	21	93-6+(8*8)	Alban a connu les comptables du ministre qui ...
stative	high	21	93-((6+8)*8)	Alban a connu les comptables du ministre qui ...
perception	low	21	93-6+8*8	Alban a espionné les comptables du ministre qui ...
perception	high	21	93-(6+8)*8	Alban a espionné les comptables du ministre qui ...
stative	low	22	87-9+(2*8)	Camille a parlé au responsable des informaticiens qui ...
stative	high	22	87-((9+2)*8)	Camille a parlé au responsable des informaticiens qui ...
perception	low	22	87-9+2*8	Camille a espionné le responsable des informaticiens qui ...
perception	high	22	87-(9+2)*8	Camille a espionné le responsable des informaticiens qui ...
stative	low	23	89-7+(4*4)	Louis a employé le manager des acteurs qui ...
stative	high	23	89-((7+4)*4)	Louis a employé le manager des acteurs qui ...
perception	low	23	89-7+4*4	Louis a surpris le manager des acteurs qui ...
perception	high	23	89-(7+4)*4	Louis a surpris le manager des acteurs qui ...
stative	low	24	96-5+(8*6)	Juliette a brusqué le doyen des habitants qui ...
stative	high	24	96-((5+8)*6)	Juliette a brusqué le doyen des habitants qui ...
perception	low	24	96-5+8*6	Juliette a surpris le doyen du village qui ...
perception	high	24	96-(5+8)*6	Juliette a surpris le doyen du village qui ...
stative	low	25	89-3+(2*4)	Victor a amusé les frères de sa copine qui ...
stative	high	25	89-((3+2)*4)	Victor a amusé les frères de sa copine qui ...
perception	low	25	89-3+2*4	Victor a rencontré les frères de sa copine qui ...
perception	high	25	89-(3+2)*4	Victor a rencontré les frères de sa copine qui ...
stative	low	26	89-7+(6*2)	Carl a sympathisé avec l'agent des chanteurs qui ...
stative	high	26	89-((7+6)*2)	Carl a sympathisé avec l'agent des chanteurs qui ...
perception	low	26	89-7+6*2	Carl a rencontré l'agent des chanteurs qui ...
perception	high	26	89-(7+6)*2	Carl a rencontré l'agent des chanteurs qui ...
stative	low	27	83-1+(7*1)	Rayan a vécu avec le capitaine des marins qui ...
stative	high	27	83-((1+7)*1)	Rayan a vécu avec le capitaine des marins qui ...
perception	low	27	83-1+7*1	Rayan a regardé le capitaine des marins qui ...
perception	high	27	83-(1+7)*1	Rayan a regardé le capitaine des marins qui ...
stative	low	28	82-2+(1*6)	Clémence a cherché le champion des cyclistes qui ...
stative	high	28	82-((2+1)*6)	Clémence a cherché le champion des cyclistes qui ...
perception	low	28	82-2+1*6	Clémence a regardé le champion des cyclistes qui ...
perception	high	28	82-(2+1)*6	Clémence a regardé le champion des cyclistes qui ...

Table 30: Items for the second experiment.

Prime	Items	Equation	Sentence
low	1	94-3+(4*5)	Grégoire a collaboré avec les avocats de l'acteur qui ...
high	1	94-((3+4)*5)	Grégoire a collaboré avec les avocats de l'acteur qui ...
low	2	98-2+(5*4)	Pierre a couru avec les amis de l'athlète qui ...
high	2	98-((2+5)*4)	Pierre a couru avec les amis de l'athlète qui ...
low	3	94-3+(4*5)	Sandra a bavardé avec les jardiniers du millionnaire qui ...
high	3	94-((3+4)*5)	Sandra a bavardé avec les jardiniers du millionnaire qui ...
low	4	80-2+(3*5)	Joel a travaillé avec les stylistes de la célébrité qui ...
high	4	80-((2+3)*5)	Joel a travaillé avec les stylistes de la célébrité qui ...
low	5	97-5+(3*2)	Tina a étudié avec les médecins du mannequin qui ...
high	5	97-((5+3)*2)	Tina a étudié avec les médecins du mannequin qui ...
low	6	98-2+(5*4)	Christophe a pardonné les sbires du dictateur qui ...
high	6	98-((2+5)*4)	Christophe a pardonné les sbires du dictateur qui ...
low	7	97-4+(5*3)	Stéphane a dansé avec les fans du chanteur qui ...
high	7	97-((4+5)*3)	Stéphane a dansé avec les fans du chanteur qui ...
low	8	90-5+(3*4)	Christian a partagé avec le père des étudiants qui ...
high	8	90-((5+3)*4)	Christian a partagé avec le père des étudiants qui ...
low	9	84-4+(5*3)	George a divorcé du représentant des employés qui ...
high	9	84-((4+5)*3)	George a divorcé du représentant des employés qui ...
low	10	82-4+(5*3)	Paul est sorti avec le coach des cheerleaders qui ...
high	10	82-((4+5)*3)	Paul est sorti avec le coach des cheerleaders qui ...
low	11	80-3+(5*4)	Franck a logé chez les invités de la mariée qui ...
high	11	80-((3+5)*4)	Franck a logé chez les invités de la mariée qui ...
low	12	87-3+(5*4)	Sarah a aimé le promoteur des musiciens qui ...
high	12	87-((3+5)*4)	Sarah a aimé le promoteur des musiciens qui ...
low	13	90-4+(5*2)	Lucie a dîné avec le maître des élèves qui ...
high	13	90-((4+5)*2)	Lucie a dîné avec le maître des élèves qui ...
low	14	98-2+(4*3)	Jeanne a marché avec le meneur des manifestants qui ...
high	14	98-((2+4)*3)	Jeanne a marché avec le meneur des manifestants qui ...
low	15	93-5+(4*2)	Melissa a hebergé les filles du voisin qui ...
high	15	93-((5+4)*2)	Melissa a hebergé les filles du voisin qui ...
low	16	90-4+(3*5)	Adrien a entraîné les assistants du PDG qui ...
high	16	90-((4+3)*5)	Adrien a entraîné les assistants du PDG qui ...
low	17	93-3+(4*2)	Alban a connu les comptables du ministre qui ...
high	17	93-((3+4)*2)	Alban a connu les comptables du ministre qui ...
low	18	89-2+(3*4)	Louis a employé le manager des acteurs qui ...
high	18	89-((2+3)*4)	Louis a employé le manager des acteurs qui ...
low	19	89-2+(4*5)	Carl a sympathisé avec l'agent des chanteurs qui ...

high	19	89-((2+4)*5)	Carl a sympathisé avec l'agent des chanteurs qui ...
low	20	83-3+(5*4)	Rayan a vécu avec le capitaine des marins qui ...
high	20	83-((3+5)*4)	Rayan a vécu avec le capitaine des marins qui ...

Table 31: Items for the third experiment.