Predicting interference effects for the processing of subject-verb agreement in comprehension in Marathi.

Bachelor's Project Thesis

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Abstract: When comprehending sentences in English, agreement attraction effects take place for subject-verb agreement sentences with a prepositional phrase. A speed-up or slow-down in reading and processing the verb is seen. These are known as the facilitatory or inhibitory effects respectively and are seen as a side effect of cue-based retrieval mechanisms in content-addressable memory architectures, such as the Lewis and Vasishth [2005] sentence processing model in ACT-R. However, this model is only for the English language. Thus, I try to use an equivalent of the ACT-R model in the R language [Team et al., 2013]. Using this new model and cue-based retrieval mechanisms, I try to predict how such effects take place and the magnitude of them in another language: Marathi. Based on the model, I conclude that agreement attraction effects most likely occur in Marathi. However, I argue that the R model can be improved to simulate the sentence processing mechanisms more biologically, allowing for more accurate predictions.

1 Introduction

Consider the following sentences [Pearlmutter et al., 1999]:

(1) * The key to the cabinets are rusty.

(2) * The key to the cabinet are rusty.

(3) The keys to the cabinet are rusty.

(4) The keys to the cabinets are rusty.

Sentences (1) and (2) are ungrammatical since they do not conform to grammatical rules: *"key"* is singular (SG) but *"are"* requires a subject which is plural (PL). Here we say that the subject head, i.e. *"key"*, does not **agree** with the verb, i.e. *"are"*, in the number feature for the subject-verb agreement dependency in English. The agreement of such features in a subject-verb dependency is important while forming correct grammatical sentences which can be comprehended correctly and without any processing difficulties.

Take the first sentence. We see that the second noun *"cabinets"*, inside the prepositional phrase *"to the cabinets"* does in fact agree with the verb in the number feature. However, the subject-verb dependency for *"are"* in English requires that the number agreement is with respect to a subject. Thus there is no syntactic agreement since *"cabinets"* is not the licit subject for the verb.

Previous comprehension studies [Wagers et al., 2009, Pearlmutter et al., 1999, Lago et al., 2015, Nicenboim et al., 2018] have shown that for sentences such as (1) and (2), the verb is read faster in (1) compared to (2) despite both sentences being ungrammatical. Additionally these studies also show that in grammaticality judgment tasks, sentence (1) is incorrectly seen as grammatical more often than sentence (2). This effect of **facilitation** in reading time and time taken for processing the sentence is known as the agreement attraction effect. It occurs in a dependency when the agreement element (like a verb) fails to match the agreement features of the grammatical controller (like a subject) and instead realizes agreement with a grammatically incorrect distractor (like a noun in a prepositional phrase). For example, in the first sentence, the plural number feature of the auxiliary verb *"are"* mismatches with the singular number of the subject head *"key"* and instead matches with an noun phrase (NP) *"the cabinets"* within the prepositional phrase *"to the cabinets"*.

Sentences (1) - (4) are seen as **retroactive interference conditions** since the licit subject of the verb is farther from the retrieval site (i.e. the verb) than the distractor. These agreement attraction errors for sentence comprehension have been explained in terms of encoding-based accounts and cue-based memory retrieval mechanisms.

The encoding based accounts such as the Marking and Morphing (MM) model [Eberhard et al., 2005] suggest that these agreement attraction effects arise due to ambiguous encoding of the features on the subject. Through some process like feature percolation, where the PL feature of the noun *"cabinets"* moves up to the head noun *"key"* (sentence (1)). This allows the PL feature of the distractor to spread activation and percolates up to the licit subject, causing it to be more plural. Since the licit subject seems more plural due to higher activation, it leads to an illusion of grammaticality and a facilitation of reading times in ungrammatical sentences.

However, attraction effects could also be a by-product of the cue-based memory retrieval mechanism as seen in the Lewis and Vasishth [2005] model (realized in ACT-R) to explain licensing of long-distance dependencies in comprehension. In cue-based memory retrieval mechanisms, the verb would have retrieval cues. For example, *"are"* would require the features subject (+SUBJ) and plural (+PL). Thus, the retrieval cues for *"are"* are +SUBJ and +PL. However, if more than one noun has features which match or partially match the retrieval cues, retrieving the licit subject becomes more difficult, leading to faster reading times at the verb, as discussed by Wagers et al. [2009]. An in-depth explanation of this mechanism will be provided later.

Such attraction effects have also been discussed in grammatical conditions. We know that in grammatical conditions, a retrieval process is also triggered [Bartek et al., 2011, Gibson et al., 2000]. Thus, it seems plausible that an attraction effect also exists in grammatical conditions, if we assume the cue-based memory retrieval mechanism. This has been explored by Nicenboim et al. [2018] for grammatical German sentences with number interference. They try to increase the attraction effect by increasing or decreasing the number of nouns which match the retrieval cue i.e. **the fan** of the retrieval cue. What they found was that the magnitude of cue-based retrieval effect in grammatical sentences with number agreement (subject-verb) might be smaller than the effect observed in ungrammatical conditions. They saw a small interference effect in terms of inhibition: a slow-down in the reading times and a greater processing time in sentences such as (4) compared to sentences such as (3). This would mean that attraction effects are seen as a **facilitatory effect** in ungrammatical sentences and an **inhibitory effect** in grammatical sentences.

In the next sections, I will describe how attraction effects appear in English [Wagers et al., 2009] and Spanish [Acuña-Fariña et al., 2014]. Based on these languages and a cue-based memory retrieval mechanism [Vasishth et al., 2019], I will look at predicting the agreement attraction effects in a language called Marathi for subject-verb agreement in prepositional phrase structures. Marathi is an Indo-Aryan language, spoken in India. As of 2022, Marathi has about 99.1 million speakers [Ethnologue, 2022]. As we saw earlier, most research in sentence processing is done in languages such as English, Spanish and German. Despite the large number of speakers of Marathi, no research is being done for sentence processing in this language and I aim to change that.

1.1 Agreement attraction effects in English

Take the study done by Wagers et al. [2009] (Experiment 5). The self-paced reading experiment tested effects of agreement attraction for subject-verb agreement in sentences with a prepositional phrase, in which the NP *"the cabinet(s)"* inside the prepositional phrase was a potential distractor with respect to the agreement between the subject *"the key"* and the copula verb *"was/were"*.

A 2x2 design was used with distractor number (SG/PL) and grammaticality (grammatical/ungrammatical). The licit subject remained singular. 13% of the items read by the participants was ungrammatical and 60 native English speakers took part in the experiment.

What Wagers et al. [2009] found was main effects of number in the distractor noun region (region 5) and next verb region (region 6). This meant that

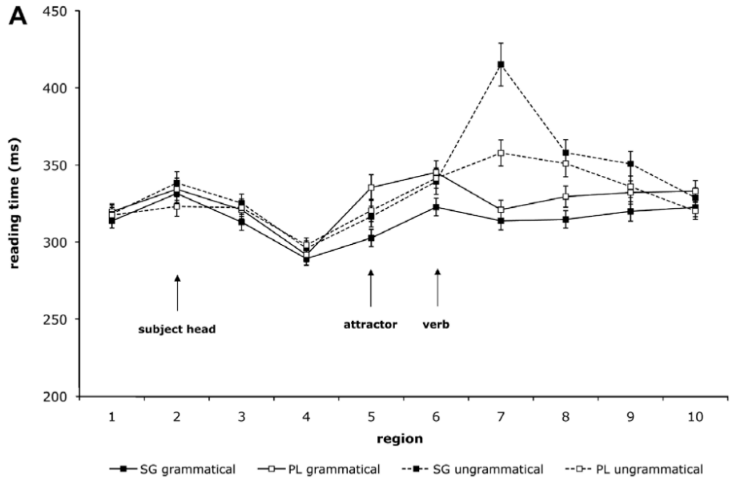


Figure 1.1: Self-paced reading results from Experiment 5 by Wagers et al. [2009, p.225] (Fig. 6). Error bars show standard error of mean. Sample sentence: The_1 key_2 to_3 the_4 $cabinet(s)_5$ $was/were_6$ $rusty_7$ $from_8$ $many_9$ $years_{10}$...

plural distractor sentences were read faster than singular distractor sentences. A reliable slow-down for ungrammatical sentences occurred in region 7 which is right after processing region 6 i.e. the verb. This suggested that ungrammatical sentences with a plural distractor were being read much faster than ungrammatical sentences with a singular distractor. Additionally, effects of grammaticality and interaction between grammaticality and distractor number were seen in the regions after region 6 i.e. the verb. Significant effect of attractor number after region 6 was seen in ungrammatical conditions only. This suggested that ungrammatical conditions only exhibited the facilitation effects.

