Cross-domain priming from mathematics to relative-clause attachment: A visual-world study in French

Abstract

Human language processing must rely on a certain degree of abstraction, as we can produce and understand sentences that we have never produced or heard before. One way to establish syntactic abstraction is by investigating structural priming. Structural priming has been shown to be effective within a cognitive domain, in the present case, the linguistic domain. But does priming also work across different domains? In line with previous experiments, we investigated cross-domain structural priming from mathematical expressions to linguistic structures with respect to relative clause attachment in French (e.g la fille du professeur qui habitait à Paris / the daughter of the teacher who lived in Paris). Testing priming in French is particularly interesting because it will extend earlier results established for English to a language where the baseline for relative clause attachment preferences is different form English: in English, relative clauses (RCs) tend to be attached to the local noun phrase (low attachment) while in French there is a preference for high attachment of relative clauses to the noun phrase (NP). Moreover, in contrast to earlier studies, we applied an online-technique (visual world eye-tracking). Our results confirm cross-domain priming from mathematics to linguistic structures in French. Most interestingly, different from less mathematically adept participants, we found that in mathematically skilled participants, the effect emerged very early on (at the beginning of the relative clause in the speech stream) and is also present later (at the end of the relative clause). In line with previous findings, our experiment suggests that mathematics and language share aspects of syntactic structure at a very high-level of abstraction.

Introduction

Abstract syntactic structures enable us to produce and understand sentences that we have never heard or produced before. Beyond these syntactic representations, human sentence processing requires cognitive resources in varying amounts depending on complexity of the sentences. A question that is still debated is how specific these abstract syntactic structures and the required cognitive capacities are to language processing (Amalric & Dehaene, 2016; Fedorenko, Gibson, & Rohde, 2007; Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009; Koelsch, Kasper, Sammler, Schulze, Gunter, & Friederici, 2004; Scheepers, Sturt, Martin, Myachykov, Teevan, & Viskupova (2011; see also Scheepers, 2003; Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016; Patel, 2003). To answer this, two main classes of questions for resource sharing between cognitive domains have been discussed in the literature:

1) *Sharing of structure building resources:* Are abstract representations and/or procedures in language different from other domains, such as mathematics or music? Or do the domains share representations and/or operations for processing? If there are shared representations and/or procedures, which level of representation do they concern? Do they concern syntactic (structural)

representations of linguistic, mathematical, or musical representations or do they concern their meaning, i.e. semantic or conceptual representations?
2) *Sharing of processing capacity*: Independent of linguistic representations, does the linguistic domain share cognitive resources with other domains like music or mathematics, meaning that domains require the same additional cognitive resources in cases of cognitive load (e.g., to process complex linguistic, mathematical or musical structures)?

Much of the literature in psycholinguistics and cognitive psychology focused on the second research question (shared cognitive capacity) or some combination of the two questions. The experiment presented in this paper focused on the sharing of structure building resources. It showed that linguistic and mathematical expressions shared abstract structural representations or structure building procedures leading to mathematical priming effects on sentence processing. Priming studies within (Bock, 1986; Pickering & Branigan, 1998) or even across languages (Hartsuiker, Pickering, & Veltkamp, 2004) have been proposed to find out more about the nature of linguistic abstractions. In particular, crosslinguistic priming effects are considered a major argument for shared representations between the first and second language of a bilingual speaker. We applied a very similar approach to cross-domain sharing of structure building resources. Before presenting our experiments, we discuss diverging approaches to the status of linguistic representations in relation to other cognitive domains.
A very strict separation between the linguistic domain and others claiming the absence of any shared resources has been suggested by Amalric & Dehaene (2016) for the relationship between language and mathematics. In their study, they aimed to find out whether mathematical capacities are active in similar brain areas as language competence (for instance, the language semantics network) or rather in separate brain circuits. They ran fMRI experiments in which they scanned the brains of mathematicians and non-mathematicians while they had to evaluate the truth of meaningful and meaningless mathematical and non-mathematical statements such as (1a,b) and (2a,b).

[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.

The results showed that left-hemispheric brain regions generally associated with language competence were not activated for meaningful mathematical statements in professional mathematicians. Conversely, regions associated with mathematical capacities were not activated during meaningful non-mathematical statements. Almaric & Dehaene (2016) concluded from their studies that high-level mathematical thinking and language did not activate the same regions in the brain and thus did not draw the same resources. However, when looking at their experimental design, the conclusions the authors drew appear to concern mainly the representation and storage of mathematical knowledge compared to general knowledge. Thus, with respect to the two research questions proposed above, this study was mostly related to possible shared relations on the semantic level and possibly with respect to general cognitive resources. The experiments did not concern possible overlap with respect to the syntactic processing of mathematical and linguistic expressions. This means, high-level mathematical knowledge seemed to activate brain regions typically involved with space and number and not the semantic network which is typically activated by encyclopedic knowledge. However, these facts did not rule out that some of the rules and processes for the two domains were shared at the syntactic level. The experiment presented in this paper is mainly about this latter aspect.

In favor of shared structure building resources, Patel (2003) suggested the *shared syntactic resource hypothesis*. This hypothesis implied that domains like music and language demanded syntactic rules for processing (linguistic or musical elements need rules to integrate them into larger units such as sentences or musical phrases). Even though these rules themselves are probably specific to their domains, they might employ shared basic structure building resources, e.g. common operations to be executed in the same neural areas. An example for this may be operations to reactivate preceding elements in order to integrate new ones. With respect to shared cognitive capacities, Kljajevic (2010) suggested that some domains like language and music shared the same syntactic working memory resources (see also Fedorenko, Gibson & Rohde, 2007; Fedorenko, Patel, Casasanto, Winawer, & Gibson 2009). However, sharing some cognitive resources for processing does not imply shared structure building resources, i.e. that a connection can be established via abstract representations across domains (and thus, priming across domains; see Koelsch, Kasper, Sammler, Schulze, Gunter, & Friederici, 2004). Domains could just refer to the same domain general cognitive resources to process complex structures (shared capacities). Cross-domain priming studies allow for a more direct test of the connection between the linguistic domain and nonlinguistic domains with respect to abstract representations.

Some of the clearest evidence established so far can be found in Scheepers, Sturt, Martin, Myachykov, Teevan, & Viskupova (2011; see also Scheepers, 2003; Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016), who found a connection between the linguistic domain and mathematics by looking at relative clause attachment *(e.g., he met the daughter of the teacher who lived in Paris)* in English. Before presenting our experiment, we describe these findings, and the rationale behind them, in more detail.

Previous Evidence

Scheepers et al. (2011) studied how mathematical expressions could influence relative clause attachment. Relative clause attachment has the advantage that it presents a syntactic ambiguity with a close correspondence in certain mathematical expressions (as explained further below). Taking an example from Spanish, in sentences like [3], the relative clause can either attach 'high' to the first noun phrase (*la criada*) or 'low' to the second noun phrase (*la actriz*). Interestingly, different languages have different basic attachment preferences: the relative clause in French (or Spanish, Portuguese, German) will more often attach to the first noun phrase (high attachment), whereas the relative clause in other languages like in English will more frequently attach to the second noun phrase (low attachment).

[3] Algúien disparó contra la criada de la actriz [que estava en el balcón].
Someone shot the maid of the actress [that was standing on the balcony].
Cuteos & Mitchell (1988)

Attachment preferences for relative clauses can be quite different across and within languages depending on the particular construction, showing that they can be influenced by a variety of factors: the anaphoric status of the relative pronoun (Hemforth, Konieczny & Scheepers, 2000), length and information structure (Hemforth, Fernandez, Clifton, Frazier, Konieczny, & Walter, 2015), prosody (Fodor, 2002), syntactic (Gibson, Pearlmutter, Canseco-González, & Hickok, 1996) or pragmatic properties (Gilboy, Sopena, Clifton, & Frazier, 1995), or presence or absence of pseudo-relatives in the grammar of the respective language (Grillo & Costa, 2014).

In this paper, we aimed to find out whether these preferences could be changed via structural priming, particularly via priming from non-linguistic structures. The hierarchical structure ambiguity involved in relative clause attachment, i.e integrating some structural element locally (low-attachment) or non-locally (high-attachment) is not specific to linguistic processing and can be found in other domains like mathematics, music, and possibly in a variety of other cognitive domains (see also Van de Cavey & Hartsuiker, 2016). Therefore, relative clause attachment constitutes a key phenomenon to study whether different domains like mathematics and linguistics have shared representations and whether a connection between the domains can be found in terms of cross-domain structural priming.

Scheepers et al. (2011) noticed a certain resemblance between the structural alternatives for sentences like [3] on the one hand and mathematical expressions like *90-(9+1)*5* versus *90-9+1*5* on the other. Apart from giving different results, these two mathematical expressions have hierarchical structures comparable to, respectively, high versus low attachment of a relative clause in a sentence like [3], and can actually be represented in similar ways. For example, in Figure 1, the expression *90-(9+1)*5* (where the final multiplication operator takes scope over a complex expression *(9+1)* on its left) is analogous to high attachment of a relative clause (where the relative clause, or "CP", takes scope over the entire preceding complex noun phrase), while in Figure 2, the expression *90-9+1*5* (where the final operator takes scope over the most recent number on the left) corresponds to low attachment of a relative clause (where the CP takes scope over the most recent noun phrase, or "DP", on its left).

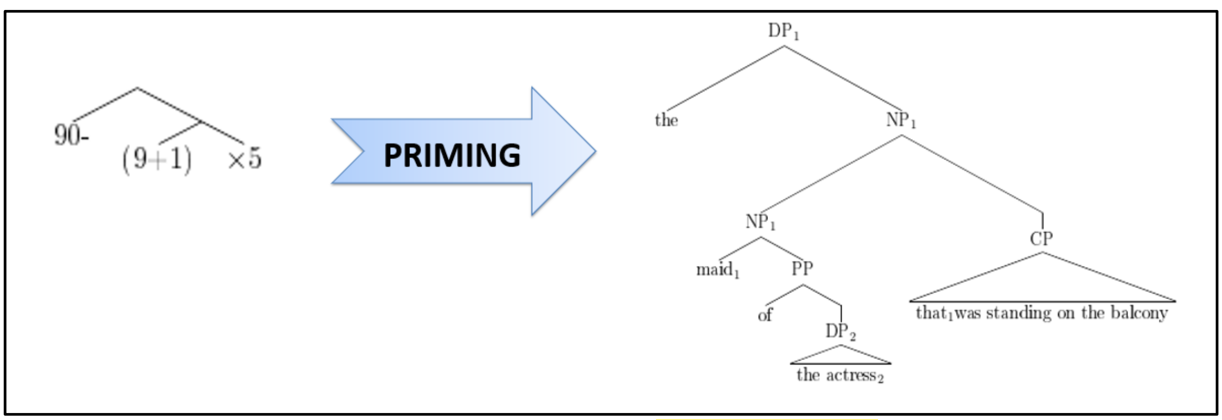

Figure 1. Correspondence between 90-(9+1)*5 and high attachment of a relative clause.

