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The Unexpected Lightness of the Main Verb: An Eye-Tracking Study on Relative Clauses and Trace Reactivation

Leonardo Concetti, Vincenzo Moscati
Università degli Studi di Siena
(<leonardo.concetti@student.unisi.it>; <vincenzo.moscati@unisi.it>)

Abstract:

A few studies on relative-clause processing report an unexpected facilitatory effect on the matrix verb that follows an Object Relative (ORC) clause (e.g. Staub, Dillon and Clifton jr. 2017). In this study we present the results of a novel eye-tracking experiment that replicated this effect on Italian. The advantage of ORCs is discussed under the hypothesis that subject-verb agreement in the matrix benefits from a general trace-reactivation mechanisms, subsumed from activation-based retrieval models (Lewis and Vasishth 2005).

Keywords: *Eye-tracking, Intervention effects, Relative clauses, Trace reactivation, Working memory*

1. Introduction

One of the most recognized findings about relative clauses is the different complexity elicited by Subject Relative Clauses (SRC) and Object Relative Clauses (ORC), also referred to as the subject-object processing asymmetry. To illustrate, consider the pair in (1):

(1) a. The student that criticizes the professors paints a landscape. (Subject Relative)
b. The student that the professors criticize paints a landscape. (Object Relative)

Although being composed of the same lexical material and roughly the same number of characters, ORCs are generally reported as being harder to process than SRCs. This has been documented in English (Ford 1983; Grodzinsky 1989; King and

Just 1991; Gibson 1998, 2000; Gordon, Hendrick and Johnson 2001, 2004; Traxler, Morris and Seely 2002; Grodner and Gibson 2005; Staub 2010; Staub, Dillon and Clifton jr. 2017; among others) and in many other languages, including Italian (Adani 2008; Grillo 2008; Di Domenico and Di Matteo 2009; Friedmann, Belletti and Rizzi 2009; Belletti *et al.* 2012; Guasti, Vernice and Franck 2018; Villata and Lorusso 2020; Biondo *et al.* 2022).

Within this rich literature, however, there is at least one important aspect that has been overlooked in previous studies: this is the relation between the filler-gap dependency generated by relativization, and the agreement between the head of the relative (i.e., *the student*) and the main verb (i.e., *paints*) in cases where the head of the relative is the matrix subject. Once the different positions of the gap/trace left behind within the relative is considered, the investigation of the processing time of both the main verb (where agreement is realized) and the embedded verb (where the trace is integrated) could provide us important insights about the elaboration of long-distance relations and the mechanisms that regulate the storage of linguistic material in working memory. The present study moves in this direction and presents new data in support of a larger facilitatory effect of ORCs on the matrix main verb, compatible with an activation-based approach on trace reactivation.

2. Structural constraints and working memory principles: a meeting point

2.1 Featural Relativized Minimality

One of the most successful frameworks in explaining the asymmetries found across types of relative clauses is the featural Relativized Minimality approach (Rizzi 1990, 2004; further analysed by Grillo 2008; Belletti and Contemori 2009; Friedmann, Belletti and Rizzi 2009; Belletti *et al.* 2012; Biondo *et al.* 2022). This approach is rooted in the Locality Principle, which states that syntactic relations must take place in the smallest possible structural domain, giving rise to a framework which has the explanatory power needed to account for a number of attested phenomena, restating them as intervention effects.

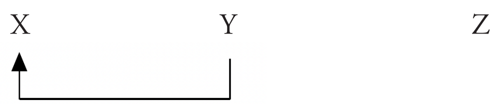
In the case of relative clauses, the filler-gap relation yields an increased processing cost (and fails in the case of young children) when the elements in the dependency are separated by an intervener which can potentially be a suitable candidate for the relation e.g., the subject position of the relative clause. Let us take a look at the configuration in (2):

(2) X … Z … Y

Given this configuration, X is the target of the relation, Z is the intervener, and Y is the origin of the dependency. According to the Relativized Minimality principle, the relation between X and Y fails if an element Z intervenes which is structurally similar to the elements in the relation, i.e., if Z shares the same relevant morphosyntactic features as X and Y.