The results of Experiment 5 by Wagers et al. [2009] also show that grammatical sentences might exhibit facilitation effects but this is much smaller than as seen in the ungrammatical sentences. However, mainly, a larger facilitation was observed in reading times for ungrammatical sentences in regions after region 6 when the sentences contained a plural attractor, as seen in Figure 1.1.

1.2 Agreement attraction effects in Spanish

Take the study done by Acuña-Fariña et al. [2014]. The eye-tracking experiment tries to find out if the NP mismatch interference (similar to sentences 1 and 2) for subject-verb agreement in sentences with a prepositional phrase appears in Spanish comprehension for number and gender agreement. Acuña-Fariña et al. [2014] only focus on grammatical sentences. Here the NP *"niño(s)/niña(s)"* inside the prepositional phrase was a potential distractor with respect to agreement between the subject *"El nombre/Los nombres"* and the verb *"era/eran"* and the adjective *"alemán/alemanes"*.

In Spanish, the number feature of the subject is seen in the verb and the following adjective, as both are marked for subject's number. However, the gender feature of the subject is seen in the subject's adjective, as the adjective is marked for the subject's gender. This can be seen in Figure 1.2. The verb *"era"* (was) requires a singular subject: *"El nombre"* (the name), *"niño"* (boy) or *"niña"* (girl). However, *"eran"* (were) requires a plural subject: *"Los nombres"* (the names), *"niños"* (boys) or *"niñas"* (girls). Thus, the verb is marked for subject number. The adjective *"alemán"* (German SG) requires a masculine singular subject: *"El nombre"* (the name) or *"niño"* (boy). Whereas, *"alemanes"* (German PL) requires a masculine plural subject: *"Los nombres"* (the names) or *"niños"* (boys).

The eight conditions were formed by crossing factors: subject number (SG/PL), subject/distractor number match and subject/distractor gender

Table 1
Beginning of sentences used, segmented in regions for analyses purposes.

Regions:	1 / 2 / 3 / 4	
1.	El nombre / del niño / era / alemán...	S G+ N+
2.	El nombre / de los niños / era / alemán...	S G+ N–
3.	El nombre / de la niña / era / alemán...	S G– N+
4.	El nombre / de las niñas / era / alemán...	S G– N–
5.	Los nombres / de los niños / eran / alemanes...	P G+ N+
6.	Los nombres / del niño / eran / alemanes...	P G+ N–
7.	Los nombres / de las niñas / eran / alemanes...	P G– N+
8.	Los nombres / de la niña / eran / alemanes...	P G– N–

Note: N+ stands for number match; N– for number mismatch; G+ gender match; and G– for gender mismatch.

Figure 1.2: Example sentences used by Acuña-Fariña et al. [2014, p.115] (Table 1)

match. 40 native Spanish speakers read 100 sentences, of which 8 were experimental stimuli sentences as seen in Figure 1.2. One of the measures used for analysis was cumulative reading times which *"is the summed fixation duration from when the region is first fixated until the eyes first move past the region"* [Acuña-Fariña et al., 2014].

Most notably, Acuña-Fariña et al. [2014] found that cumulative reading times were longer in the gender mismatch conditions as compared to the gender match conditions for region 3 and 4 together (886 ms vs 858 ms). Additionally, cumulative reading times were longer in the number mismatch condition compared to the number match conditions for region 3 and 4 together (895 ms vs 848 ms). According to Acuña-Fariña et al. [2014], the interference caused by gender/number mismatch is only significant for singular subjects and when the verb matches with the subject in number. They also suggest that gender and number mismatches do not interact.

1.3 Mechanisms underlying the Lewis and Vasishth (2005) model

To understand the attraction effects as shown by Wagers et al. [2009] and Acuña-Fariña et al. [2014] in sentence comprehension, we first need to understand how a sentence is comprehended. We need to explain the mechanisms which are involved in the formation of long-distance dependencies such as a verb and its subject. This requires storing and accessing information in the working memory. For human cognition, such underlying mechanisms can be explained using the content-addressable memory architecture [Anderson et al., 2004, McElree et al., 2003, Van Dyke and Lewis, 2003]. An example of such a model is the Lewis and Vasishth [2005] model I discussed earlier. In content-addressable memory, a cue-based retrieval mechanism takes place. This mechanism suggests that when readers parse the verb of a sentence, they have to retrieve the noun which properly licenses the subject-verb dependency so that the sentence is interpreted correctly. To retrieve a noun, the model conducts a **memory search** at the verb (i.e. the **retrieval point**) and tries to match all previously read nouns in memory* against the verb. The retrieval cues for this memory search are the grammatical or thematic requirements of the noun. The memory search results in **one** noun being retrieved from the memory to license the dependency. For example take the sentence: *"The keys to the cabinet are rusty"*. As we saw earlier, *"were"* requires a subject which is plural to correctly licence the subject-verb dependency. Thus, the retrieval cues of *"were"* are +SUBJ and +PL. We also see that there are two noun phrases in this sentence: *"The keys"* and *"the cabinet"*. To correctly license the subject-verb agreement, the noun needs to be a subject and plural. In terms of the cue-based mechanism, we say that the features of the desired noun need to be SUBJ and PL. The result of this memory search at *"were"* give us **one full match**. This is the noun *"keys"* since it is a plural noun which is the subject of the sentence. Here we say that the features of the noun: PL and SUBJ match perfectly with the retrieval cues +PL and +SUBJ.

*Here, I talk about memory in terms of long term memory (semantic and episodic memory) and short-term working memory.

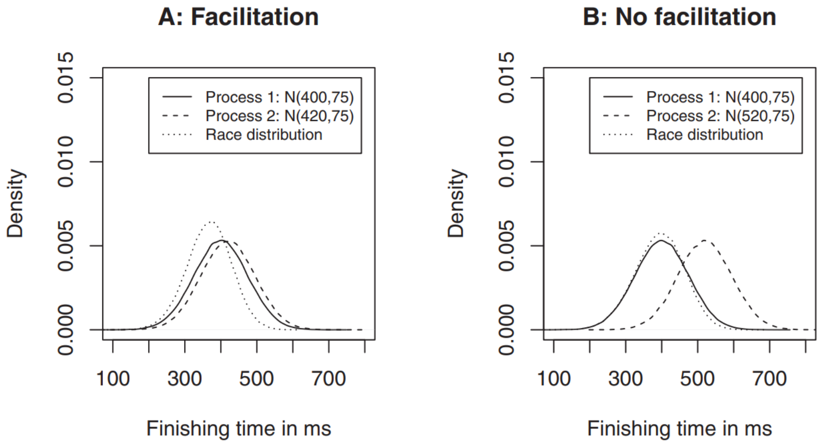


Figure 1.3: Illustration of statistical facilitation as described by Vasishth and Engelmann [2021, p.58] (Figure 3.4). Similar means in retrieval times of two chunks in memory (A) give rise to a race process, hence facilitation occurs. Due to dissimilar means in retrieval times of two chunks in memory (B), there is no race process, hence no facilitation is seen.