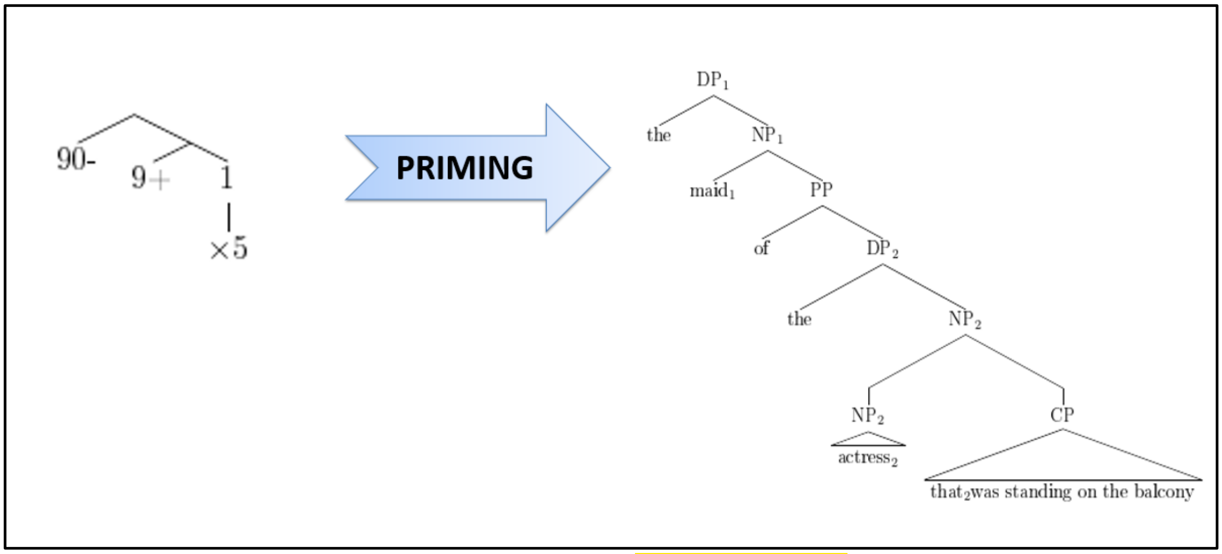

Figure 2. Correspondence between 90-9+1*5 and low attachment of a relative clause.

Figure 1 and Figure 2 illustrate that at an abstract level, the hierarchical structure of mathematical expressions can be analogous to that of linguistic expressions. However, there is an important difference between mathematical expressions and relative clause sentences with respect to their ambiguity. Indeed, when considering mathematical operator-precedence rules, mathematical expressions like *90-(9+1)*5* and *90-9+1*5* are not ambiguous at all. By contrast, sentences with relative clause attachment like *Someone shot the maid of the actress that was standing on the balcony* remain ambiguous on the surface. The main research question of Scheepers et al. (2011) was whether unambiguous mathematical expressions (like the ones discussed above) could influence relative clause attachment via structural priming, which would suggest shared (abstract) structural representations between mathematics and language, or shared procedures to process them, i.e. shared structure building resources.

To answer this question, they set up off-line sentence completion experiments in English. Participants were presented with a questionnaire composed of equations to solve and sentence preambles to complete (starting with the relative pronoun, see table 1). Critical relative clause items were preceded by mathematical expressions to solve (equations analogous to the high-attachment or low-attachment option for relative clause sentences, and 'control' equations that did not entail hierarchical structuring).

Table 1. Example of an item in the experiment from Scheepers et al. (2011)

Category	Item
High attachment equation	90-(5+15)/15
Low attachment equation	90-5+15/15
Control equation	5+15
Incomplete sentence to fill	The tourist guide mentioned the bells of the church that…

Their results showed a priming effect with more high attachment completions after “high” attaching mathematical expressions and more low attachment completions after “low” attaching mathematical expressions, but interestingly, only in subgroups of participants who were adept in solving the mathematical equations correctly (i.e., business and maths students). Another subsample of participants (psychology students) did not show reliable cross-domain structural priming effects, presumably due to a lack of knowledge of the arithmetic operator-precedence rules, as suggested by a high number of mathematical errors in that group (see also Scheepers & Sturt, 2014)

To address this problem, Scheepers et al. (2011) ran another experiment where they added redundant brackets to the critical mathematical equations (e.g. *90-((5+15)/15)* or *90-5+(15/15)*, respectively). This time, psychology students made far fewer mathematical mistakes and showed clear cross-domain structural priming effects.

Thus, the experiments from Scheepers et al. (2011; see also Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016) suggested that linguistic structural processing (more specifically, sentence completion) could be influenced by structural processing in a non-linguistic domain, in this case the mathematical domain.

The Present Study

While being fairly conclusive in terms of shared structural representations across different cognitive domains, the previous research left many questions unanswered. The one we’re interested in is whether this cross-structural priming effect can also be generalized to on-line language comprehension, which is less prone to metalinguistic or strategic effects.

To address this question, we conducted an experiment using an on-line comprehension paradigm, namely *visual-world eye-tracking* (e.g., Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). This technique combines spoken language with a simultaneously presented visual scene, measuring how auditory language comprehension affects scene perception (more specifically, attention-allocation to syntactic interpretation-relevant referents in the scene) in real time. We chose this paradigm because it has previously been successfully used to investigate language-internal structural priming (from reading to listening) of constituent order in German (Scheepers & Crocker, 2004), or of priming of ditransitive structures in English, for example (Arai, Van Gompel & Scheepers, 2007).

Another question addressed by our study is whether cross-structural priming from mathematical equations to relative-clause attachment can also be observed in French where relative clause attachment preferences differ from those in English. As discussed earlier, English exhibits a general low-attachment preference for relative clauses, whereas French (the language used in the present study) shows a general high-attachment preference. Indeed, for the notion of cross-domain structural priming to bear substance, it is important to demonstrate that it is independent from language-specific structural biases.

For the current experiment, we expected early as well as late effects of priming from mathematical expressions to relative clause attachment, particularly for participants with good mathematical knowledge and less so for mathematically less adept participants. Similar to Patel (2003), we assumed that basic processing operations for building hierarchical structures were shared between mathematical and linguistic expressions. Thus, participants with good knowledge of the relevant mathematical operations should show fixations corresponding to a stronger tendency to attach the relative clause high after “high attachment” equations than after “low attachment” equations at the beginning of the relative clause, and also (potentially) towards the end of the sentence. No clear predictions could be made at this point for participants with low mathematical knowledge.

Experiment

Scheepers et al. (2011) found an influence from mathematical expressions on relative clause attachment in English. Still, they (and others) only focused on language production and used off-line questionnaires, which only provided indirect access to linguistic processing. Our study extended this work by setting up an on-line paradigm (visual-world eye-tracking) in another language, i.e. French, a high-attachment preference language. Moreover, we studied priming in comprehension where priming effects have been shown somewhat less consistently (see Traxler, Tooley & Pickering, 2014, for a discussion).
An important fact about French is that it has *different types* of relative clauses depending on the verb in the main clause, and this peculiarity (which does not exist in English) can have a modulating influence on relative clause attachment preferences (Grillo & Costa, 2014). Therefore, it was imperative to pre-test our French materials in order to confirm the general high attachment preference for relative clauses.

1. Norming study

According to Grillo & Costa (2014), relative clauses introduced by a perceptual verb are called *pseudo-relatives*, which are structurally different from traditional relative clauses because they refer to events and will modify the verb and not any of the nouns. As an illustration, the relative clause in [5a] only denotes a property of the lawyer while in [4a] it can also denote an event. It is also possible to pronominalize the head noun with the relative clause like in [4b] contrary to [5b]. In that case, [4] has two readings: a pseudo-relative reading and a traditional relative reading, and according to Grillo & Costa (2014), the pseudo-relative reading is preferred, meaning that the relative clause take the first noun as its subject (here, the son), an interpretation that superficially resembles high attachment (and this relative clause attaches to the verb). This type of relative clause, pseudo-relatives, exists in French but not in English.

[4] a. Le médecin voit le fils de l'avocat qui court.
The doctor sees the son of the lawyer that runs.
b. Le médecin le voit qui court.
The doctor sees him that runs.

[5] a. Le médecin déteste le fils de l'avocat qui court.
The doctor hates the son of the lawyer that runs.
b. *Le médecin le déteste qui court.
*The doctor hates him that runs.

Thus, in order to avoid having different structures of relatives which could add noise to our experimental results, we decided to have the same main clause for every item: *Voici* …. Indeed, Grillo & Costa (2014) attribute the high attachment preference for relative clauses in French mainly to the existence of pseudo-relative clauses. By excluding pseudo-relative readings in French, the high attachment preference for sentences like [5] is therefore less certain[1]. This is why we decided to run a forced choice task with our items to test attachment preferences.

1.1 Participants

50 native speakers of French participated in the experiment (mean age: 35 years old, σ=17). They were recruited via the RISC (http://www.risc.cnrs.fr) platform. 3 participants were excluded because their first language was not French.

1.2 Material

The items consisted of 30 sentences containing an ambiguous relative clause, followed by two possible interpretations of the relative clause (see [6]). The interpretations were either about the first noun (NP1, [6a]) or the second noun (NP2, [6b]).

[6] Voici le cuisinier de l'ingénieur qui va finir ce sur quoi il travaillait.
Here we have the cook of the engineer who will finish what he was working on.

a. Le cuisinier va finir ce sur quoi il travaillait.
The cook finished what he was working on.
b. L'ingénieur va finir ce sur quoi il travaillait.
The engineer finished what he was working on.

Orders of interpretation-paraphrases (NP1-related first or NP2-related first) were counterbalanced across the 30 items per presentation list. There were two such lists, with order of paraphrases swapped across lists. 30 filler sentences concerning determiners were also added for which participants had to choose between two interpretations (*These areas are important for the wealth and health of biodiversity / These areas are important for the health and wealth of biodiversity*). Items were randomized and two lists were generated.

1.3 Procedure

The experiment was run online via the Internet-based platform *IbexFarm (Drummond, 2010)*. For each trial, participants read a sentence with an ambiguous relative clause and they had to choose which of the two interpretations was more natural and acceptable. The experiment lasted around 20 minutes.

1.4 Results

No significant difference was found concerning the order of the interpretation paraphrases. Participants chose NP1-attachment paraphrases 71% of the time and NP2-attachment paraphrases

[1] Still, it can be argued that the *voici* construction resembles a pseudo-relative construction (Lahousse, 2016). Nevertheless, since the construction was systematically the same for all items, the preference should be the same, and it cannot explain differences in attachment preferences due to priming.

29% of the time. A logistic regression model with simple intercept showed a significant difference between NP1-and NP2-attachment: $\beta = 1.44$, $z = 4.85$, $p < .001$. Thus, we found that the NP1-modifying high-attachment interpretation was strongly preferred, contrasting with English which is more biased towards low attachment.

2. Eye-Tracking experiment

We ran an Eye-Tracking experiment using the Visual World paradigm in French. With this design, we manipulated mathematical equations in order to investigate directly their priming effect on ambiguous relative clause comprehension.

2.1 Participants

For the eye-tracking experiment, 36 native speakers of French participated, living in Paris at the time of the experiment (mean age: 30 years old, $\sigma = 11$). All participants gave written informed consent before taking part and the study was approved by the College of Science and Engineering Committee (Application Number for the University of Glasgow: 300150090; Application Number for the University of Paris-Descartes: 2018-34).

2.2 Materials

For this experiment, we applied the Visual World paradigm using Experiment Builder for the setup. There were 30 items (see Appendix), each comprising two types of prime equations (see below), plus a picture and a spoken sentence as target visual-world materials. Each of the 30 target pictures (Figure 3) comprised cartoon-like depictions of several objects and characters in an arbitrary layout (with changing positions across items): two human protagonists (e.g. a chef and an engineer, serving as referents for NP1 and NP2 in the spoken sentences, respectively), two objects associated with those protagonists (e.g., a roast chicken and a tall building), and two unrelated distractor objects (e.g. a broom and a coat). The association between nouns and their related objects was based on semantic and pragmatic similarity.