A graphical representation of the principle is provided in (3):

(3) a. The teacher [that <the teacher> helped the student.] (Subject Relative)



b. The teacher [that the student helped <the teacher>.] (Object Relative)

X Z Y

In the case of a SRC (3a), the relation only involves two positions, the *origin* Y (i.e., the relativization site/trace) and the *target* X (the head of the relative); Z does not intervene, therefore the computation does not give rise to high processing costs. In the case of an ORC (3b), the configuration involves all three positions, with Z intervening between the *origin* Y and the *target* X.

The reason why this structure is still licit (at least for adults), is that the intervener Z does not carry the exact same relevant morphosyntactic features as X and Y. In the case of (3b), here represented again as (4b) the displaced element and the intervener only share the [+NP] feature, which makes the structure harder to process but still valid:

(4) a. The teacher [that <the teacher> helped the student.] (Subject Relative)

X [+NP, +Rel] Y [+NP, +Rel] Z [+NP]

b. The teacher [that the student helped <the teacher>.] (Object Relative)

X [+NP, +Rel] Z [+NP] Y [+NP, +Rel]

The notion of structural similarity, rooted in the featural properties of the elements involved in the relation, has been further discussed in Friedmann, Belletti and Rizzi (2009) and Belletti *et al.*, (2012). The two studies, the first of which has been conducted on Hebrew speaking children (age 3;7 – 5;0), and the second one on both Hebrew and Italian speaking children of similar age, observed that only syntactically active features (i.e., capable of triggering movement) are relevant to define the structural composition of an element. In this sense, the gender feature affects the configuration in Hebrew, but does not in Italian. The authors conclude that this is because in Hebrew gender is a movement attracting feature, while the same is not true for Italian. For the same reason, the number feature is syntactically relevant in Italian, thus having the effect of overcoming (or decreasing) the complexity of an intervention configuration (e.g., a number mismatch between the target and the intervener in an Italian ORC can decrease the complexity of the dependency).

The subject-object asymmetry, and the role played by different kinds of grammatical features in modulating such asymmetry, has been experimentally replicated also for adults in a recent study by Biondo *et al.* (2022). Two self-paced reading experiments on Italian, testing the role of feature match/mismatch in both centre-embedded and final relative clauses, consistently found higher reading times for ORCs when compared to SRCs. Moreover, the facilitatory effect was larger in the number mismatch condition than in the gender mismatch condition. The fRM framework offers a clear picture regarding the processing asymmetry of Relative Clauses and the role of morpho-syntactic features in modulating the processing cost of the different structures.

This approach, however, does not make any explicit prediction on the elaboration of the matrix verb. For this reason, less attention has been devoted to relations holding in the matrix clause, that may span across the relative and that can be influenced by the trace position therein. To illustrate, consider again the pair in (1a-b) repeated below in (5), where the position of the trace and the subject-verb agreement relation are indicated:

S-V Agreement

(5) a. The student [that __ criticizes the professors] paints a landscape.

(Centre-Embedded SRC)

S-V Agreement

b. The student [that the professors criticize __] paints a landscape.

(Centre-Embedded ORC)

On matrix subject-verb agreement across a relative, only sparse and inconclusive data exist. While some eye-tracking studies reported a significant increase in processing cost on the ORC matrix verb region (Traxler, Morris and Seely, 2002, Experiments 1 and 3; Traxler *et al.*, 2005, Experiments 1 and 3; Gordon *et al.*, 2006, Experiment 1) others only found a descriptive trend (Traxler, Morris and Seely, 2002, Experiment 2; Traxler *et al.*, 2005, Experiment 2). A comparably unclear picture emerges from self-paced reading experiments, where only a handful of studies reported clause-type effects on the matrix verb (King and Just 1991; Gordon, Hendrick and Johnson 2001; Gennari and MacDonald 2008; 2009).