Unfortunately, in comprehension, it is not so straightforward. Take the sentence: *"The keys to the cabinets were rusty"*. Here the memory search results in 2 matches: **one full match** for the noun *"keys"* as we saw earlier and **one partial match** for the noun *"cabinets"*. This happens since *"cabinets"* is a plural noun but not the subject of the verb. Here we see that the retrieval cue +PL has two nouns to match. This **overload** (1 match vs 2 matches) of retrieval cue leads to *"keys"* being less distinguishable than *"cabinets"*. Thus, the retrieval cue +PL loses its effectiveness in aiding retrieval from memory. Since more nouns are associated with the retrieval cue +PL, the fan of the retrieval cue increases. This leads to the **fan effect**: the larger the fan, the longer the retrieval time from memory when conducting the memory search at the verb, according to Anderson [1974]. Thus, the larger the fan of the cue, the more processing and time it takes for licensing to take place correctly. Here we can say that agreement attraction effects take place as the inhibitory effect I discuss earlier in **Section 1**: a slow-down of reading and processing time is observed since the reader is also attracted to the distractor as opposed to only the target due to the fan effect.

Now, take the sentence: *"The key to the cabinets are rusty"*. Here, the memory search at the verb results in **two partial matches**: *"key"*, since it is the subject; and *"cabinets"*, since it is plural. However, there is no overload of the cues taking place and thus, no fan effect is observed as I discussed earlier. Since each cue has one match respectively, both cues are equally effective while retrieving a noun from memory. This leads to both cues entering a race process to retrieve a noun from memory. A race process means that both nouns are equally likely to be retrieved as they are equally activated in the memory due to the retrieval cues being partial matches to both nouns. Thus, the probability of retrieving a noun becomes 50%, since the sentence only has two nouns. However, the nouns in the memory are subject to **decay** over time, as discussed by Berman et al. [2009]. Since the noun *"cabinets"* is closer to the verb where the memory search takes place, it is subject to less time decay, meaning that *"cabinets"* in memory is stronger than *"keys"* in memory. This means that the noun *"cabinets"* can sometimes be misretrieved, leading to the illusion of grammaticality I discussed earlier. Due to fewer cues to process for retrieval and no fan effect, the time taken to retrieve a noun is now lower than when we saw earlier. Due to each noun having the same amount of cues to process, the time taken is most likely similar to retrieve both nouns, not simultaneously. This results in **statistical facilitation**: on average, over many trials the retrieval time of a noun is shorter when two nouns in memory have similar mean retrieval times, as opposed to when the two nouns in memory have a bigger difference in mean retrieval times (Figure 1.3). Here we can say that agreement attraction effects take place as the facilitatory effect I discuss earlier in **Section 1**: a speed-up of reading and processing time is observed since the reader is attracted to the distractor and the target equally, leading to statistical facilitation.

Now we know the cue-based retrieval mechanism of the Lewis and Vasishth [2005] model. But what about the content-addressable memory architecture part of this model?

1.4 Architecture of the Lewis and Vasishth (2005) model

As we saw earlier, the Lewis and Vasishth [2005] model is realised in ACT-R. ACT-R also happens to have a content-addressable memory architecture. ACT-R (Adaptive Control of Thought-Rational) [Anderson et al., 2004] is a cognitive architecture which can be used to model high level cognition phenomena as it integrates theories of cognition, visual attention and motor movement. Using ACT-R allows us to model a hypothesis of the general cognitive mechanisms (seen in **Section 1.3**) behind sentence processing as accurately as possible.

ACT-R consists of two types of memory: declarative memory and procedural memory. Procedural memory is represented as production rules and declarative memory is represented in chunks which are a type of structure. For example take the scenario discussed in **Section 1.3**.

The ACT-R model assumes that the constituents of a sentence are represented in declarative memory as *chunks*, for example, the nouns we saw in **Section 1.3**. These chunks contain feature values which encode the constituent's syntactic position and its features. To license dependencies, previously encoded chunks in the declarative memory† which are in a heightened state of activation need to be retrieved from declarative memory through cues: the cue-based retrieval mechanism we saw earlier.

As we saw before, the constituents of the sentence are represented as chunks in declarative memory. The retrieval of chunks to license the subject-verb dependency is possible through the cue-based mechanisms we saw earlier. Firstly, the probability and the time taken (i.e. the **latency**) to retrieve a chunk from declarative memory is dependent on the chunk's activation value: A_i.

The chunk's activation value at retrieval is the sum of: base-level activation B_i, to represent the decay and frequency of use; spreading activation S_i, to represent similarity-based interference; mismatch penalty component P_i, to represent mismatches with retrieval cues and a random noise component ϵ_i (Equation 1.1).

$$A_i = B_i + S_i + P_i + \epsilon_i \tag{1.1}$$

The base-level activation of a chunk tells us that the further the chunk is from the retrieval point, the more decay the chunk will experience and the chunk is less likely to be retrieved, similar to what I discussed in **Section 1.3**. B_i is computed using a base-level constant β_i and the previous retrievals of the chunk (Equation 1.2).

$$B_i = log(\sum_{j=1}^{n} t_j^{-d} + \beta_i) \tag{1.2}$$

Where n is the number of times the chunk i has been accessed in memory, t_j is the time (ms) since the jth access and d is the decay parameter. Importantly, Equation 1.2 shows us that when each time a chunk is accessed, there is a increase in the chunk's base-level activation. If the chunk is accessed, it receives a small reactivation boost, which is also subject to decay.

Chunks in declarative memory can also be associated to each other through spreading activation. Activation spreads from retrieval cues to all matching chunks. The spreading activation is limited for each cue and is distributed between the chunks which share the matching retrieval cue. A chunk with a higher number of competitors (i.e. higher fan, other available chunks which (partially) match the retrieval cues) for the spreading activation from a retrieval cue would receive less spreading activation compared to a chunk with lower or no competitors. Thus, modelling spreading activation allows for simulating the fan of a retrieval cue and the fan effect I discussed earlier in **Section 1.3**. The spreading activation S_i received by a chunk i

†Here, the declarative memory component in ACT-R consists of both long term memory (semantic and episodic memory) and short-term working memory.

is summed over all cues J (Equation 1.3).

$$S_i = \sum_{j}^{J} W_j \cdot S_{ji} \tag{1.3}$$

Where W_j is the weight for cue j. This is set to $1/$*number of cues*, which means that all cues are of the same weight. S_{ji} is the strength of association from the cue j to chunk i. S_{ji} is a function of the fan of chunk i for retrieval cue j (Equation 1.4).

Modelling the strength of association from a retrieval cue to a chunk allows us to simulate a retrieval cue losing its effectiveness in aiding retrieval due to overloaded cues (i.e. higher fan), as I discussed in **Section 1.3**.

$$S_{ji} = S - log(fan_{ji}) \tag{1.4}$$

Where S is the maximum associative strength. fan_{ji}, i.e. the fan for the chunk i. This tells us that for each matching retrieval cue to a chunk's feature, a chunk's spreading activation is increased (Equation 1.3), and, for each competitor which matches or partially matches with retrieval cues, a chunk's spreading activation is decreased (Equation 1.4).

To introduce partial matching of retrieval cues as discussed in **Section 1.3**, a penalty for mismatched cues P_i is introduced. Here, some activation of the chunk i in declarative memory is taken away for each retrieval cue j which is not matched to the chunk i's features (Equation 1.5). This again simulates a retrieval cue losing its effectiveness in aiding retrieval due to overloaded cues (i.e. higher fan), as I discussed in **Section 1.3**.

$$P_i = \sum_{j}^{J} P \cdot M_{ji} \tag{1.5}$$

Where P is the mismatch penalty parameter and M_{ji} is the similarity between cue value j and value of the corresponding slot for chunk i. A value of 0 means that the retrieval cue and the chunk's feature are identical and a value of -1 means that they are completely different. Thus, the more different the feature of a chunk is to the retrieval cue, the more activation is subtracted for the chunk. We can now determine the activation of each chunk in declarative memory using Equation 1.1 that was presented earlier.