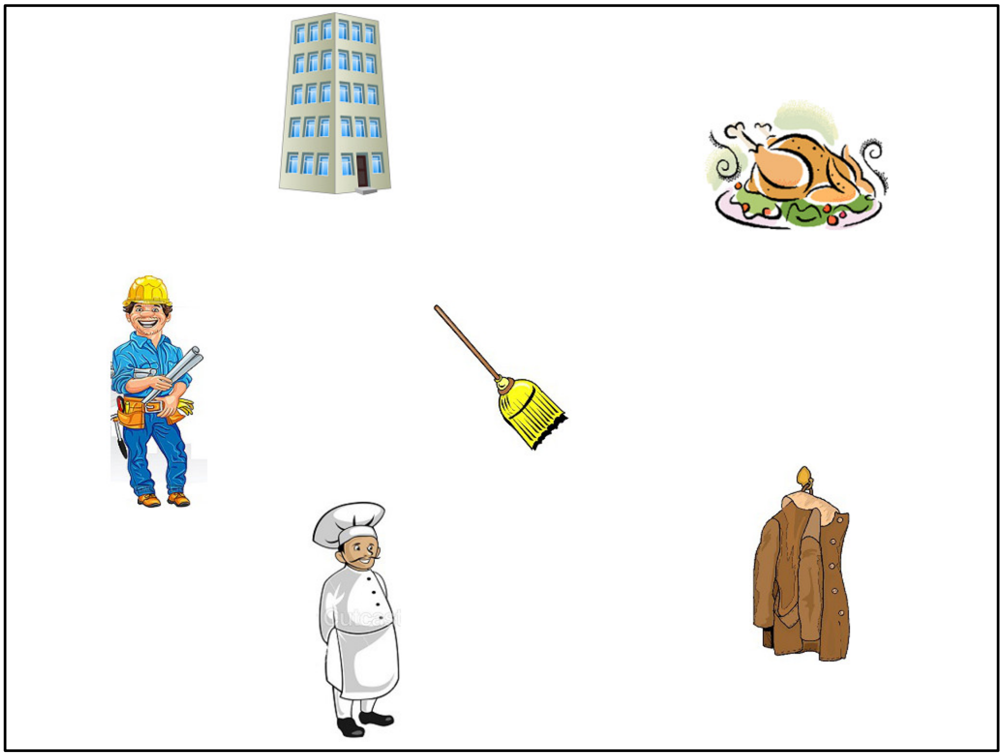

Figure 3. Example of a picture used as target visual-world materials

Audio stimuli were spoken French sentences like [6], which ended in an attachment-ambiguous relative clause (e.g., English translation: "*Here we have the cook of the engineer who will finish what he was working on*"). Relative clauses were constructed to be 'semantically neutral', i.e. they were equally plausible modifiers of either NP1 or NP2. The sentences were spoken by a female native French speaker using neutral intonation, and digitized for later presentation using Audacity and checked in PRAAT (Boersma & Weenink, 2018).

Each item included two types of priming equations – high-attachment (e.g., 4+(6-2)/2) and low-attachment (e.g., 4+6-2/2) – which were paired with one of the pictures (composed of four objects and two human characters) plus a spoken sentence as target for visual-world trials. See Table 2 for examples equations in the two conditions (high attachment and low attachment). The equations were structurally equivalent to the high- and low-attachment equations used in Scheepers et al. (2011). They were easily solvable without using a calculator and always resulted in a non-negative whole number. In high-attachment equations, a multiplication or division operation at the end was preceded by a bracketed term (either an addition or a subtraction) on its left, whereas in low-attachment equations, the brackets were omitted so that the final multiplication or division took scope over the most recently encountered number. Participants were thus presented with 30 experimental items, 15 items per condition.

56 fillers were also added. These comprised 26 equations (structurally different from the critical prime equations, Table 3) and 30 pictures combined with auditory French sentences that ended in

unambiguous relative clauses (e.g., English translation: "*Here we have the gardeners who will offer a necklace to the sculptor*", Figure 4)[2].

Table 2. Example equations in the two conditions

Conditions	Equations
High attachment	77-(14+21)/7
	56-(5+3)*4
Low attachment	77-14+21/7
	56-5+3*4

Table 3. Example equations for the fillers

Fillers
10-5+22
(17+11)/7
(27-(8+1))/9

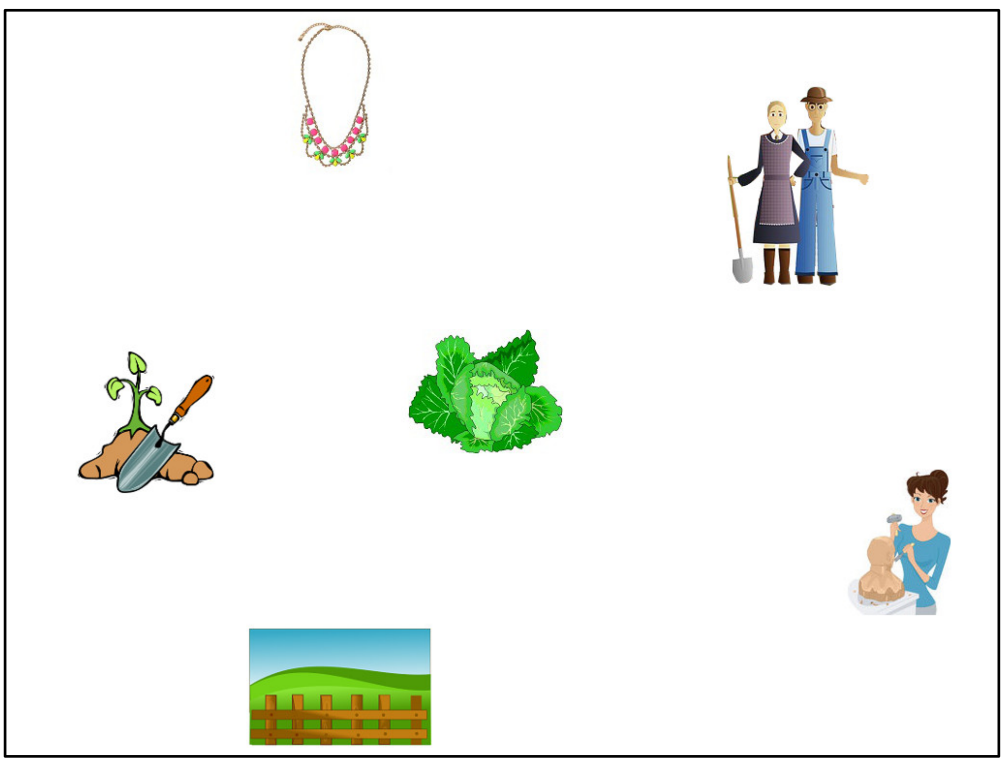

Figure 4. Example of a picture used as filler visual-world materials

[2] See https://www.dropbox.com/sh/cs5e1fv195sgva4/AAAD4eDOvmqUJcnbPpRbb397a?dl=0 for more details (Appendix A).

Two counterbalanced presentation lists were generated such that (a) half of the experimental picture-sentence combinations (serving as targets) were preceded by high-attachment prime equations and the other half by low-attachment prime equations and (b) item-condition combinations were swapped across the two lists.

The materials per list were pseudo-randomised, ensuring that each experimental pair of prime equation and picture-sentence combination was separated from the others by at least one filler trial, randomly chosen from the pool of filler equations and filler visual-world trials. Because of the latter, there was no regular sequencing of mathematical versus visual-world trials (i.e., it was not the case that a mathematical trial was always followed by a visual-world trial or vice versa). To ensure that participants paid attention to the pictures and sentences, comprehension questions were included after 16 of the (filler or experimental) visual-world trials. Eight concerned the spoken sentence (e.g. "*was a cowboy mentioned?*"), and eight referred to the picture itself (e.g., "*was there a broom in the picture?*").

The incorrect answer option for the mathematical equations always corresponded to the result of linear processing of the equation without taking operator-precedence rules into account (i.e., the result according to an incorrect structuring of the equation). Positioning of correct/incorrect answer options was counterbalanced across items.

2.3 Hypothesis

Based on our experimental design, upon hearing "*qui va finir ce sur quoi il travaillait*" ("*who will finish what he was working on*") in the sentence, we expected participants to look more at the NP1-related object (roast chicken) in Figure 3 if they had been primed towards assuming a high-attachment structure, and to look more at the NP2-related object (building) if they had been primed towards assuming a low-attachment structure. In principle, such priming effects could manifest themselves as early as during encountering the relative pronoun ("qui") in the sentence if participants expect references to NP1- and NP2-related objects in the relative clauses. Alternatively, such effects could take more time to emerge (e.g., towards the end of the relative clause, when all interpretation-relevant information is available). As for both groups of participants, we expected that mathematical priming would affect attachment preferences for the *mathematical group*, but no clear predictions could be made for the *no mathematical* group.

2.4 Procedure

Before the experiment started, participants had to solve the following equation: *1+2*3=?*. Depending on the answer (7 or 9), participants were divided into two groups[3]: a *mathematical knowledge* group (if they gave the correct answer 7) and a *no mathematical knowledge* group (if they gave the incorrect answer 9), see also Scheepers and Sturt (2014).

[3] Participants were unaware of this classification, and none of them produced a result other than 9 or 7 (except one participant, whose data was thus excluded from analysis).

The eye-tracking experiment was run with an SR Research Eyelink 2 system in a sound attenuated booth. We recorded eye fixations from the dominant eye based on the Miles Test (1930). Each experiment started with a nine-point calibration.

As for the procedure, participants were instructed that there were two types of trials: (i) mathematical trials and (ii) picture-sentence trials[4]. Each picture-sentence trial was preceded by the presentation of a fixation dot for drift-correction. On mathematical trials, participants saw an equation on screen with two possible answer options below it (see Figure 5). They had to choose the correct answer by pressing the left button on a gamepad for the answer on the left, and the right button for the answer on the right.

In picture-sentence trials, they had to look at pictures while listening to related spoken sentences. Participants were informed that after some of the picture-sentence trials, a question related to either the picture or the sentence would appear, which they were to answer with either the right-hand button (for 'yes') or the left-hand button (for 'no') on the gamepad. Eye movements were recorded throughout the presentation of each picture, which stayed on screen for 5000ms. The speech recordings for the sentences started playing right after the onset of each picture presentation. Figure 5 illustrates the presentation sequence for a critical prime-target pair of trials and Figure 6 for a non critical prime-target pair of trials. There was a practice session before the actual experiment (4 trials) so that the participants could get used to the task.

Importantly, participants remained unaware about the pairing of critical prime-target trials until debriefing at the end of the experimental session.

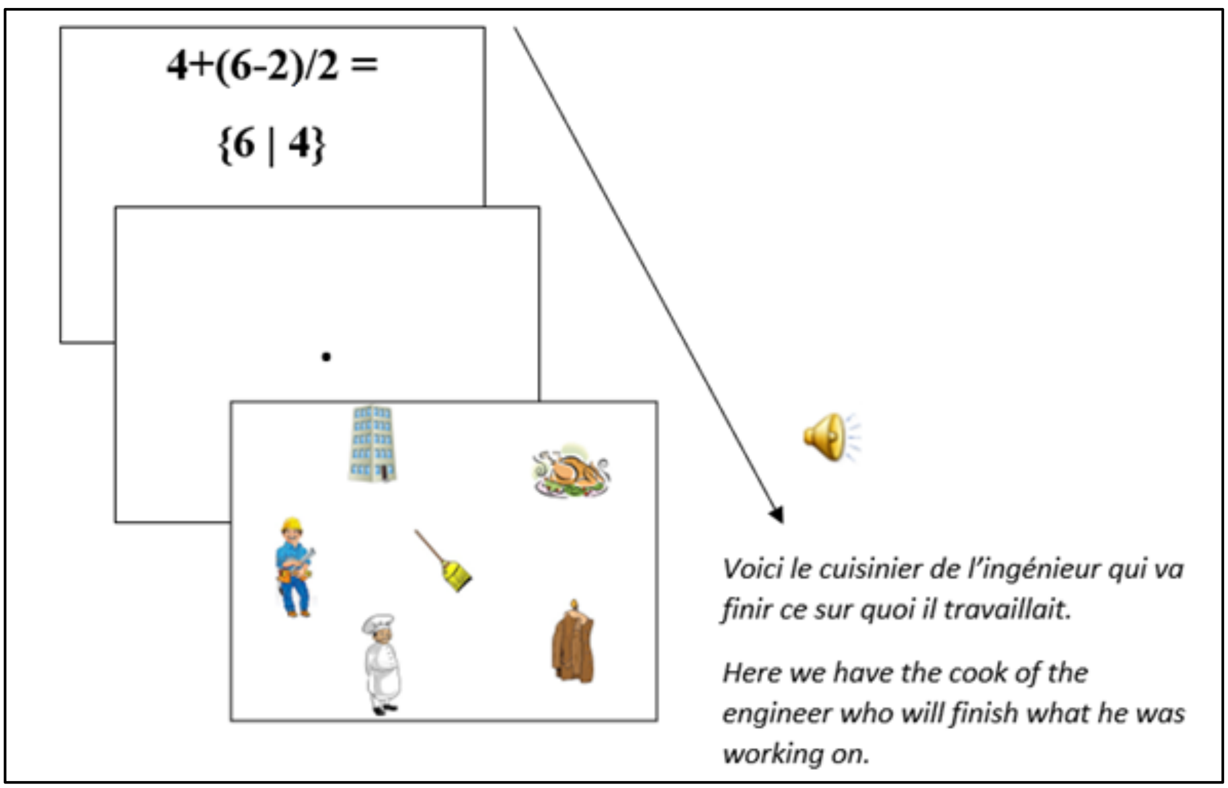

Figure 5. Presentation sequence for a critical prime (equation) – target (visual-world trial) pair of stimuli.