Other experimental work renders instead an interesting and unexpected pattern. Grodner and Gibson (2005) did not find any greater difficulty in processing the matrix verb after an ORC than a SRC. Even more indicative is the fact that Staub, Dillon and Clifton jr. (2017) reported an advantage for matrix verb following the ORC. Our study explicitly focuses on this alleged facilitatory effect, trying to replicate it in Italian using the same eye-tracking procedure as in Staub, Dillon and Clifton jr. (2017). We will consider the results also in light of previous proposals on memory effects on trace-reactivation, that we illustrate next.

2.2 The unexpected data and a possible explanation

Grodner and Gibson (2005) investigated the role of integration cost in long-distance dependencies by means of two self-paced reading tasks, directly comparing the predictions of resource-based and experience-based approaches to sentence processing complexity.[1] The most

[1] The authors argue in favour of a resource-based integration cost theory, according to which complexity increases as a function of the distance between the two elements in a dependency, with distance measured as the number of discourse referents that are introduced between the endpoints of an integration. Experience-based accounts, also referred to as surprisal theories, assumes that processing complexity results from encountering rare constructions, such as object relatives.

interesting result for the purpose of the present study, however, is that while participants spent more time at the embedded verb of ORCs than they did on SRCs, this difference was not detected on the matrix verb. Reading Times (RTs) are reported to be decreasing in the transition between the embedded verb and the matrix verb in the ORC condition, but increasing in the same transition in the SRC condition. This result was not predicted by the authors and, in our view, it may be connected to more recent studies in which *spill-over* (Biondo *et al.* 2022) or *retrieval bottleneck* (Staub, Dillon and Clifton jr. 2017) effects have been reported for the region immediately following the embedded verb.[2] The fact that RTs at the matrix verb in the ORC condition were not inflated, as it should be in light of documented spill-over or bottleneck effects, could be accounted for by assuming the presence of an opposite (facilitatory) effect.

A study conducted by Staub (2010) investigated a similar matter by means of an eye-tracking reading experiment. The results point towards the same pattern outlined above: although the experimental materials did not directly control for spill-over effects, no slow-down was detected on the matrix verb of ORCs.

The issue regarding the potential spill-over confound is directly targeted in a follow-up study by Staub, Dillon and Clifton jr. (2017), which specifically focused on the processing of the matrix verb in relative clauses with an eye-tracking while reading paradigm. The authors added a factor to the experimental design: in addition to *type of clause* (SRC vs ORC) they also included *length of clause*: short-RC with no PP attachment and long-RC with a PP that linearly distanced the Matrix Verb from the RC Verb. The PP insertion had the precise purpose of avoiding the complexity from the relative clause region to carry over to the matrix verb region, so to uncover potential clause-type effects on the matrix verb processing. The authors found an expected slow-down on the matrix verb for the short conditions but, interestingly, this difficulty is completely eliminated in the long condition: lengthening the ORC reduced reading times on the matrix verb region, while lengthening the SR actually increased reading times on the same region.

The pattern emerging from these studies points towards the presence of a facilitatory effect on the ORC matrix verb, which cannot be explained on the basis of either the structural constraints acting on the relative clause (i.e., locality, as in Friedman, Belletti and Rizzi, 2009), nor by resource-based explanations (Grodner and Gibson 2005).