As we saw earlier, the retrieval time of a chunk from declarative memory is dependent on its activation A_i, as in Equation 1.6. Modelling retrieval time of a chunk as being dependent on the chunk's activation is analogous to the retrieval time being dependent on the time-based memory decay, overloading of retrieval cue (i.e. the fan of the retrieval cue) and partial matching of retrieval cue as I discussed in **Section 1.3**.

$$RT = \begin{cases} \mathrm{Fe}^{-f \cdot A_i}, & if \mathrm{A}_i \geq \tau \\ \mathrm{Fe}^{-f \cdot \tau}, & otherwise \end{cases} \tag{1.6}$$

Where F is the latency factor and f is the latency exponent. If chunk(s) i has an activation above some threshold τ, chunk(s) i will be retrieved. Otherwise, no item is retrieved since retrieval fails. This equation shows us that the higher the activation of a chunk in declarative memory, the faster the chunk will be retrieved from the declarative memory.

Unfortunately, problems arise while implementing the Lewis and Vasishth [2005] model for a different language. The content-addressable memory part of the model is all fine since it uses ACT-R to show general cognitive mechanisms of sentence processing. However, the Lewis and Vasishth [2005] model also consists of a parser which is implemented using production rules which incrementally build a structural representation of a sentence using left corner parsing which follows X-bar syntax rules Chomsky [1986]. This structural representation is then used as input for the content-addressable memory part of the model.

The parser in the model is for parsing English dependencies in English sentences. In the time frame that I was given to conduct an analysis, it would not have been feasible for me to create a new parser for the Marathi language by modifying the Lewis and Vasishth [2005] model to process sentences in Marathi. Therefore, I will attempt to use the mathematics behind ACT-R (as described earlier) to model and predict how interference effects would look like for sentences following the prepositional phrase structure in Marathi.

2 Implementing an R model

To model the memory interference process in dependency resolution, I use an R implementation

[Vasishth et al., 2019][‡] of the previously explained sentence comprehension model by Lewis and Vasishth [2005] realised in ACT-R. An R implementation [Team et al., 2013] was used since the ACT-R model is for sentences only in English. Additionally, the R implementation provides a more intuitive way to understand the content-addressable memory architecture and the cue-based retrieval mechanism I discuss earlier.

The basic R implementation model simulates the retrieval process for a dependency such as subject-verb, assuming that the retrieval cues for the subject are **number** and **gender**. It also assumes that there are two chunks in declarative memory: **the target** (i.e. the licit subject) and **the distractor** (i.e. the other noun in the sentence). As seen in Figure 3.1, a 2x2 design is used to simulate **four conditions**: condition (a): distractor mismatch & target match; condition (b): distractor match & target match; condition (c): distractor mismatch & target mismatch; and condition (d): distractor match & target mismatch. The R implementation uses the basic equations explained in the ACT-R model section to find out the activations of the chunks in memory over time (Equation 1.1). It implements decay and reactivation of a chunk in the memory (Equation 1.2); similarity based interference using spreading activation (Equations 1.3 and 1.4) and a mismatch penalty if the wrong chunk is retrieved (Equation 1.5). From these, the time to retrieve a chunk is then determined (Equation 1.6).

The model simulates over n iterations the chunk activations at the retrieval point for each condition as described in Figure 3.1. For a more in-depth setup and corresponding sentences, refer to **Appendix A**, Figure A.1. For this model, we assume that the retrieval cues for the Marathi verb *"hotya"* (were) are +FEM and +PL as seen in Figure 3.1. This interference model of Marathi with four conditions is then given certain parameters. For a more in-depth description of these parameters, refer to Table A.1 in **Appendix A**. Originally, these parameters can be set individually, or can be based on previous experiments such as the Experiment 5 conducted by Wagers et al. [2009] (Table 3.1) I discuss in **Section 1.1**. Here, the parameters are determined using numerical fit so that the model matches the effects found in these experiments. Then the model simulates the n iterations for each condition.

As seen earlier, we assume that there are two chunks in the memory: the target and the distractor. In each iteration, the model calculates the activations of both chunks using Equation 1.1 and the retrieval latency using Equation 1.6. After the n iterations for each condition, the model knows: the mean number of times each chunk was retrieved for each condition, the mean time it took for a chunk to be retrieved in each condition (in ms) and how many failed retrievals & misretrievals took place for each condition. Using these, I can predict the magnitude of interference effects observed in the model. Additionally, after comparing to existing literature [Wagers et al., 2009, Acuña-Fariña et al., 2014], I will then be able to look at how these effects would generally look like in comprehension of subject-verb agreement sentences (as seen in **Appendix A**) with a prepositional phrase in Marathi.

3 Predicting the interference effects

In this section, I will present my initial qualitative predictions of the interference effects according to the model. First I argue that processing subject-verb agreement in Marathi is very similar to processing subject-verb agreement in English and Spanish. Then, I argue for the parameters I set for the interference model for Marathi. Thus, from these assumptions, I predict how agreement attraction effects (i.e. inhibitory and facilitatory effects) would arise in the interference model for Marathi sentences.

3.1 How does Marathi differ from English and Spanish?

To predict how the interference effect would generally look like in comprehension of subject-verb agreement sentences with a prepositional phrase in Marathi, I would be looking at existing literature, mainly the experiments done by Wagers et al. [2009] and Acuña-Fariña et al. [2014]. However, to do this, I would need to argue that sentence processing of subject-verb agreement with a preposi-

[‡] Available at `https://vasishth.github.io/RetrievalModels/`.

(5) *Darwaj-ya-c-a* *chavya* *kharab* *ho-t-ya* *baryaca* *varsancya*
door.M.SG.3-OBL-PP-M.SG.3 key.F.PL.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The door's keys were bad from many years use'
(intended) 'The keys to the door were bad from many years of use'

tional phrase is similar in Marathi when compared to English and Spanish.

Like the subject-verb agreement in English and Spanish, verbs in Marathi need to agree with the subject's number. Simultaneously, like Spanish, in Marathi, the gender feature of the subject is seen in the subject's adjective sometimes. However, unlike Spanish and English, verbs in Marathi also need to agree with the subject's gender along the subject's number. As we saw earlier, we assume that the retrieval cues for the subject are number and gender. Thus, I will say that the process of gender licensing in subject-verb agreement sentences is the same as the process of number licensing in subject-verb agreement sentences. This will allow me to directly compare the results of Wagers et al. [2009] and Acuña-Fariña et al. [2014] to my own results.

Further, in both English and Spanish, the subject in subject-verb agreement sentences with a prepositional phrase occurs before the potential distractor. However, in Marathi, the potential distractor occurs before the target i.e. the subject. For example, take sentence (5). From the interlinear gloss, we see that the noun *"door"* inside the prepositional phrase occurs before the subject of the sentence *"keys"*. This leads to **proactive interference conditions** as opposed to a retroactive interference conditions as seen in English in **Section 1** and in Spanish in Figure 1.2.

3.2 Which values for the parameters should be chosen?

Before constructing an agreement attraction effects model for Marathi, we would need to determine which preset parameters are suitable for the model. For these parameters, I implement the numerically fitted parameters which were used in Experiment 5 of Wagers et al. [2009] (Table 3.1). This would mean that I am predicting the magnitude of the interference effect based on the results seen by Wagers et al. [2009]. The experiment conducted by Wagers et al. [2009] consists of retroactive interference conditions where the distractor occurs after the target.

Parameter	Value
lf	0.15
le	1
rth	-1.5
mas	1.5
mp	0.25
bll	0.5
ans	0.2
ga	1
lp	1300
ldp	700
ndistr	1
n	5000

Table 3.1: Values of parameters used to approximate the interference effect seen in Experiment 5 by Wagers et. al (2009) using the R implementation of the Lewis and Vasishth (2005) model.