[4] The instructions can be found in Appendix B https://www.dropbox.com/sh/cs5e1fv195sgva4/AAAD4eDOvmqUJcnbPpRbb397a?dl=0.

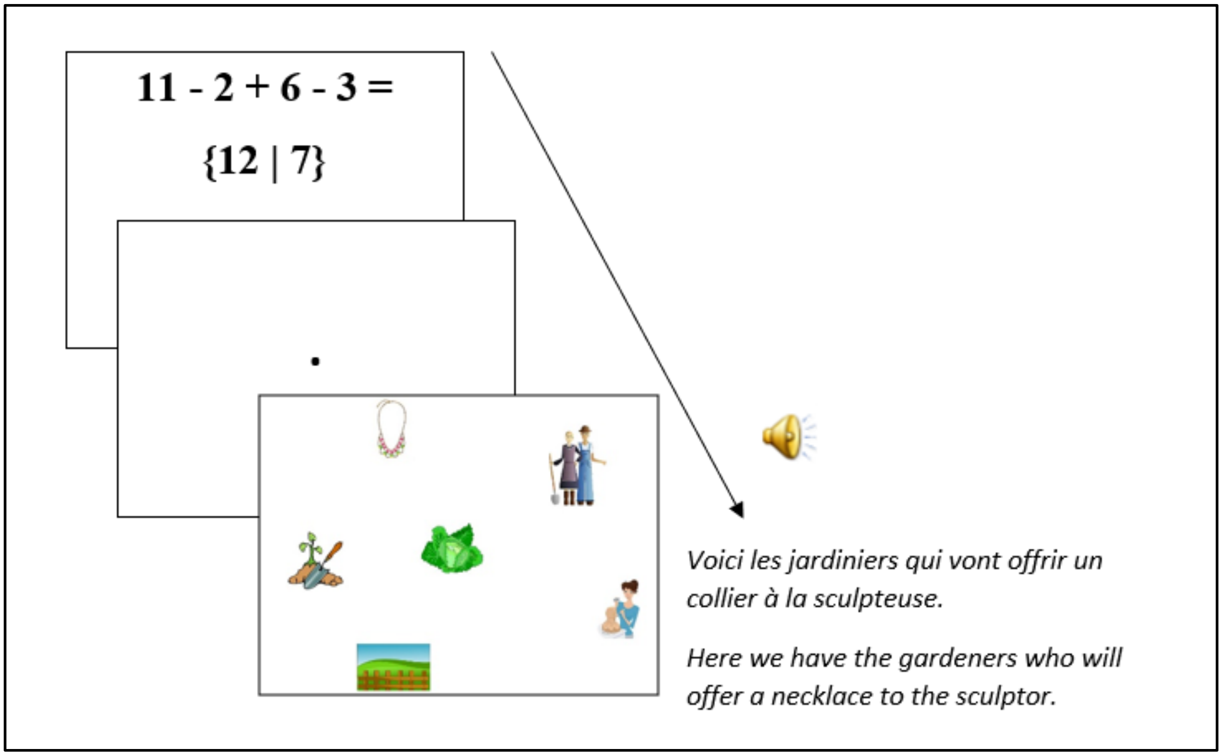

Figure 6. Presentation sequence for a non critical prime (equation) – target (visual-world trial) pair of stimuli.

2.5 Analysis methods

We used the R package EyetrackingR (Dink & Ferguson, 2015) to analyse the Eye-Tracking data. We then analyzed them by running growth curve analyses (Mirman, Dixon & Magnuson, 2008). Independent variables (predictors) were Prime Condition (high attachment vs. low attachment), Time and Group (mathematical knowledge and no mathematical knowledge). Dependent variables (outcome variables) were fixations on the NP1-related object or on the NP2-related object (For the results presented in this paper, we excluded the four other objects from analysis). The reason to look at the targeted object lied on the fact that the ambiguous relative clause was about the objects, and not the protagonists. As a result, participants should look more at the object during that period of time. Random variables were participants and items.

We chose growth curves due to the fact that eye fixations on the target objects should change depending on what part of the sentence participants are listening to at a certain moment. Thus, time is a very strong predictor that needs to be taken into account. This is why we ran growth-curve analyses in order to include time as a continuous predictor with the dependent variable being categorical (binary).

In the procedure for the growth-curve analysis for visual world data, we ran Bayesian generalized linear mixed models (Sorensen, Hohenstein & Vasishth, 2016, among others) using the R package Rstan. Our main motivation behind choosing a Bayesian modelling framework was that previous frequentist analyses (using the lme4 package) often failed to converge when a maximal random effects structure justified by the design was used (cf. Barr, Levy, Scheepers & Tily, 2013). Bayesian models are much less prone to convergence failure, even with relatively small data sets.

Another advantage of Bayesian analysis is that it directly tests the likelihood of the hypothesis of interest, contrasting with indirect null-hypothesis testing as in frequentist frameworks. Moreover, we express the uncertainty of the effects by the means of credible intervals.

Our hypothesis was that a priming effect would show up especially for the mathematical knowledge group. In other words, looks to the NP1-related object would be more frequent in the high attachment condition for the mathematical knowledge group. The opposite pattern was expected for the NP2-targeted object. As for the choice for NP1- and NP2-related objects, we expected that participants would look more at the objects in order to disambiguate the relative clause.

Fixed effects were Time, Group and Prime Condition as well as their interactions. Random effects were participants and items, and we also included random slopes for the effects of Prime Condition and Group for items, as well as their interactions. For participants, we only included random slopes for Prime Condition.

As for the coding, the group factor was coded 1 for the mathematical knowledge group and -1 for the no mathematical knowledge group. The Prime Condition factor was coded 1 for high attachment and -1 for low attachment. Normal distributions with $\mu = 0$, $SD = 10$ on a logit scale were used as weakly informative priors.

To determine the shape of the fixed effect of time, we ran three linear mixed models with simple intercepts to test which polynomial function corresponds best to our data (see Appendix C)[5]. Then, we ran Bayesian models with 4 chains and 6000 iterations each. Model convergence was verified graphically and by inspecting model coefficients in R.

According to our hypothesis, potential priming effects may show up either at the beginning of the relative clause or towards the end of the sentence (when all the information is available). We therefore analyzed the data per participant group in two separate time-windows: (i) 200ms before the beginning of the relative clause until 200ms after the beginning of the relative clause, and (ii) 500ms before the end of the sentence until the end of the sentence.

Concerning the pre-test (1+2*3=?), in the *mathematical knowledge* group, there were 20 participants, and the *no mathematical group* counted 16 participants. But after inspecting the results more closely, we found that the accuracy rate for the condition equations of two participants from the *mathematical knowledge* group was lower than 70%. We decided to put them in the other group: the *no mathematical knowledge* group, which counts now 18 participants. We present here the analysis with this change[6].

2.6 Results

Comprehension Accuracy

To be sure that participants were engaged to the task, there were comprehension questions on the pictures. Participants from the *mathematical knowledge* group answered 87% of the comprehension questions correctly, while participants from the *no mathematical knowledge* group answered 85% of the comprehension questions correctly.

[5] This is available on https://www.dropbox.com/sh/cs5e1fv195sgva4/AAAD4eDOvmqUJcnbPpRbb397a?dl=0.

[6] The former analysis is available in Appendix D on https://www.dropbox.com/sh/cs5e1fv195sgva4/AAAD4eDOvmqUJcnbPpRbb397a?dl=0.

Mathematical Performance

When looking at the percentage of correct answers to the equations, we found that participants from the *mathematical knowledge* group answered 84% of the high-attachment equations and 97% of the low-attachment equations correctly. By contrast, participants in the *no mathematical knowledge* group answered 12% high-attachment equations and 19% low-attachment equations correctly. As for the structurally simpler filler equations, participants in the *mathematical knowledge* group answered them correctly 96% of the time, and participants of the *no mathematical knowledge* group 90% of the time.

These results suggest that participants in the *mathematical knowledge* group generally 'understood' the structure of the prime equations, whereas participants in the *no mathematical knowledge* group had difficulty particularly with identifying the correct operator-precedence relations in the equations (as already suggested by the initial classification).

Eye fixations on the NP1 (vs NP2)-related object

In this paper, we excluded the four other objects from the analysis, and since we only took the probability of looks to the NP1-object out of all NP1- and NP2-object fixations, we only show looks to the NP1-related object because looks to the NP2-object would be the mirror image of the other.

Figure 7 shows raw proportions of looks to the NP1-related object (out of fixations to NP1-related object + fixations to NP2-related object) in relation to Prime Condition (high attachment vs. low attachment) every 50 ms, from the first noun to the end of the sentence. Figure 7 concerns the results from the *mathematical knowledge* group, and from the *no mathematical knowledge* group. The blue line refers to fixations to the NP1-related object under the low attachment condition while the red line concerns fixations to the NP1-related object under the high attachment condition.

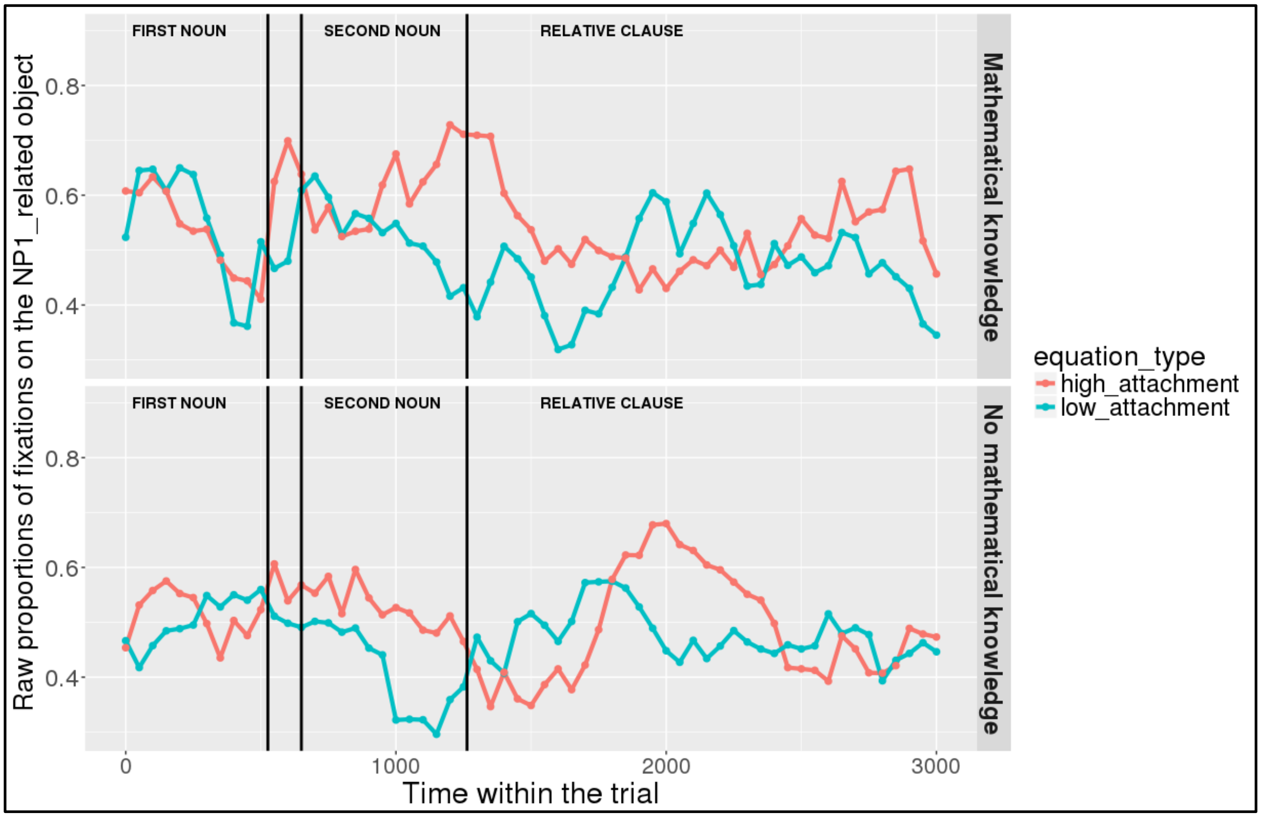

Figure 7. Raw proportions of fixations on the NP1-related object (roasted chicken) in relation to Prime Condition for both groups.