It can however be accounted for by taking into consideration the Activation-based Retrieval Model of sentence comprehension (proposed by Lewis and Vasishth 2005; further developed by Lewis, Vasishth and Van Dyke 2006; Vasishth *et al.* 2008; Yadav, Smith and Vasishth 2021; among others). According to the model, one of the working memory constraints on sentence processing is represented by the fluctuation in the activation levels of the encoded (linguistic) items: once a constituent is encountered and encoded in working memory, it naturally starts to decay as a function of time elapsed from its encoding. The activation level can however be boosted by syntactically reactivating the encoded item, e.g., when its trace is encountered (Lewis, Vasishth and Van Dyke 2006). This is illustrated in the following contrast between SRCs and ORCs:

[2] Spill-over refers to the complexity in the processing of a constituent carrying over to the following region. The slightly different formulation of retrieval bottleneck assumes this effect to arise because of the need to retrieve two different constituents one immediately after the other, leading to a processing bottleneck which results in inflated reading times on the second verb.

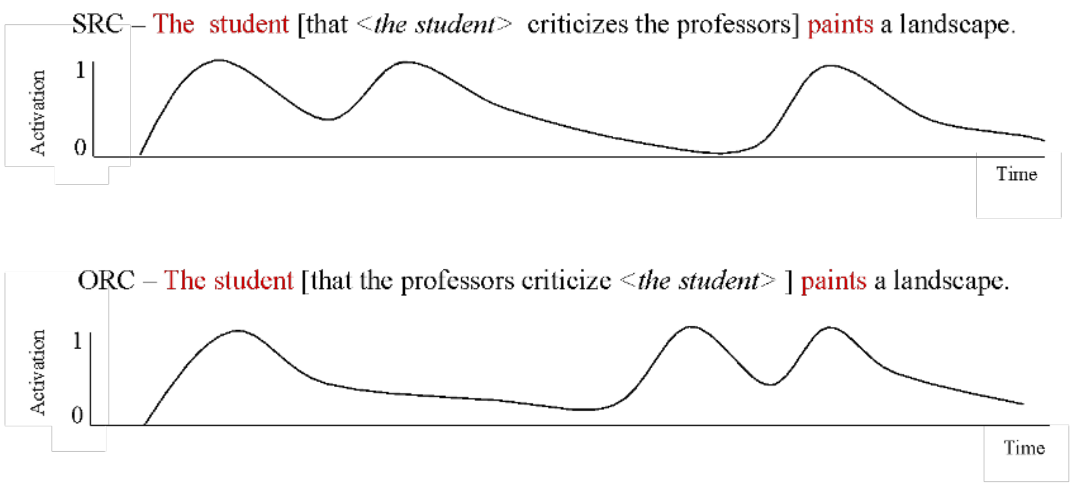


Figure 1. Hypothetical activation profiles of items encoded in working memory, following a series of boosts at retrieval points

As we can see in Fig.1, the matrix subject "The student" is encoded in working memory upon its first encounter, and its activation is at peak. From this moment on, it starts to decay until it is re-activated either by processing its trace, or by establishing the agreement relation with the main verb "paints". The crucial difference between SRCs and ORCs lies in the position where the trace is situated: in SRCs the trace is in the subject position of the relative clause, while in ORCs it is in the object position of the relative clause. This means that when the matrix subject has to be retrieved from working memory in order for agreement to take place, the constituent is more readily available to the parser in ORCs, leading to a faster integration into the structure.

We thus hypothesize that the facilitatory effect found on the matrix verb might be due to the closer position of the trace in ORCs. If empirically supported, this hypothesis would lead to a better understanding of the complex mechanisms involved in the specialized task of sentence comprehension, departing from views that explain the complexity of syntactic structures solely on the basis of structural or resource-based constraints, but rather recognizing the role of both (potentially independent) components. In order to directly test this hypothesis and add results of a different language to the ones already available for English (i.e., Staub, Dillon and Clifton jr. 2017) we designed an eye-tracking reading experiment on Italian.