However, as seen earlier, subject-verb agreement sentences with a prepositional phrase in Marathi have proactive interference conditions. Due to this, I will change the parameters which depend on time based decay: *lp* which describes the time since the last presentation of a target from verb, in milliseconds and *ldp* which describes the time since the last presentation of a distractor from verb. These were changed to **800** and **1700** respectively. To change these parameters, I timed myself reading the subject-verb agreement sentences with prepositional phrases as seen in **Appendix A**. An average of 10 times was taken from each target and each distractor in each condition. Due to the proactive interference condition, we see that *ldp* is larger than *lp* for the Marathi model when comparing to the English model as seen in Table 3.1. Now, since we have a complete model, we can proceed to predict the interference effects in comprehension

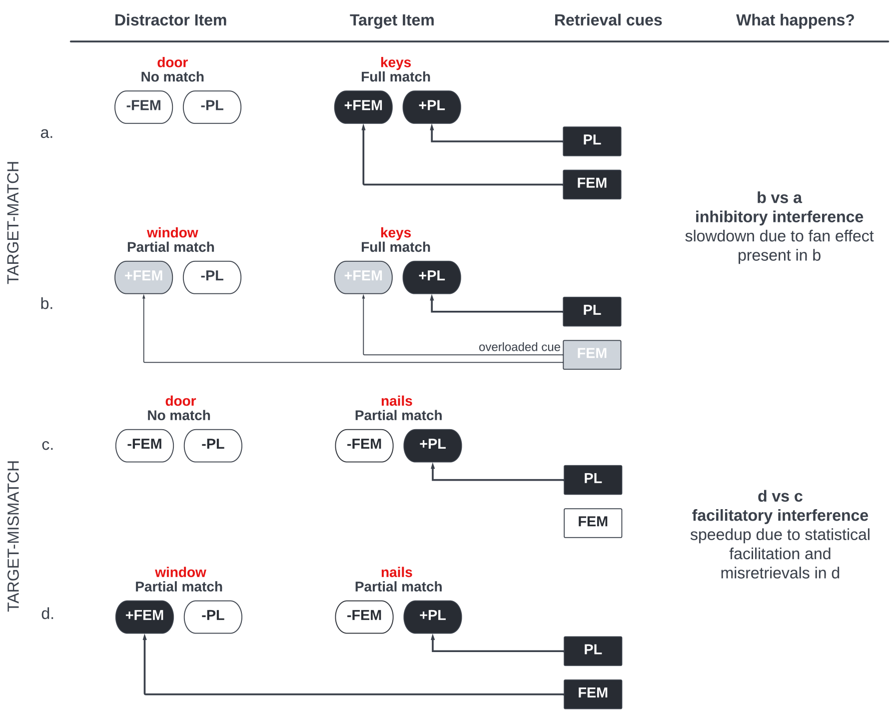


Figure 3.1: Example setup for a 2x2 model with 4 conditions for sentences in Marathi. Modified from Vasishth and Engelmann [2021, p.73] (Figure 4.1). Line weights show amount of spreading activation from a cue to an chunk. Black boxes show a feature match. Grey boxes show features matching an overloaded cue and white boxes show a mismatch. For a full setup and corresponding Marathi sentences of this setup, refer to Appendix A.

for subject-verb agreement sentences with prepositional phrases in Marathi.

3.3 Predictions for the R model

In this section, I make some qualitative predictions for the Marathi subject-verb agreement sentences with prepositional phrases based on the cue-based retrieval mechanism and the content-addressable memory architecture discussed earlier. As we saw earlier, inhibitory interference, i.e. a slowdown in retrieval times (Figure 3.1, b vs a), arises in grammatical sentences. These are described as **target-match conditions** in Figure 3.1. Facilitatory interference, i.e. a speedup in retrieval times (Figure 3.1, d vs c), arises in ungrammatical sentences. These are described as **target-mismatch conditions** in Figure 3.1.

3.3.1 Inhibitory interference predictions

We see that in condition (a) the target receives all of the limited spreading activation at retrieval due to no overloaded cues and perfect matching of the features to the retrieval cues. This would mean that the target has the highest activation in condition (a) at the retrieval point when compared to other conditions. Due to the cue overload in condition (b), the limited spreading activation for cue is now split between the target and the distractor, leading to the **fan effect** we saw earlier in **Section 1.3**. Each chunk which matches the retrieval cue reduces the spreading activation to the target chunk which makes the target chunk less likely to be distinguishable from the distractor.

Additionally, the reduction in spreading activation for the target in condition (b) leads to a reduction in the total activation of the target chunk (Equation 1.1). The reduction in total activation leads to an decrease in retrieval time (Equation 1.6) for the target chunk in condition (b) compared to condition (a). This can also be seen as a result of the fan effect as discussed earlier in **Section 1.3**. This would be seen as an inhibition in processing as processing time, at the verb where retrieval is triggered. Further, due to the increased distractor activation from spreading activation and due to the Gaussian noise (Equation 1.1), there is a higher probability of misretrieving the distractor in condition (b) when compared to condition (a). But due to the proactive interference condition,the distractor will have a slightly larger decay than the target. Thus, the probability of a misretrieval would not be very high. This would mean that readers see sentences of condition (a) as slightly more grammatical than sentences of condition (b), even when both sentences are equally grammatical. Thus the fan effect would lead to slower processing of the verb in sentences in Marathi of condition (b) when compared to sentences in Marathi of condition (a). The slower retrieval time will be seen at the verb and immediately after the verb as seen by Acuña-Fariña et al. [2014] for number and gender mismatch of the distractor with respect to the verb.

3.3.2 Facilitatory interference predictions

Due to no overloaded cues in condition (d), there is no fan effect, thus, no inhibitory interference.

In condition (d) the target and distractor receive the same amount of spreading activation due to each having one unique retrieval cue match (Equation 1.3). Thus, the activations of the target and the distractor in condition (d) are very similar to each other at the retrieval point, even with the Gaussian noise seen in Equation 1.1. Therefore, the winning chunk is chosen randomly at retrieval time with a probability of around 0.5, as there are only two chunks in the memory. This results in **statistical facilitation** as we discussed earlier in **Section 1.3**.

Thus, the retrieval times of condition (d) would be shorter than the retrieval times of condition (c). Due to similar activations of the target and the distractor, it is likely that the distractor will also be retrieved more often in condition (d) when compared to condition (c). But due to the proactive interference condition,the distractor will have a slightly larger decay than the target. So the misretrieval of the distractor will not be of a large magnitude. This would mean that readers see sentences of condition (d) as slightly more grammatical than sentences of condition (c), even when both sentences are equally ungrammatical.

Thus, statistical facilitation will lead to faster processing of the verb in sentences in Marathi of condition (d) when compared to sentences in Marathi of condition (c). This facilitatory effect will be seen at the verb and immediately after the verb according to Wagers et al. [2009] and Acuña-Fariña et al. [2014].

Now, as we have a complete model of interference effects for subject-verb agreement sentences with prepositional phrases in Marathi and our a priori predictions, we can proceed towards the results of this model.

4 Model results

In this section, I will describe the quantitative results seen from modelling the interference effects for subject-verb agreement sentences with prepositional phrases in Marathi for comprehension. I will also show how the model agrees and disagrees with the qualitative predictions I make in **Section 3.3**. Additionally, as reminder,the four conditions are: condition (a): distractor mismatch & target match; condition (b): distractor match & target match; condition (c): distractor mismatch & target mismatch; and condition (d): distractor match & target mismatch.