As shown respectively in Figures 8 and 9, an interaction of Time, Group and Prime Condition was observed when looking at the beginning of the relative, that is to say 200ms before and 200ms after the beginning of the relative clause (poly1, β^=8.20, 95% CrI=[1.95, 14.34], P(β^) < 0 <.006) and (less so) 500ms before the end of the sentence until the end of the sentence (poly1, β^=3.69, 95% CrI=[-1.17 8.67], P(β^) < 0 <.07). This means that there was an effect of mathematical attachment over time and that the difference between high attachment and low attachment is not the same in both groups over time.

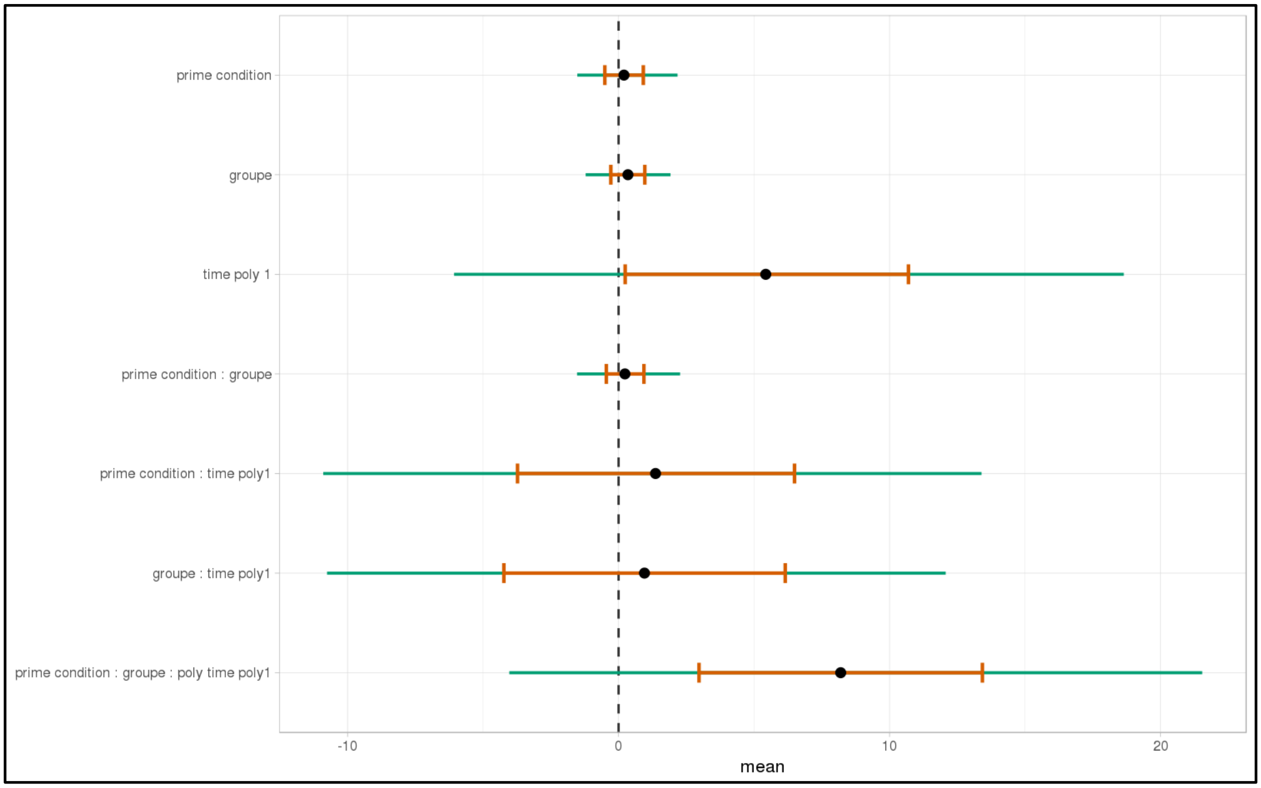

Figure 8. Posterior distribution of independent variables for the first part: during the beginning of the relative clause (1063-1463ms)

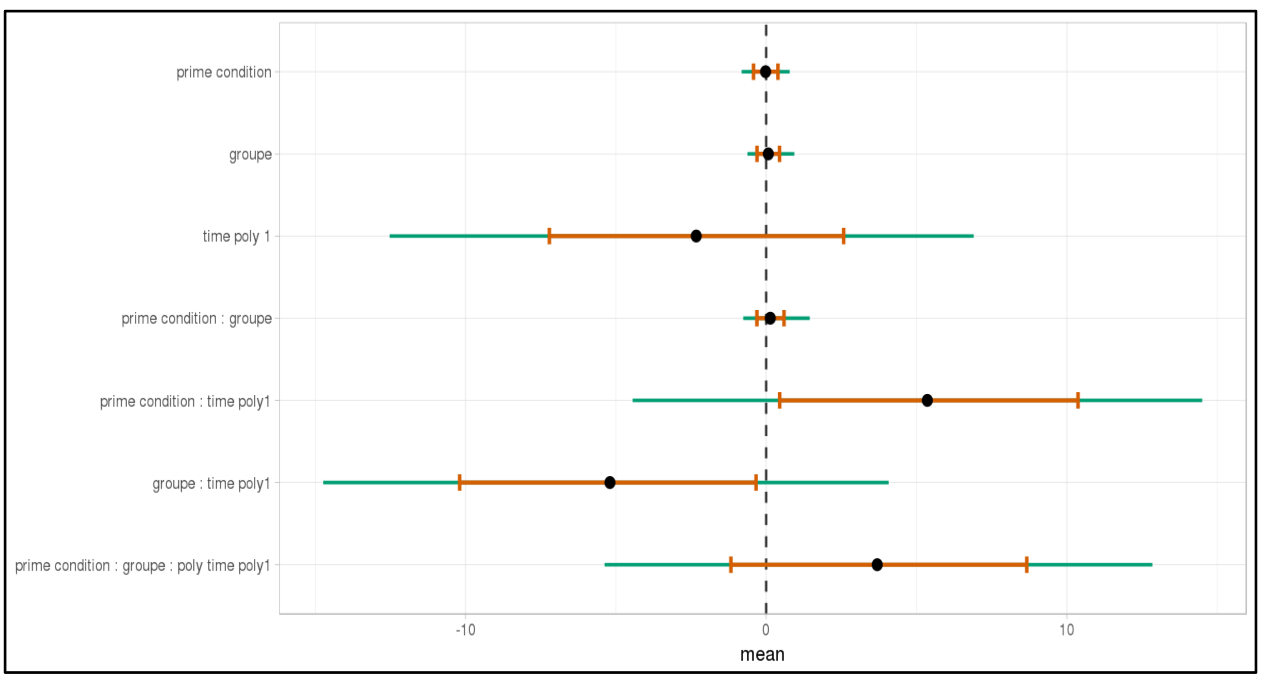

Figure 9. Posterior distribution of independent variables for the second part : from the relative to the end of the sentence (2523-3023ms)

When sub-setting the data by group, we found a different pattern between the *mathematical knowledge* group and the *no mathematical knowledge* group in the two time-windows.

Indeed, at the beginning of the relative clause in Figure 10, we found for the *mathematical knowledge* group an interaction between Prime Condition and Time (Figure 11, poly1: $\hat{\beta}$=6.43, 95% CrI=[.58, 12.36], P($\hat{\beta}$) < 0 <.02)[7] but the pattern is different for the *no mathematical knowledge* group: the potential difference between high attachment and low attachment at first tends to disappear over time (see the results for this group on the right in Figure 10), which explains why there is an inverse pattern between time and Prime Condition in Figure 12 (poly 1: $\hat{\beta}$=-5.27, 95% CrI=[-11.54, 1.03, P($\hat{\beta}$) < 0 =.95).

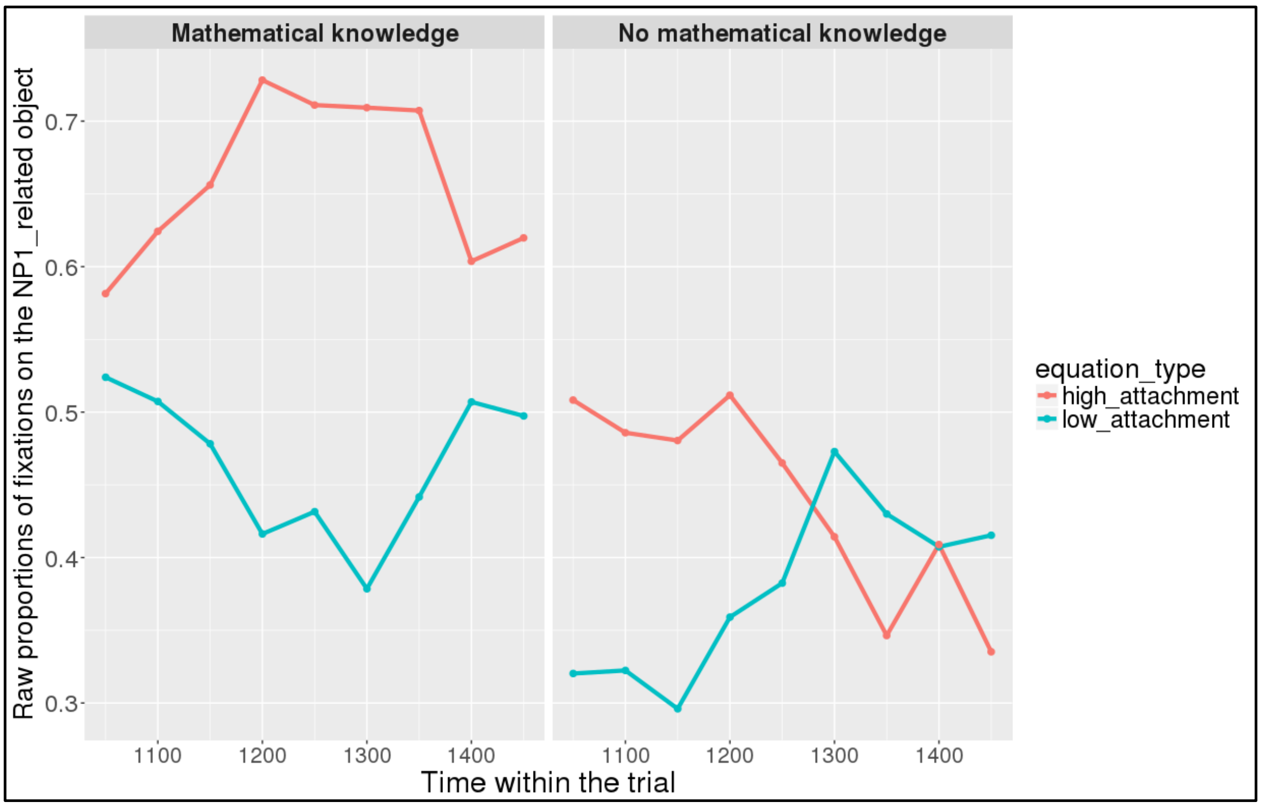

Figure 10. Proportions of looks towards the NP1-related object in each of the two groups at the beginning of the relative clause (1063-1463ms). Red curves: high-attachment prime condition; blue curves: low-attachment prime condition.