3. Methods and materials

The experiment consists of a two conditions within-participant design in which we only manipulated Clause Type, that was made of two levels: Subject Relative and Object Relative. In both conditions, a temporal PP was added before the matrix verb, so to add linear distance that would avoid spill-over effects from the relative. The reason behind the choice of a temporal PPs is to be found in the different possibilities of attachment of temporal vs locative PPs: locative prepositional phrases have an ambiguous attachment site (i.e., they can either be attached to the relative clause VP or NP) which could potentially constitute a confounding factor. Temporal PPs, on the other hand, are unambiguously attached to the relative clause VP.

In order to single out and highlight the trace-reactivation effect on the matrix verb, we minimized possible intervention effects that could hamper the trace integration within the relative. We did this by introducing a number mismatch in both conditions. As observed by Friedmann, Belletti and Rizzi (2009), Belletti *et al.* (2012) and Biondo *et al.* (2022), this featural mismatch significantly reduces the processing cost of the relative clause itself. In addition, all the NPs involved in the relative clause configuration are lexical and animate, in order to avoid potential animacy effects reported in the literature (e.g., Traxler, Morris and Seely 2002).

An example of the two conditions, with the sentences segmented into interest areas, is provided in (6):

(6) a. L'allievo | che | critica | i pittori | durante l'esame | dipinge | un paesaggio. (SRC)
'The student | that | criticizes | the painters | during the exam | paints | a landscape.'

b. L'allievo | che | i pittori | criticano | durante l'esame | dipinge | un paesaggio. (ORC)
'The student | that | the painters | criticize | during the exam | paints | a landscape.'

Sixty pairs of sentences as in (6) were divided into two lists, so that every participant was exposed to each of the two conditions 30 times, but never to the same lexical content twice. Each participant was either assigned to list 1 or 2, and items were pseudo-randomized so as to never have more stimuli of the same condition appearing in sequence. Experimental items were also intermixed with 40 filler sentences (40 fillers per list).

Sentences appeared on the screen as a whole. Half of the stimuli were followed by a comprehension question, in order to ensure that participants were actively reading for comprehension. Once the sentence was completed, participants moved to the next stimulus (or the comprehension question) by pressing the spacebar.

Participants were 20 undergraduate students at the University of Siena, of age between 20 and 30. All of them were Italian native speakers, with no reported history of reading or language disorders, and normal or corrected-to-normal vision. No participant was excluded on the basis of accuracy scores or extensive track loss. One participant was excluded from the analysis because of the impossibility to complete the task due to the calibration process repeatedly failing during the experimental session. No participant had expertise in the field of linguistics and none of them reported having understood the manipulation of the materials, thus assuring a natural reading setting, with no specific strategy emerging for the processing of the structures under investigation.

Eye-movements were recorded using an Eye Link Portable Duo (SR Research Ltd., ON, Canada), interfaced with a Display PC (a 17-inch screen laptop in a fixed position, with the eye-tracker mounted on it) in which the stimuli are presented, and a Host PC, from which the experimenter controls the procedure. The sampling rate was set to 1000Hz, only the right eye was tracked, and the calibration was set to 13-point.

4. Results

Eye-movement data were visualized and cleaned through the Data Viewer software (SR Research Ltd., ON, Canada). Fixations with a duration lower than 80ms and in the immediate proximity of the previous or following fixation were merged together.

The analysis was conducted on two regions: the RC verb and the Matrix Verb. The matrix verb is the main focus of the study: under our working hypothesis, we expected lower reading time measures for the ORC condition with respect to the SRC condition. On the embedded verb, instead, the inverse pattern is predicted in line with much previous literature that consistently report a greater processing load with ORCs than SRCs.

As for the dependent variables, we collected *First Fixation* duration, *First Pass* duration, *Regression Path* duration (also referred to as '*go-past time*'), *Total Time* (also referred to as '*dwell time*' or '*gaze duration*').