As we saw earlier, I predicted that condition (a) would have a higher overall activation at retrieval point than other conditions seen in Figure 3.1. I also predicted that the target in condition (b) would have a lower activation than the target in condition (a) at retrieval point. From Figure 4.1, we see that the average target activation at the retrieval point is the highest in the distractor mismatch & target match condition (1.62, condition (a)) when compared to target activations in other conditions: 1.25 in condition (b), 0.61 in condition (c) and 0.61 in condition (d). Here, the model match my quali-

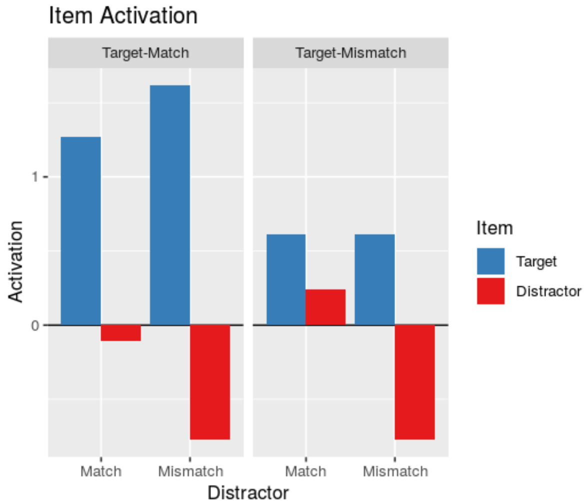


Figure 4.1: Activation levels of the target and the distractor when a retrieval process is triggered

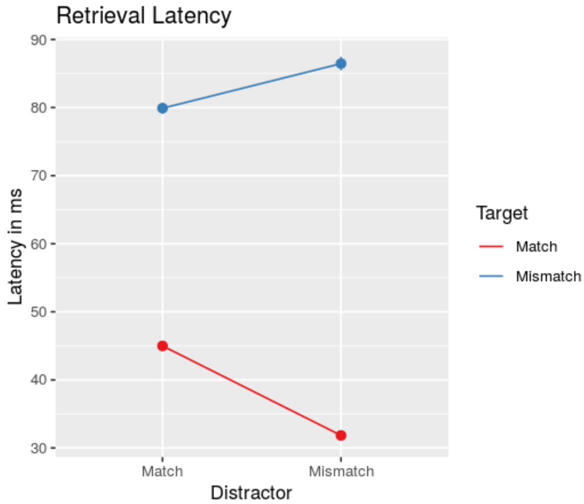


Figure 4.2: Retrieval times of the winning chunk for target match/mismatch and distractor match/mismatch sentences in milliseconds.

tative predictions.

Additionally, I predicted that due to the lower activation in condition (b), the retrieval time would be larger in condition (b) when compared to condition (a). From Figure 4.2, we see that the distractor match & target match condition, i.e. condition (b), has a higher retrieval latency (45.5 ms) on average than the distractor mismatch & target match condition, i.e. condition (a) (31.9 ms). Here, the model my qualitative predictions.

I also predicted that condition (b) would have a higher probability of retrieving distractor instead of the target when compared to condition (a). From Figure 4.3, we see that the model here does not match my qualitative predictions, since in both conditions the probability of retrieving the target is 1. Further, I predicted that in condition (d) (as seen in Figure A.1) the activations of the target and the distractor at retrieval point are most likely similar. This does not seem to be the case as seen in Figure 4.1. We see that for the distractor match & target mismatch condition, i.e. condition (d), the activation of the target (0.61) is much higher than the activation of the distractor (0.24).

Additionally, I predicted that the retrieval time of condition (d) is shorter than the retrieval time of condition (c). As we see in Figure 4.2, the retrieval latency of the distractor match & target mismatch condition, i.e. condition (d), is much lower (79.94 ms) than the the distractor mismatch & target mismatch condition, i.e. condition (c) (87.07 ms). Here, the model matches my qualitative predictions.

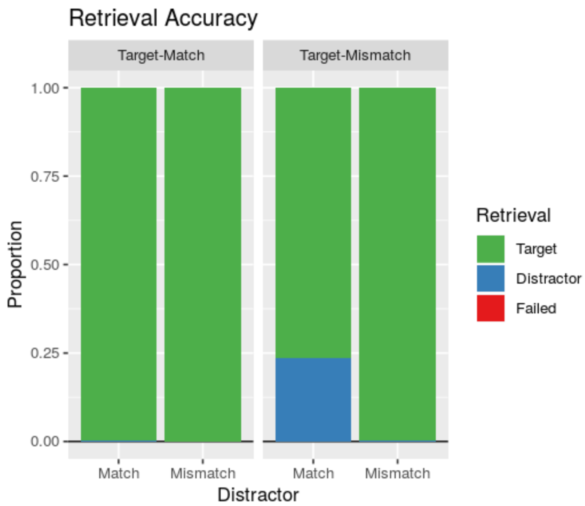


Figure 4.3: Proportion of times the target or the distractor was retrieved.

I also predicted that due to the race process and similar mean retrieval times, it is likely that the distractor is retrieved as opposed to the target in condition (d). This can be seen in Figure 4.3, where the distractor is retrieved with a probability of 0.23 in the distractor match & target mismatch condition, i.e. condition (d), as opposed to a retrieval probability of 0 in the distractor mismatch & target mismatch condition, i.e. condition (c). Here, the model matches my qualitative predictions.

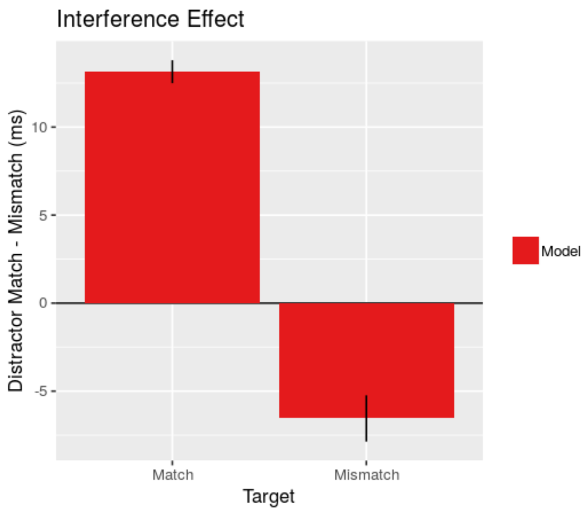


Figure 4.4: Magnitude of interference effect for target match and mismatch sentences in milliseconds. Error bars represent the 95% confidence intervals.

Based on these results, we see that the model does show inhibitory and facilitatory interference effects in their respective conditions as seen in Figure 4.4. Here, the model matches my predictions. The magnitude of the inhibitory effect is **13.31 ms**, with 95% credible interval [12.67, 13.95] ms. The magnitude of the facilitatory effect is **-7.05 ms**, with a 95% credible interval [-8.37, -5.73] ms. However, these magnitude of interference effects are quantitatively smaller than the interference effects observed by Wagers et al. [2009] and Acuña-Fariña et al. [2014], which is as expected due to the proactive interference conditions of the Marathi sentences.

4.1 Analysing the model's results

After seeing how the model matches with my predictions, I need to see if the model matches the predictions made by Wagers et al. [2009] and Acuña-Fariña et al. [2014]. To do so, I try to determine if the effect of target (match-mismatch) and distractor (match-mismatch) on the retrieval times were statistically significant. By doing so I can see if ungrammatical sentences give rise to facilitation in the model (as seen by Wagers et al. [2009]) and if grammatical sentences give rise to inhibition in the model (as seen by Acuña-Fariña et al. [2014]).

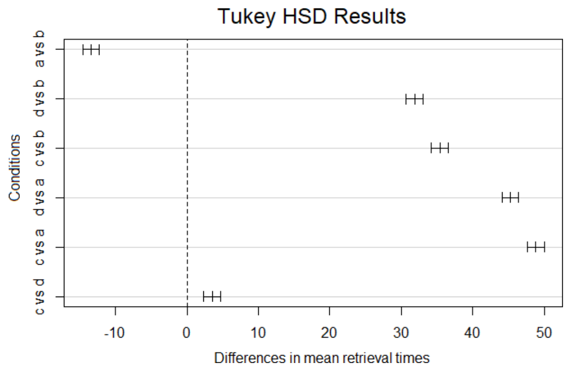
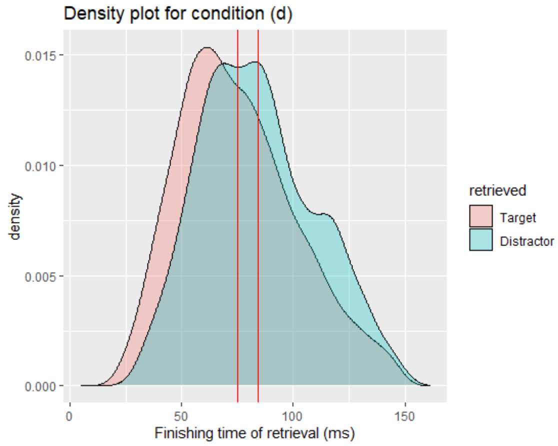


Figure 4.5: Significant results of Tukey HSD test with 95% confidence level.