---

[7] The fact that P($\hat{\beta}$) < 0 <.02 means that the probability of the hypothesis "<0" is very low, meaning that participants from the *mathematical knowledge* group look more to NP1-targeted object across the relevant time period when the Prime Condition is high attachment. This is not the case for the participants from the *no mathematical knowledge* group with P($\hat{\beta}$) < 0 =.95, where the priming effect disappears over time.

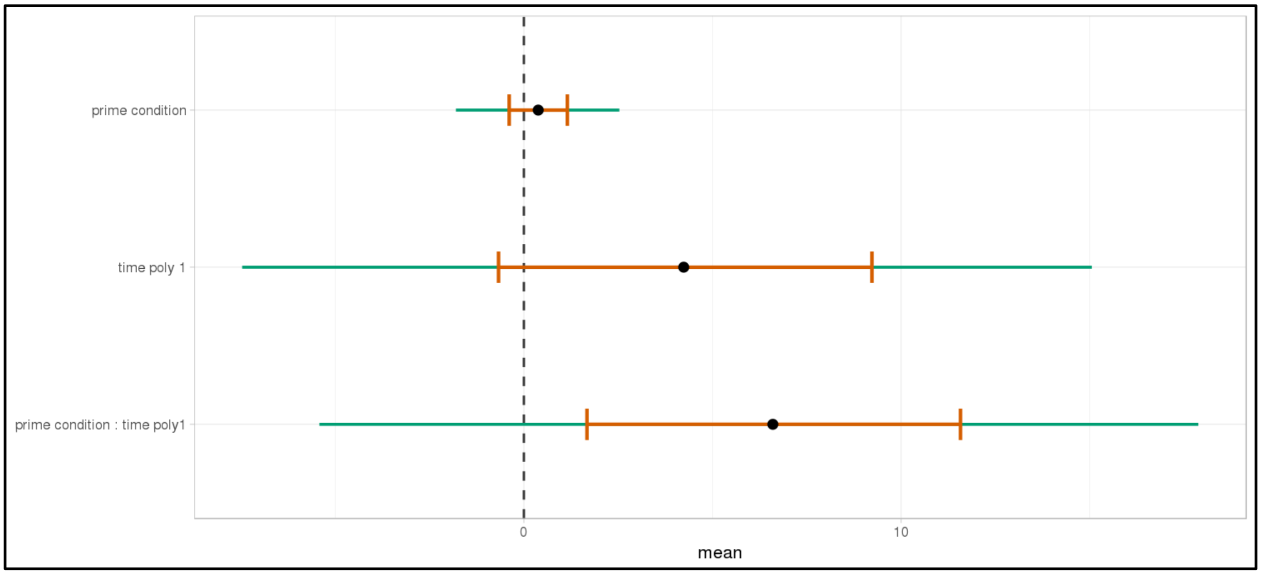

Figure 11. Posterior distribution of independent variables for the first part (1062-1462ms) in the *mathematical knowledge* group

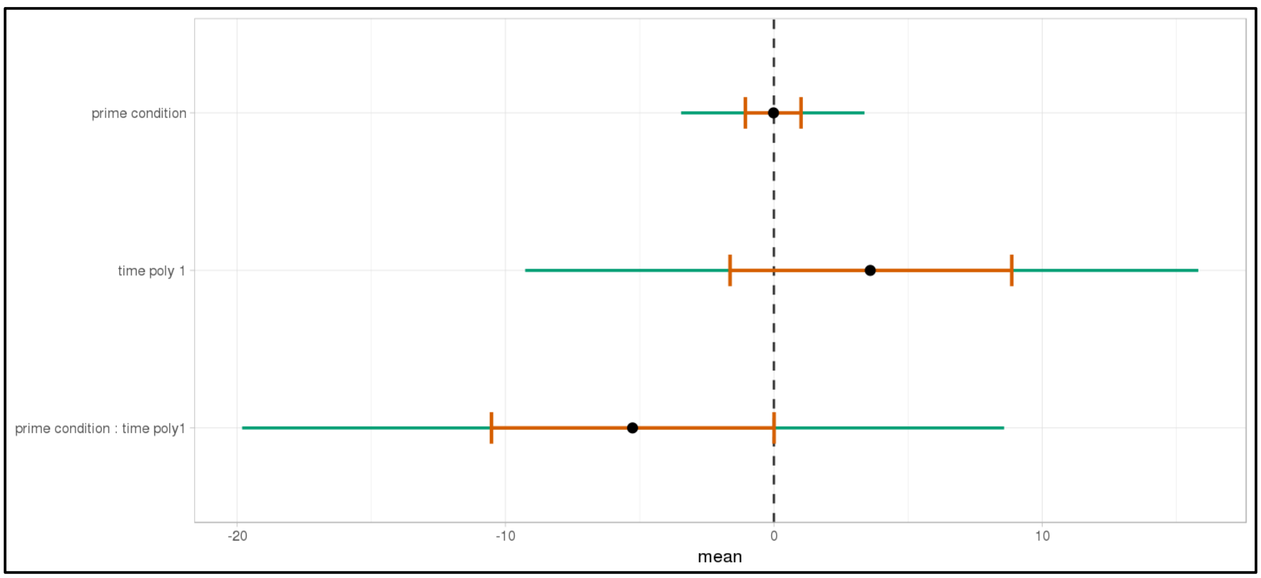

Figure 12. Posterior distribution of independent variables for the first part (1064-1464ms) in the *no mathematical knowledge* group

At the end of the sentence (Figure 13), the interaction of time and Prime Condition is still there for the *mathematical knowledge* group (Figure 14, poly 1: $\hat{\beta}$=6.91, 95% CrI=[1.99, 11.82], P($\hat{\beta}$) < 0 <.003) but not for the *no mathematical knowledge* group (Figure 15, poly 1: $\hat{\beta}$=1.42, 95% CrI=[-3.79, 6.60], P($\hat{\beta}$) < 0 <.30).

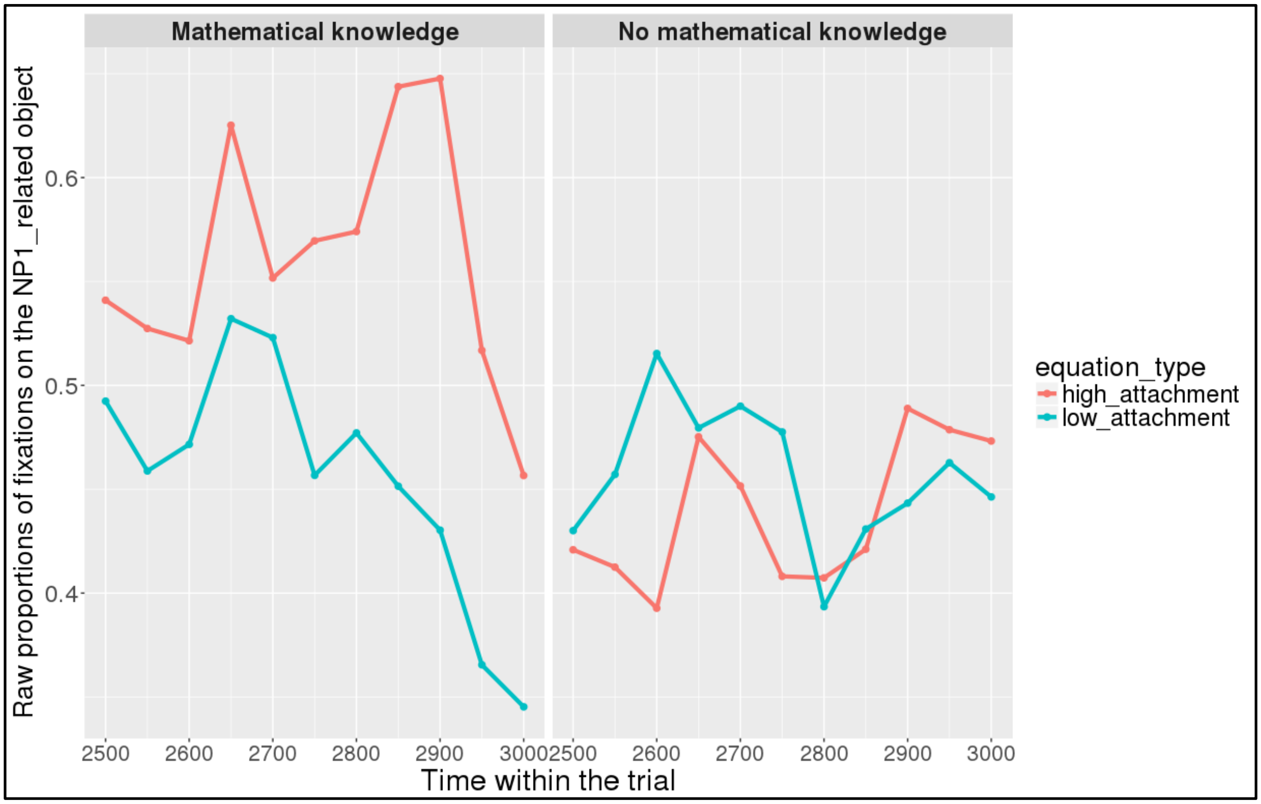

Figure 13. Proportions of looks towards the NP1-related object in each of the two groups at the end of the sentence (2523-3023ms). Red curves: high-attachment prime condition; blue curves: low-attachment prime condition.

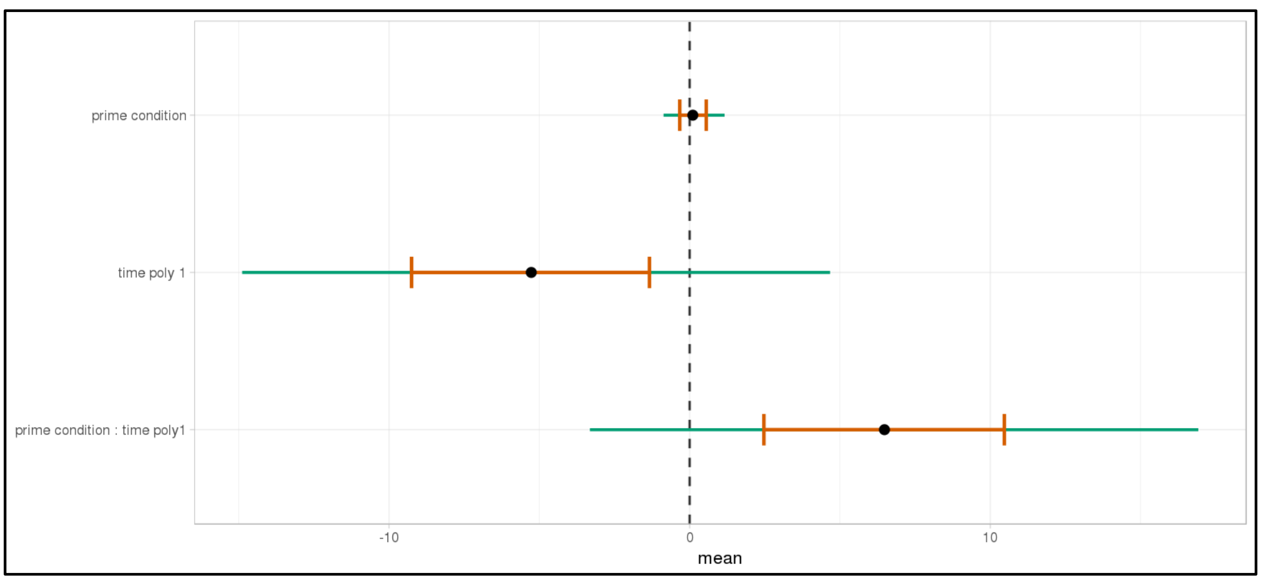

Figure 14. Posterior distribution of independent variables for the second part (2515-3015ms) in the *mathematical knowledge* group