Let us inspect first the reading times on the RC-verb. In figure 2, we report the four reading measures in the SRC and ORC condition. Here, a general processing advantage is visible for SRCs, since all our measure show longer reading times for ORCs: *First Fixation* has a mean value of 224ms in the SR condition, and 258ms for the OR condition, *First Pass* means are 275ms for the SR condition, and 356ms in the OR condition, *Regression Path* means are 374ms for the SR condition, and 480ms for the OR condition, *Total Time* has a mean value of 548ms in the SR condition, and 659 in the OR condition.

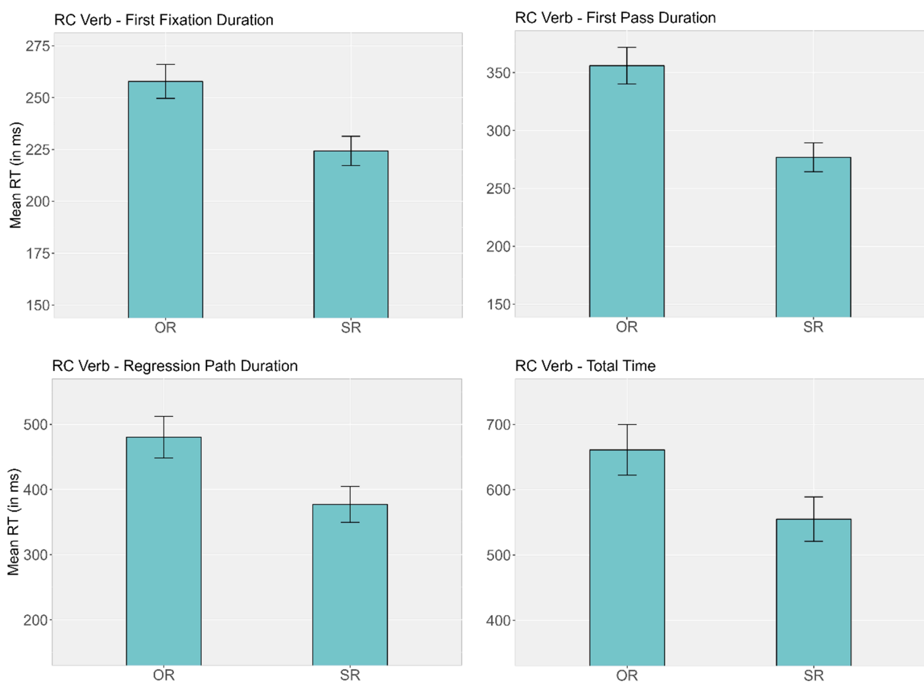


Figure 2. Mean Reading Time measures for the RC verb region in SRCs and ORCs. Error bars represent 2 times S.E.

The pattern is partially reversed on the matrix verb region, at least in the *Regression Path* duration and *Total Time*, as shown in Figure 3: on those "late measures", processing of the matrix verb elicited higher reading times in the SR condition than in the OR condition. *First Fixation* has a mean value of 255ms in the SR condition, and 253ms for the OR condition, *First Pass* means are 305ms for the SR condition, and 302ms in the OR condition, *Regression Path* means are 689ms for the SR condition, and 574ms for the OR condition, *Total Time* has a mean value of 503ms in the SR condition, and 462 in the OR condition.