To do the above, I decided to conduct a two-way ANOVA. It revealed there was a statistically significant difference in average retrieval latency by target ($f(1) = 7510010, p < 0.001$) and by distractor ($f(1) = 157986, p < 0.001$) in the model. This matches the predictions made by Wagers et al. [2009] and Acuña-Fariña et al. [2014]. However, the ANOVA also revealed that there was a statistically significant interaction between the effects of target and distractor in the model ($f(1) = 305650, p < 0.001$). This does not match my qualitative predictions and the predictions made by Wagers et al. [2009] and Acuña-Fariña et al. [2014].

Further, A Tukey HSD post-hoc test revealed significant pairwise differences ($p < 0.05$) as seen in Figure 4.5. Conditions a vs b in Figure 4.5 shows us that the average retrieval time, according to the model, in condition (b) is 13.44 ms (95% credible interval [-14.58, -12.30] ms) longer than the average retrieval time in condition (a). Conditions c vs d in Figure 4.5 shows us that the average retrieval time, according to the model, in condition (d) is 3.54ms (95% credible interval [2.37, 4.71] ms) shorter than condition (c). These match with the qualitative predictions I made previously. There are other interactions being present in the model, which does not match my qualitative predictions and the quantitative results and analysis done by Wagers et al.



(a) Density plot for retrieval times of two chunks in memory for condition (d). Red line indicates similar means can be observed.

(b) Density plot for retrieval times of two chunks in memory for condition (c). Red line indicates dissimilar means can be observed.

Figure 4.6: llustration of statistical facilitation taking place in the model as described by Vasishth and Engelmann (2021). Similar means in retrieval times of two chunks in memory (condition d) give rise to a race process, hence facilitation occurs. Due to dissimilar means in retrieval times of two chunks in memory (condition c), there is no race process, hence no facilitation is seen.

[2009] and Acuña-Fariña et al. [2014]. A complete analysis of Figure 4.5 can be found in **Appendix A**.

Further, to see why my qualitative prediction of activations of the target and the distractor being similar in condition (d) was false, I decided to look at the density plot for retrieval latencies in conditions (c) and (d) for when the target was retrieved and when the distractor was retrieved (Figure 4.6). When comparing Figures 4.6b and 4.6a to Figure 1.3, we see that in Figure 4.6a the two distributions do have similar means in retrieval times for both chunks when compared to the means in retrieval time in Figure 4.6b. This is in line with my predictions for the model I make earlier as it signifies that there is statistical facilitation taking place. This is also confirmed when we see a facilitation in the model for retrieval times when comparing condition (d) to condition (c) in Figure 4.2, and, as explained earlier in Tukey HSD test in Figure 4.5. From this I can conclude that the activations of the target and the distractor in condition (d) (as seen in Figure A.1) are similar enough for a race process to occur in the model, and thus, are enough for the facilitatory effect to take place in the model.

5 Conclusions

Based on the quantitative results from the model and after conducting an ANOVA test & a Tukey HSD test, I can suggest that interference effects would most likely be observed in subject-verb agreement sentences in Marathi with a prepositional phrase. According to the model, these effects would most likely be seen as a speed-up in reading time and processing in ungrammatical sentences or be seen as a slow-down in reading time and processing in grammatical sentences. Further, these effects would most likely arise in the model due to the match and mismatch of the subject and another noun in the sentence while licensing the subject-verb agreement.

The model suggests that inhibitory interference effect could arise in the target-match conditions due to the fan effect leading to an increase/slow-down in retrieval time and processing of a noun from the memory while licensing the subject-verb agreement. Further, the model also suggests that a reader will see sentences of condition (a) and (b) as equally grammatical. The model also suggests that a facilitatory interference effect could arise in the target-match conditions due the partial matches of the target and the distractor, but no overloaded cues. The model suggests that this leads to statistical facilitation in readers, where the retrieval time of the noun is faster since both nouns in the sentence would likely have similar processing times when licensing the subject-verb agreement. Further, the model suggests that a reader will see sentences of condition (d) as more grammatically correct than sentences of condition (c) when both are equally ungrammatical.

From the quantitative results of the effects, we now know the approximate magnitude of the agreement attraction effect which might be observed in the comprehension of subject-verb agreement sentences with prepositional phrases in the Marathi language. Based on the previous comparison to Wagers et al. [2009] and Acuña-Fariña et al. [2014], these effects would most likely be seen right after the reading of the verb in the sentence.

6 Discussions

From the model results and the conclusions I make based on the model, we can now see how the agreement attraction effects could potentially arise and the possible magnitude of these effects. However, certain questions arise about the model that I implement. For example, to what extent are the results obtained from the model accurate to agreement attraction effects observed in real-life experiments? As I mention earlier, no study has yet been performed to explore agreement attraction effects in Marathi. One way to see if my predicted results are accurate is by comparing them to the results of an experiment. In the future, an experiment with native Marathi speakers can be conducted to observe agreement attraction effects in Marathi. This experiment can re-use the same experimental setup as seen in Figure A.1 in **Appendix A**. Such an experiment could use sentence processing measures to see which conditions give rise to which effects. Since this model does predict significant effects of target/distractor match/mismatch on processing and reading times, a power analysis can also be conducted to see how many participants are needed for such a study. Unfortunately, an experiment of this capacity would take a lot of time and effort to conduct. Further, the lack of access to a larger sample of native Marathi speakers in Groningen could prevent such an experiment from taking place.

Another way to make my results more accurate to real-life sentence processing would be better parameters. As I mentioned in **Section 3.2**, I timed myself for the parameters which describe the time-based decay of the target and the distractor. This was done in a very rudimentary way. Perhaps a better and a more accurate measure of time taken to process the target and the distractor from the verb can be used to make the model more biologically plausible.

Finally, to make this model even better, I can closely implement more mechanisms which would be able to accurately describe sentence processing of a native speaker. One way to do so is implement a parser for the Marathi language for subject-verb agreement sentences with prepositional phrases. This will allow for more accurate way to process the dependencies, instead of just saying a subject of the verb *"hotya"* is plural and feminine. It will also allow me to take into account all constituents of the sentence instead of just the target and the distractor. Another way to implement this is using chunk prominence and multi-associative cues as described by Engelmann et al. [2019]. Chunk prominence will allow us to describe how prominent the chunk to be retrieved is in current context of discourse. It tells us how relevant certain chunks are based on syntactic relations in the sentence or based on informational structure or discourse properties. Multi-associative cues suggests that the associative strength between a retrieval cue and a chunk can be the result of multiple cues being associated to multiple features at varying degrees, resulting in a cue spreading activation between similar features. It suggests that there is no binary (match or mismatch) result of the one-to-one mapping between the cue and a feature, but rather it is spectrum between match or mismatch. This would allow me to model sentence processing more accurately by simulating the mechanisms behind sentence processing in native speakers in a slightly more biologically correct way as memory and representation are not the only aspects of sentence processing.

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A Appendix

Setup according to the model by Lewis and Vasishth [2005] can be seen in Figure A.1.