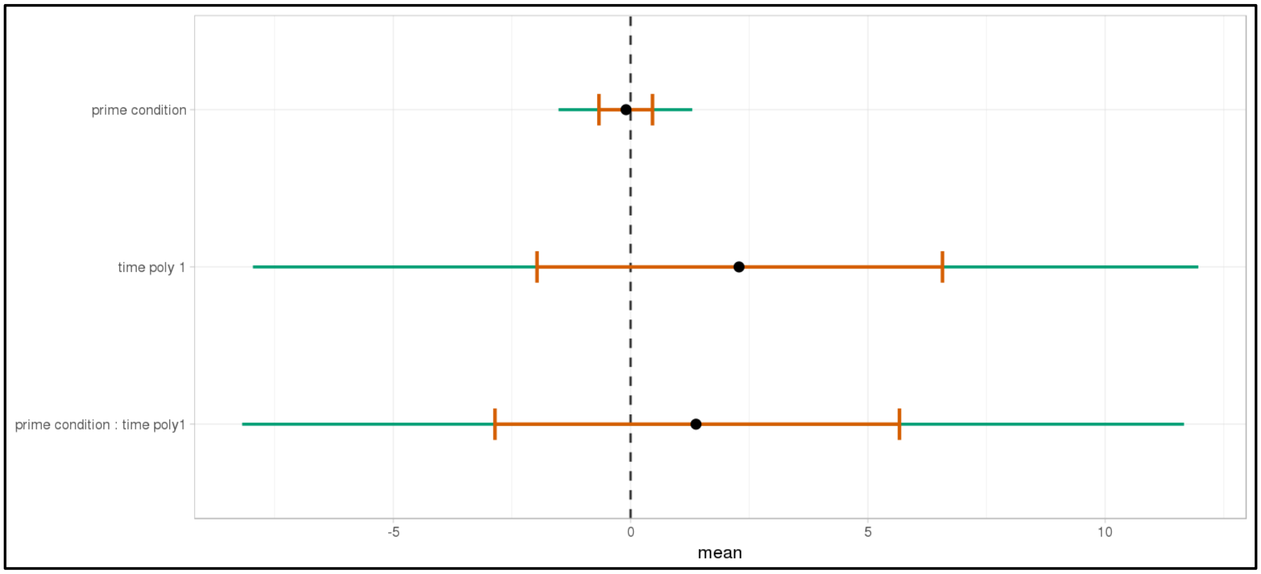

Figure 15. Posterior distribution of independent variables for the second part (2530-3030ms) in the *no mathematical knowledge* group

Overall, it can be concluded that cross-domain structural priming effects emerged very early on (even before the onset of the relative pronoun itself) and were especially robust and persistent in the *mathematical knowledge* group of participants compared to the *no mathematical knowledge* group.

General discussion

The present study replicated and extended aspects of earlier off-line results by Scheepers et al. (2011) and others (e.g., Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016) in interesting and important ways. Specifically, we investigated structural priming across cognitive domains – from mathematical equations to relative-clause attachments in spoken sentences – in French, a language known to contrast with English in terms of general relative clause attachment preferences: whereas English speakers/listeners usually prefer to attach relative clauses low to the most recent NP in a sentence, French speakers typically prefer high attachment of relative clauses, as was also confirmed in the pre-test of our materials. More importantly, the present study was the first to investigate cross-domain structural priming effects within the context of *on-line* sentence comprehension: indeed, the visual-world eye-tracking paradigm allowed us to pin down more precisely than previous studies at which point during processing of an attachment-ambiguous relative clause potential cross-domain syntactic priming effects would emerge. Another potentially important aspect of the present study was that the visual world paradigm is arguably less prone to strategic effects, as it required no metalinguistic judgement or explicit syntactic attachment decisions by the participants (i.e., they just "look and listen" and are unlikely to become aware of their syntactically driven visual biases). Although there was no norming study concerning the association between the nouns and they related objects, looks at the targeted object during the ambiguous relative clause showed the association was still relevant for the task.

Given that structural priming relies on the accurate processing of the structural primes (mathematical equations in this case), clear structural priming effects were in fact only expected for mathematically adept participants – in line with Scheepers et al. (2011) who found that without additional help in solving the mathematical primes (such as additional redundant brackets in the prime equations) mathematically less skilled participants would not only struggle to solve the priming equations correctly, but also show a generally less robust priming effect from mathematical equations to linguistic expressions. The latter was also evident in the *no mathematical knowledge* group of participants in our study: although there was evidence of cross-domain structural priming in this group as well, effects were less pronounced and more distributed over time than in the *mathematical knowledge* group who were much more likely to solve the prime equations correctly, and who showed cross-domain structural priming effects during the earliest stages of integrating the ambiguous relative clause into the preceding sentence context (specifically, around the onset of the relative pronoun in the spoken target sentence).

The early effect was interesting in terms of when exactly during sentence processing cross-domain structural priming effects would emerge. Scheepers et al. (2011) actually speculated about potential processing mechanisms that could underlie their off-line results. In what they called the *incremental-procedural account* they proposed that, just as the processing of linguistic materials, processing of mathematical equations structured like $A+(B+C)*D$ respectively $A+B+C*D$ would proceed in an incremental 'left-to-right' fashion. This would trigger a form of mild (monotonic) revision as soon as the final multiplication or division operator is encountered at the end of the equation, because the operator-precedence rules require that this operation is applied before the preceding term ($(B+C)$ respectively C) is added; in 'high-attachment' equations like $A+(B+C)*D,$ the final operator would combine with a complex expression on its left ($B+C$), whereas in 'low-attachment' equations like $A+B+C*D$ it would combine with the most recent number (C) on its left. In analogy to this, a form of mild revision is also likely to take place when encountering a relative pronoun after incrementally processing a partial sentence such as *The tourist guide mentioned the bells of the church…* (*that*) because (i) the sentence is obviously not complete at this point and (ii) the relative pronoun needs to be integrated with a preceding noun phrase. In analogy to the mathematical primes, this relative pronoun can either combine with a complex noun phrase on its left (e.g., *the bells of the church*, yielding high attachment) or with the most recent noun phrase on its left (e.g., *the church*, yielding low attachment). Scheepers et al. (2011) proposed that it is this combinatorial choice that is affected by cross-domain structural priming, and the present findings (particularly for the mathematically adept group of participants) seem to support this *incremental-procedural* view: Evidence for structural priming became manifest as soon as the relative pronoun (*qui*) was encountered in the spoken speach stream, i.e., in a time window from 200ms before to 200ms after the onset of the relative pronoun. This early onset of effects is in line with the hypothesis that cross-domain structural priming influences the immediate (incremental) syntactic integration of relative pronouns during sentence processing. However, one probably needs to be cautious with this interpretation, as a different treatment of the response proportions in a supplemental analysis (using NP1-related object fixations in proportion to fixations on all the other objects available[8]) suggested more delayed effect onsets relative to the relative pronoun, while still showing clear support for cross-domain structural priming.

[8] This is available on https://www.dropbox.com/sh/cs5e1fv195sgva4/AAAD4eDOvmqUJcnbPpRbb397a?dl=0.

What are the more general implications of cross-domain structural priming between mathematics and language processing? In the introduction, we discussed seemingly conflicting evidence suggesting a strict separation between language and mathematics in the brain (e.g., Amalric & Dehaene, 2016). We would argue that this conclusion was too narrowly focused on the semantics of linguistic vs. mathematical expressions and did not apply to the processing of abstract hierarchical structure as investigated here and in previous studies. It is also important to keep in mind that shared processing resources for mathematical and linguistic expressions must not necessarily rely on networks that are *specialized* for linguistic and/or mathematical processing. Indeed, it is conceivable that potentially shared representations may be processed at some separate, *domain-general* level that is independently accessible by brain networks that are more specialized for mathematics and language. Such a view also concurs with findings from Varley, Klessinger, Romanowski, & Siegal, (2005) showing that patients with severe agrammatic aphasia can nevertheless perform well at various mathematical tasks.

To conclude, in line with previous findings (e.g., Scheepers et al., 2011), the present visual-world eye-tracking experiment suggested that mathematics and language shared aspects of syntactic structure at a very high-level of abstraction. These effects appeared to be largely independent of baseline RC-attachment preferences (low attachment in English, high attachment in French). More importantly, for mathematically skilled participants at least, the present study appears to indicate that cross-domain priming from mathematics to language influences the very earliest stages of integrating a relative clause into the prior sentence context, in line with an *incremental-procedural* account of hierarchical structure priming.

References

Amalric, M., & Dehaene, S. (2016). Origins of the brain networks for advanced mathematics in expert mathematicians. *Proceedings of the National Academy of Sciences*, *113*(18), 4909-4917.

Arai, M., Van Gompel, R. P., & Scheepers, C. (2007). Priming ditransitive structures in comprehension. *Cognitive psychology*, *54*(3), 218-250.

Barr, D. J. (2008). Analyzing 'visual world'eyetracking data using multilevel logistic regression. *Journal of memory and language*, *59*(4), 457-474.

Bock, J. K. (1986). Syntactic persistence in language production. *Cognitive psychology*, *18*(3), 355-387.

Boersma, P. & Weenink, D. (2018): *Praat: doing phonetics by computer [Computer program].* Version 6.0.37, retrieved 14 March 2018 from http://www.praat.org/

Cooper, R. M. (1974). The control of eye fixation by the meaning of spoken language: A new methodology for the real-time investigation of speech perception, memory, and language processing. *Cognitive Psychology*.

Cuetos, F., & Mitchell, D. C. (1988). Cross-linguistic differences in parsing: Restrictions on the use of the Late Closure strategy in Spanish. *Cognition*, *30*(1), 73-105.

Dink, J. W., & Ferguson, B. (2015). eyetrackingR: An R library for eye-tracking data analysis. *Available at www. eyetracking-r. com. Accessed July*, *6*, 2017.

Drummond, A. (2010). Internet Based EXperiments (IBEX)(version 0.3). Available at: http://spellout.net/ibexfarm.

Fedorenko, E., Gibson, E., & Rohde, D. (2007). The nature of working memory in linguistic, arithmetic and spatial integration processes. *Journal of Memory and Language*, *56*(2), 246-269.

Fedorenko, E., Patel, A., Casasanto, D., Winawer, J., & Gibson, E. (2009). Structural integration in language and music: Evidence for a shared system. *Memory & cognition*, *37*(1), 1-9.

Fodor, J. D. (2002). Prosodic disambiguation in silent reading. In M. Hirotani (Ed.), *Proceedings of the North East*. GSLA, University of Massachusetts, Amherst.

Grillo, N., & Costa, J. (2014). A novel argument for the universality of parsing principles. *Cognition*, *133*(1), 156-187.

Gibson, E., Pearlmutter, N., Canseco-González, E., & Hickok, G. (1996). Cross-linguistic attachment preferences: Evidence from English and Spanish.

Gilboy, E., Sopena, J. M., Clifton Jr, C., & Frazier, L. (1995). Argument structure and association preferences in Spanish and English complex NPs. *Cognition*, *54*(2), 131-167.

Hartsuiker, R. J., Pickering, M. J., & Veltkamp, E. (2004). Is syntax separate or shared between languages? Cross-linguistic syntactic priming in Spanish- English bilinguals. *Psychological Science*, 15(6), 409-414.

Hemforth, B., Konieczny, L., & Scheepers, C. (2000). Syntactic attachment and anaphor resolution: The two sides of relative clause attachment. *Architectures and mechanisms for language processing*, 259-281.

Hemforth, B., Fernandez, S., Clifton Jr, C., Frazier, L., Konieczny, L., & Walter, M. (2015). Relative clause attachment in German, English, Spanish and French: effects of position and length. *Lingua*, *166*, 43-64.