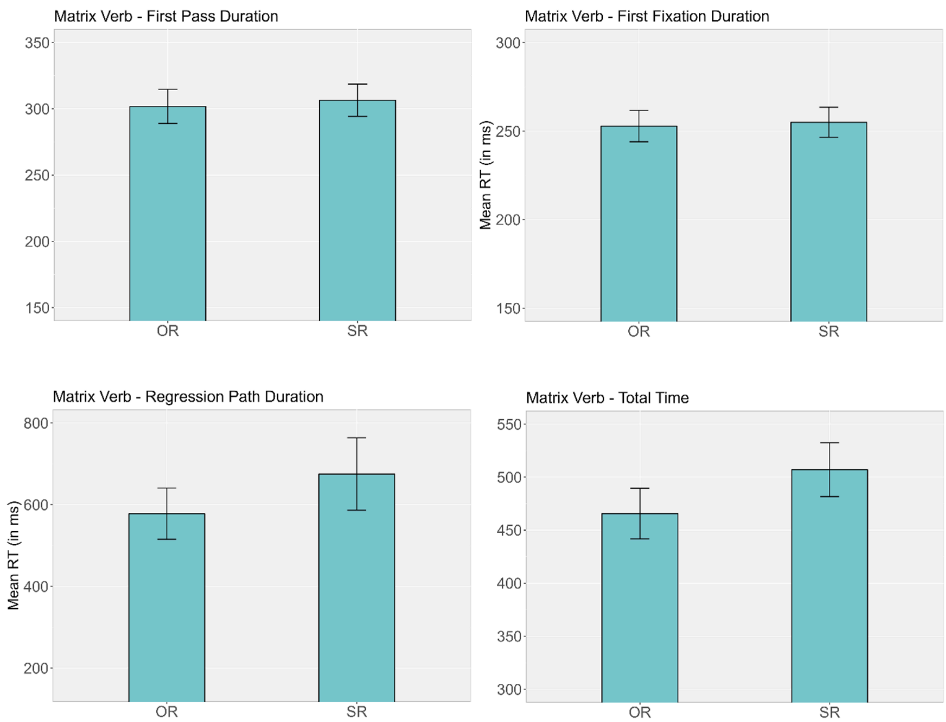


Figure 3. Mean Reading Time measures for the matrix verb region in SRCs and ORCs. Error bars represent 2 times S.E.

Data were analysed with linear mixed-effect regression models for every reading time measure at the two regions of interest: the RC verb and the Matrix Verb. A summary of the results from the analysis of the two regions of interest is shown in table 1:

Relative Clause Verb				
	β	S.E.	t-value	p-value
First Fixation	-34	5,22	-6,44	< 0,001 ***
First Pass	-81	9,55	-8,52	< 0,001 ***
Regression Path	-106	20,57	-5,15	< 0,001 ***
Total Time	-111	22,11	-5,014	< 0,001 ***
Matrix Verb				
	β	S.E.	t-value	p-value
First Fixation	2	5,84	0,31	0,754
First Pass	3	8,43	0,4	0,688
Regression Path	115	48,35	2,38	0,0176 *
Total Time	41	15,8	2,61	0,0092 **

Table 1. Linear mixed-effect model estimates of effect of RC type on each measure. A positive estimate of β reflects an increase in RT (in ms) in the SR condition compared to the OR condition, while a negative value reflects a decrease in RT in the SR condition compared to the OR condition.

The analysis carried out on the RC verb confirmed the SR-OR asymmetry, with ORs eliciting significantly higher reading times than SRs at all measures. On the matrix verb, no (significant) clause-type effect emerged on "early" measures such as first fixation duration and first pass duration, but a statistically significant effect emerged in later measures, namely regression path duration and total time: processing of the matrix verb elicited higher reading times in the SR condition than in the OR condition.

5. Discussion

The results obtained by the analysis of the matrix verb data are consistent with the predictions outlined in the introduction: all else being equal, the agreement operation between the subject and the verb of the main clause is harder to process in the case of (embedded) SRCs when compared to ORCs. This facilitatory effect is accounted for by considering the activation levels of the matrix subject, which has to be maintained in working memory until it agrees with the main verb: the activation boost, closer to the matrix verb in ORCs than in SRCs, facilitates the following agreement operation.

An interesting question arises regarding the nature of the different eye-movement measures included in the analysis: why is facilitation detected in measures such as regression-path and total time, but not in first pass measures? If we assume first pass measures to be reflecting the early stages of processing, namely when linguistic information is extracted from the fixated word and encoded into working memory, a significant difference is not predicted under any approach taken into consideration: neither the Relativized Minimality framework nor the resource-based approaches. The same can be said in general for the working memory mechanisms investigated here: the position of the main subject's trace has negligible impact on the encoding of the matrix verb, but a significant one on the agreement relation between the verb just encoded and the subject which needs to be retrieved. Under this view it is indeed expected that if a difference in the processing of this operation should arise, it would be more easily detected by eye-movement measures reflecting later stages of processing, such as regressive eye-movements and total time spent on the region of interest.