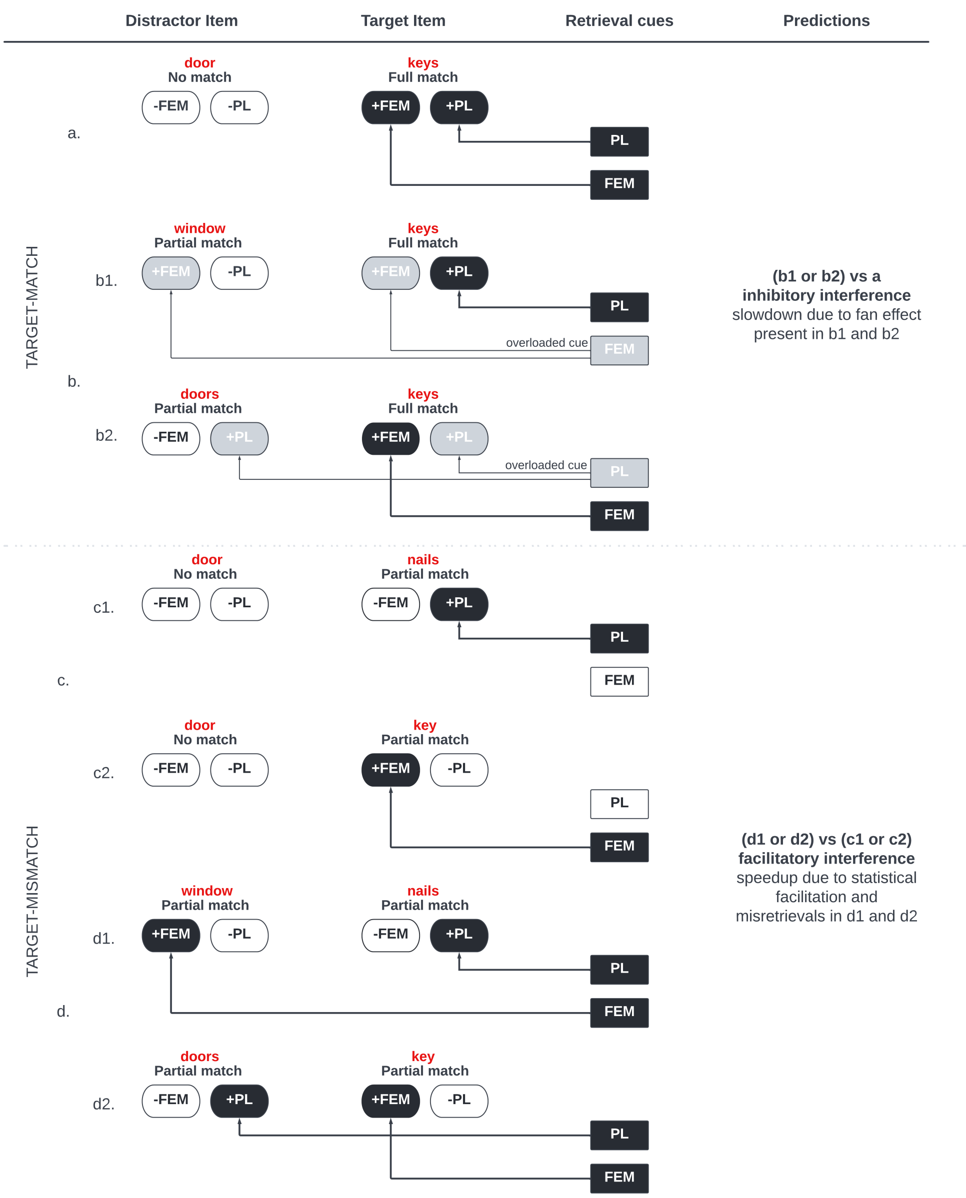

Figure A.1: How a gender and number mismatch setup would look like for a 2x2 model with 4 conditions for sentences in Marathi. Modified from Vasishth and Engelmann [2021, p.73] (Figure 4.1). Line weights show amount of spreading activation from a cue to an item. Black boxes show a feature match. Grey boxes show features matching an overloaded cue and white boxes show a mismatch.

Corresponding sentences:
Distractor mismatch, Target match: **Condition a**

(6) *Darwaj-ya-c-a chavya kharab ho-t-ya baryaca varsancya*
door.M.SG.3-OBL-PP-M.SG.3 key.F.PL.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The door's keys were bad from many years use'
(intended) 'The keys to the door were bad from many years of use'

Distractor match, Target match: **Conditions b**

(7) *Khidaki-∅-c-i chavya kharab ho-t-ya baryaca varsancya*
window.F.SG.3-OBL-PP-F.SG.3 key.F.PL.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The window's keys were bad from many years use'
(intended) 'The keys to the window were bad from many years of use'

(8) *Darwajyan-a-c-ya chavya kharab ho-t-ya baryaca varsancya*
door.M.PL.3-OBL-PP-M.PL.3 key.F.PL.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The doors' keys were bad from many years use'
(intended) 'The keys to the doors were bad from many years of use'

Distractor mismatch, Target mismatch: **Condition c**

(9) **Darwaj-ya-c-a khilae kharab ho-t-ya baryaca varsancya*
door.M.SG.3-OBL-PP-M.SG.3 nail.M.PL.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The door's nails were bad from many years use'
(intended) 'The nails to the door were bad from many years of use'

(10) **Darwaj-ya-c-a chavi kharab ho-t-ya baryaca varsancya*
door.M.SG.3-OBL-PP-M.SG.3 key.F.SG.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The door's key were bad from many years use'
(intended) 'The nails to the door were bad from many years of use'

Distractor match, Target mismatch: **Condition d**

(11) **Khidaki-∅-c-i khilae kharab ho-t-ya baryaca varsancya*
window.F.SG.3-OBL-PP-F.SG.3 nail.M.PL.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from
'The window's nails were bad from many years use'
(intended) 'The nails to the window were bad from many years of use'

(12) **Darwajyan-a-c-ya chavi kharab ho-t-ya baryaca varsancya*
door.M.PL.3-OBL-PP-M.PL.3 key.F.SG.3 bad be-PST-F.PL.3 many years
vapara-pasun
use-from

‘The doors’ key were bad from many years use’
(intended) ‘The key to the doors were bad from many years of use’

Parameter	Explanation
lf	Latency factor, determines the magnitude of the activation effects on latency as seen in Equation 1.6.
le	Latency exponent, exponent factor while determining the activation effects on latency as seen in Equation 1.6.
rth	Retrieval threshold, chunks in memory with activation levels below this threshold cannot be retrieved.
mas	Maximum associative strength, used in Equation 1.4. It is the theoretical maximum associative strength a chunk in memory could have if it has no associations, i.e. no similar chunks in memory.
mp	Mismatch penalty. Each mismatched chunk is scaled with this parameter to determine its mismatch penalty, which is then used to calculate the activation (Equation 1.5).
bll	Decay parameter, used in Equation 1.2. Determines by how much the activation of a chunk in memory should decay over time.
ans	Used to generate instantaneous activation noise. This noise is generated using a logistic distribution characterised by the ans value. If ans is set to a value, Gaussian noise is added to each chunk’s activation at retrieval as seen in Equation 1.1.
ga	Goal source activation, i.e. the weight for a cue as described in Equation 1.3.
lp	Time since the last presentation of a target in a sentence, in milliseconds.
ldp	Time since the last presentation of a distractor in a sentence, in milliseconds.
ndistr	Number of distractors in a given sentence.
n	Number of iterations to simulate the chunk activations at retrieval point for each condition.

Table A.1: Explanation of parameters used in the R implementation of the ACT-R model.

Conditions	Interpretation of Tukey HSD test	95% confidence interval of difference
a vs b	Average retrieval time in condition (a) is 13.44 ms faster than condition (b)	[-14.58, -12.30]
d vs b	Average retrieval time in condition (d) is 31.87 ms longer than condition (b)	[30.72, 33.02]
c vs b	Average retrieval time in condition (c) is 35.41 ms longer than condition (b)	[34.25, 36.58]
d vs a	Average retrieval time in condition (d) is 45.31 ms longer than condition (a)	[44.16, 46.46]
c vs a	Average retrieval time in condition (c) is 48.85 ms longer than condition (a)	[47.69, 50.01]
c vs d	Average retrieval time in condition (c) is 3.54 ms longer than condition (c)	[2.37, 4.71]

Table A.2: Results of the post-hoc Tukey HSD test