Kljajević, V. (2010). Is syntactic working memory language specific?. *Psihologija*, *43*(1), 85-101.

Lahousse, K., & Karssenberg, L. (2016). *Les «pseudo-relatives» dans les structures clivées en il ya... qui.*.

Miles, W. R. (1930). Ocular dominance in human adults. *The journal of general psychology*, *3*(3), 412-430.

Mirman, D., Dixon, J. A., & Magnuson, J. S. (2008). Statistical and computational models of the visual world paradigm: Growth curves and individual differences. *Journal of memory and language*, *59*(4), 475-494.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature neuroscience*, *6*(7), 674.

Pickering, M. J., & Branigan, H. P. (1998). The representation of verbs: Evidence from syntactic priming in language production. *Journal of Memory and language*, *39*(4), 633-651.

Pickering, M. J., & Ferreira, V. S. (2008). Structural priming: a critical review. *Psychological bulletin*, *134*(3), 427.

Scheepers, C. and Crocker, M.W. (2004) Constituent order priming from reading to listening: a visual-world study. In: Carrerias, M. and Clifon, C.(eds.) *The On-Line Study of Sentence Comprehension: Eyetracking, Erps, and Beyond.* Psychology Press: New York, NY, pp. 167-185.

Scheepers, C., & Sturt, P. (2014). Bidirectional syntactic priming across cognitive domains: From arithmetic to language and back. *The Quarterly Journal of Experimental Psychology*, *67*(8), 1643-1654.

Scheepers, C., Sturt, P., Martin, C. J., Myachykov, A., Teevan, K., & Viskupova, I. (2011). Structural priming across cognitive domains: From simple arithmetic to relative-clause attachment. *Psychological Science*, *22*(10), 1319-1326.

Sorensen, T., Hohenstein, S., & Vasishth, S. (2016). Bayesian linear mixed models using Stan: A tutorial for psychologists, linguists, and cognitive scientists. Quantitative Methods for Psychology.

Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., & Sedivy, J. C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, *268*(5217), 1632-1634.

Traxler, M. J., Tooley, K. M., & Pickering, M. J. (2014). Syntactic priming during sentence comprehension: Evidence for the lexical boost. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(4), 905.

Van de Cavey, J., & Hartsuiker, R. J. (2016). Is there a domain-general cognitive structuring system? Evidence from structural priming across music, math, action descriptions, and language. *Cognition*, *146*, 172-184.

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

Appendix: Materials used for the spoken sentences and the equations (items)

Spoken sentences

Number	Spoken sentence	Translation
Item1	Voici le fils du jeune papa qui veut faire ce qu'il préfère.	Here we have the son of the father who fancies riding what he likes best.

Item2	Voici le plombier du technicien qui va réparer ce qu'on lui a demandé.	Here we have the plumber of the technician who will set up what he was asked to.
Item3	Voici le père du petit garçon qui s'apprête à avoir sa boisson.	Here we have the father of the baby boy who is about to have his drink.
Item4	Voici le cuisinier du touriste qui va préparer ce qu'il a besoin de faire.	Here we have the cook of the tourist who will prepare what he needs to.
Item5	Voici le jardinier du cuisinier qui va couper ce qu'il doit faire.	Here we have the gardener of the cook who will cut what he has to.
Item6	Voici le tailleur de l'architecte qui s'apprête à créer un chef d'œuvre.	Here we have the tailor of the architect who is about to create a masterpiece.
Item7	Voici l'architecte du producteur qui va dévoiler sa dernière création.	Here we have the architect of the film producer who will reveal his latest creation.
Item8	Voici la cartomancienne de la femme d'affaires qui va lire ce qu'elle préfère d'habitude.	Here we have the fortune teller of the businesswoman who will read what she's used to.
Item9	Voici la costumière de l'actrice qui va continuer à travailler sur son dernier projet.	Here we have the costume designer of the actress who will continue working on her latest project.
Item10	Voici le postier du boulanger qui doit livrer ce qu'il possède.	Here we have the postman of the baker who will deliver what he has.
Item11	Voici le sculpteur de la fleuriste qui va présenter sa nouvelle œuvre.	Here we have the sculptor of the florist who will present his recent work.
Item12	Voici l'électricien du conducteur qui va changer ce qui ne fonctionne plus.	Here we have the electrician of the driver who will change what doesn't work anymore.
Item13	Voici la fille de la dame qui va boire sa boisson préférée.	Here we have the daughter of the lady who will sip her favourite drink.
Item14	Voici la grand mère de l'adolescente qui va chercher ce qu'elle a l'habitude d'utiliser.	Here we have the grandmother of the teenage girl who will fetch what she's used to.

Item15	Voici le professeur du serveur qui va au travail.	Here we have the teacher of the waiter who is going to work.
Item16	Voici le photographe de l'homme d'affaires qui va acheter ce dont il a besoin.	Here we have the photographer of the businessman who will purchase what he needs.
Item17	Voici le confiseur du menuisier qui va créer ce qu'il fait de mieux.	Here we have the confectioner of the carpenter who will create what he's best known for.
Item18	Voici la mère de la jeune fille qui va chercher son objet favori.	Here we have the mother of the girl who will fetch her favourite item.
Item19	Voici l'électricien du professeur qui va travailler sur ce qu'il est censé faire.	Here we have the electrician of the teacher who will work on what he's supposed to.
Item20	Voici la fille de la dame qui va porter son vêtement préféré.	Here we have the daughter of the lady who will wear her favourite clothes.
Item21	Voici la fillette de la femme de ménage qui va prendre ce qu'elle cherchait.	Here we have the baby girl of the cleaner who will grab what she was looking for.
Item22	Voici le fermier du chanteur qui va devoir vendre son objet préféré.	Here we have the farmer of the pop star who'll have to sell his favourite possession.
Item23	Voici le grand père du végétarien qui va manger son déjeuner.	Here we have the grandfather of the vegetarian who will eat his lunch.
Item24	Voici le fils du jeune papa qui va prendre son diner.	Here we have the son of the father who will have his dinner.
Item25	Voici l'ami du soldat qui va mettre sa tenue habituelle.	Here we have the friend of the soldier who will put on his usual outfit.
Item26	Voici le cuisinier de l'ingénieur qui va finir ce sur quoi il travaillait.	Here we have the cook of the engineer who will finish what he was working on.
Item27	Voici le fermier du menuisier qui va finir son travail.	Here we have the farmer of the carpenter who will finish what he started to work on.

Item28	Voici la fille du chimiste qui va mettre sa tenue habituelle dans la matinée.	Here we have the daughter of the chemist who will put on her usual outfit in the morning.
Item29	Voici le père du jeune garçon qui va lire ce qu'il préfère.	Here we have the father of the boy who will read what he's most interested in.
Item30	Voici l'enfant malade de l'homme d'affaires qui va avoir ce qu'il veut désespérément.	Here we have the sick son of the businessman who will have what he's desperate for.

Equations

Number	**Equation**
Item1 high attachment	4 + (6 - 2) / 2 = { 6 | 4 }
Item1 low attachment	4 + 6 - 2 / 2 = { 4 | 9 }
Item2 high attachment	60 - (9 + 1) * 5 = { 10 | 250 }
Item2 low attachment	60 - 9 + 1 * 5 = { 260 | 56 }
Item3 high attachment	10 + (7 - 5) * 3 = { 16 | 36 }
Item3 low attachment	10 + 7 - 5 * 3 = { 36 | 2 }
Item4 high attachment	60 - (24 - 12) / 3 = { 56 | 16 }
Item4 low attachment	60 - 24 - 12 / 3 = { 8 | 32 }
Item5 high attachment	41 - (8 + 3) * 3 = { 8 | 90 }
Item5 low attachment	41 - 8 + 3 * 3 = { 108 | 42 }
Item6 high attachment	7 + (28 - 4) * 2 = { 55 | 62 }
Item6 low attachment	7 + 28 - 4 * 2 = { 62 | 27 }
Item7 high attachment	20 + (32 - 6) / 2 = { 33 | 23 }
Item7 low attachment	20 + 32 - 6 / 2 = { 23 | 49 }

Item8 high attachment	10 + (20 + 10) / 5 = { 16 | 8 }
Item8 low attachment	10 + 20 + 10 / 5 = { 8 | 32 }
Item9 high attachment	56 - (5 + 3) * 4 = { 24 | 192 }
Item9 low attachment	56 - 5 + 3 * 4 = { 216 | 63 }
Item10 high attachment	16 - (12 - 4) / 2 = { 12 | 4 }
Item10 low attachment	16 - 12 - 4 / 2 = { 0 | 2 }
Item11 high attachment	31 + (8 - 5) * 2 = { 37 | 68 }
Item11 low attachment	31 + 8 - 5 * 2 = { 68 | 29 }
Item12 high attachment	2 + (6 + 4) * 3 = { 32 | 36 }
Item12 low attachment	2 + 6 + 4 * 3 = { 36 | 20 }
Item13 high attachment	45 - (27 - 9) / 3 = { 39 | 9 }
Item13 low attachment	45 - 27 - 9 / 3 = { 3 | 15 }
Item14 high attachment	77 - (14 + 21) / 7 = { 72 | 6 }
Item14 low attachment	77 - 14 + 21 / 7 = { 12 | 66 }
Item15 high attachment	16 + (24 - 8) / 4 = { 20 | 8 }
Item15 low attachment	16 + 24 - 8 / 4 = { 8 | 38 }
Item16 high attachment	10 + (6 + 3) * 2 = { 28 | 38 }
Item16 low attachment	10 + 6 + 3 * 2 = { 38 | 22 }
Item17 high attachment	90 - (5 + 15) / 5 = { 14 | 86 }
Item17 low attachment	90 - 5 + 15 / 5 = { 88 | 20 }
Item18 high attachment	56 + (6 + 6) / 2 = { 34 | 62 }
Item18 low attachment	56 + 6 + 6 / 2 = { 65 | 34 }
Item19 high attachment	48 - (9 + 6) * 2 = { 66 | 18 }
Item19 low attachment	48 - 9 + 6 * 2 = { 51 | 90 }

Item20 high attachment	4 + (22 - 4) / 2 = { 11 | 13 }
Item20 low attachment	4 + 22 - 4 / 2 = { 24 | 11 }
Item21 high attachment	45 - (10 + 5) * 3 = { 90 | 0 }
Item21 low attachment	45 - 10 + 5 * 3 = { 50 | 120 }
Item22 high attachment	90 - (50 - 30) / 10 = { 7 | 88 }
Item22 low attachment	90 - 50 - 30 / 10 = { 37 | 1 }
Item23 high attachment	70 - (25 + 5) / 5 = { 8 | 64 }
Item23 low attachment	70 - 25 + 5 / 5 = { 46 | 10 }
Item24 high attachment	1 + (26 - 1) * 4 = { 104 | 101 }
Item24 low attachment	1 + 26 - 1 * 4 = { 23 | 104 }
Item25 high attachment	13 + (17 - 10) * 3 = { 60 | 34 }
Item25 low attachment	13 + 17 - 10 * 3 = { 0 | 60 }
Item26 high attachment	3 + (2 + 1) * 4 = { 24 | 15 }
Item26 low attachment	3 + 2 + 1 * 4 = { 9 | 24 }
Item27 high attachment	21 + (84 - 14) / 7 = { 13 | 31 }
Item27 low attachment	21 + 84 - 14 / 7 = { 103 | 13 }
Item28 high attachment	54 - (30 + 12) / 6 = { 2 | 47 }
Item28 low attachment	54 - 30 + 12 / 6 = { 26 | 6 }
Item29 high attachment	99 - (27 - 18) / 9 = { 10 | 98 }
Item29 low attachment	99 - 27 - 18 / 9 = { 70 | 6 }
Item30 high attachment	40 - (4 + 8) * 3 = { 84 | 4 }
Item30 low attachment	40 - 4 + 8 * 3 = { 60 | 132 }