As to the question of why it is the case that no conclusive evidence of this effect emerged in the last decades of research on relative clauses, there is more than one plausible explanation.

One aspect to consider in this respect is the type of task employed: grammaticality/acceptability judgements, accuracy rates on comprehension questions and related off-line methodologies can be very informative, but fail in pinpointing the exact location where complexity arises. On-line methodologies such as self-paced reading, although more informative in this sense, are still not sensible to the different mechanisms arising in the real-time processing of sub-parts of sentences (e.g., no consistent data on regressive eye-movements). Eye-tracking, on the other hand, offers a fine-grained picture of how comprehension unfolds in real time, thus allowing for inferences to be drawn at the single constituent level, with precision expressed on the millisecond scale.

Another reason has to do with the materials employed in the past studies on relative clauses: apart from very few exceptions (i.e., Staub, Dillon and Clifton jr., 2017), no study controlled for spill-over/retrieval bottleneck effects. The fact that in all these cases the stimuli were composed of sentences in which the matrix verb immediately followed the embedded verb means that the high cognitive load associated with the processing of the relative clause (especially in the case of an ORC) carried over to the matrix verb, counterbalancing the facilitatory effect due to the different position of the trace.

6. Conclusion and future directions

The present study replicated classical results concerning the subject-object relative clauses' asymmetry, but also the less-known observation that centre-embedded object relative clauses lead to a facilitatory effect on the following matrix verb, once subject-verb agreement is computed. Complexity in long-distance dependencies is seen here as being due to a series of distinct factors, both specific to language (locality principles) and to more general cognitive constraints (e.g. Chomsky and Miller 1963; Miller and Chomsky 1963) such as those of working memory. In order to correctly parse syntactic structures, some elements must be held in memory until they can be correctly interpreted. This approach has been explored in detail in more recent years by Lewis and Vasishth (2005) and subsequent work, with the underlying theoretical assumption that language processing, although being a specialized task acting on specialized representations, cannot exist in a vacuum where other cognitive domains are excluded.

This prolific line of inquiry has not fully explored the relationship between syntactic parsing and working memory, including encoding and retrieval mechanisms. Multiple questions arise from the present study: what exactly are the atomic elements that need to be encoded in working memory in order for parsing to successfully unfold, and how are they represented in the mind/brain? There is not, at least to our knowledge, conclusive evidence regarding the nature of these representations.

One interesting possibility is the one outlined in the already mentioned activation-based retrieval model of sentence comprehension (Lewis and Vasishth 2005), which builds on the independent cognitive architecture ACT-R (Adaptive Control of Thought-Rational, Anderson *et al.* 1998; and much related work). According to these models, linguistic items are encoded in working memory as bundles of features, which are then used as cues for a fast, associative retrieval of items that feeds the parsing of syntactic structures.

This raises a series of questions regarding the nature of both the terminal representations and the features encoded. Are the terminal representations wholly encoded as encountered with no possibility of real-time update, or are they incrementally updated as novel information comes into play (e.g., with coordinate structures, where two items carrying the *singular* number feature can be seen as functionally constituting a single component carrying the *plural* number feature)? Are the features encoded just the ones that carry morpho-syntactic information useful for the parse, or are all kinds of different features (semantic, pragmatic-contextual, phonological, etc.) encoded as well? Are all features encoded with the same strength or are they weighted differently?

All these questions need to be answered if we are to come closer to understanding the complex relationship between distinct but intertwined areas of cognition, which are central to many human abilities. We leave these investigations to future research.

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