Prediction advantage as retrieval interference: an ACT-R model of processing possessive pronouns

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Abstract

We propose a retrieval interference-based explanation of a prediction advantage effect observed in Stone et al. (2021). They reported two dual-task eye-tracking experiments in which participants listened to instructions involving German possessive pronouns, e.g. 'Click on **his** blue button', and were asked to select the correct object from a set of objects displayed on screen. Participants' eye movements showed predictive processing, such that the target object was fixated before its name was heard. Moreover, when the target and the antecedent of the pronoun matched in gender, predictions arose earlier than when the two genders mismatched — a prediction advantage. We propose that the prediction advantage arises due to similarity-based interference during antecedent retrieval, such that the overlap of gender features between the antecedent and possessum boosts the activation level of the latter and helps predict it faster. We report an ACT-R model supporting this hypothesis. Our model also provides a computational implementation of the idea that prediction can be thought of as memory retrieval. In addition, we provide a preliminary ACT-R model of how linguistic processes could drive changes in visual attention.

Keywords: pronoun resolution; prediction; retrieval interference; ACT-R; possessive pronouns

Introduction

In a sentence such as "Peter wanted to go jogging with Paula, but his sneakers were torn out", finding out the referent of the pronoun *his* involves: (i) using the linguistic knowledge that the referent should prototypically have a masculine gender, (ii) maintaining the memory representation of all the referents encountered so far, i.e. *Peter* and *Paula*, and (iii) retrieving the correct antecedent, *Peter*, and co-referring it with *his*. The task of finding an appropriate antecedent is partly facilitated by the gender feature of the pronoun, at least in languages where gender is reflected in the surface form of words.

Pronoun resolution as cue-based retrieval

The psycholinguistic processes involved in pronoun resolution can be modeled well in the cue-based retrieval (henceforth CBR) theory of sentence processing (Lewis & Vasishth, 2005; Lewis, Vasishth, & Van Dyke, 2006). The CBR theory, implemented in ACT-R (Anderson, Byrne, Douglass, Lebiere, & Qin, 2004), describes sentence processing as a series of activation-based skilled memory retrievals. Lexical knowledge and a current partial representation of the input (the parse) are maintained in declarative memory (chunks) and psycholinguistic processes are represented in procedural memory (production rules). Incremental sentence processing occurs through the selection of production rules, which retrieve chunks from declarative memory and operate on them to update the representation of the sentence. In a CBR model of pronoun resolution, antecedent retrieval is achieved by using features such as the gender of the pronoun (Patil, Vasishth, & Lewis, 2016; Parker & Phillips, 2017; Engelmann, Jäger, & Vasishth, 2019). The CBR theory has also been used to model retrieval processes with other linguistic dependencies such as subject-verb agreement and negative polarity items (Vasishth, Brüssow, Lewis, & Drenhaus, 2008; Dillon, Mishler, Sloggett, & Phillips, 2013).

Pronoun resolution and prediction

In addition to the backward-looking processes implemented through memory retrieval, some types of pronouns also involve forward-looking processes, i.e., expectations about the identity of upcoming words. Predictions about upcoming material are an integral part of sentence processing (Huettig, 2015; Kuperberg & Jaeger, 2016). Comprehenders can generate these expectations based on the dependencies between the predicted words and previously processed ones. For example, in languages where articles and determiners need to agree in gender with a following noun, an article with masculine gender allows comprehenders to predict an upcoming noun, e.g., in the German phrase "der Knopf" ('the.MASC button.MASC'). These agreement-based predictions are not restricted to gender, but extend to different kinds of morphosyntactic features, such as number, person and case (Dahan, Swingley, Tanenhaus, & Magnuson, 2000; Kamide, Scheepers, & Altmann, 2003; Lew-Williams & Fernald, 2010; Hopp, 2012; Zhang & Knoeferle, 2012; Grüter, Lau, & Ling, 2020).

In previous work, predictions have mostly been studied in words that solely encode forward-looking agreement, such articles and determiners. However, there are linguistic categories that simultaneously encode backward- and forward-looking dependencies, such as linking elements (e.g. "however" or "despite of"), verbs and possessive pronouns. The current study focuses on possessive pronouns (e.g. "his" or "her") because they are useful to investigate the interaction between antecedent retrieval and word predictions.

German possessive pronouns

Our study models the comprehension of German possessive pronouns. A German possessive pronoun such as "seinen" ('his') shows a bi-directional pattern of agreement: The stem "sein-" indicates a preceding masculine possessor (like "his" in English) but additionally, the suffix "-en" indicates an upcoming masculine possessum noun. These backward- and forward-looking agreement relationships mean that German comprehenders can use the two gender features of the possessive to retrieve a preceding antecedent and to predict an upcoming possessum. Thus, German possessives provide a good test case to examine whether retrieval and prediction mechanisms interact during sentence processing.

Stone et al. (2021) addressed this question in a visual world eye-tracking study and reported an interaction between these mechanisms: Participants predicted the upcoming possessum noun faster when the possessum and possessor matched in gender than when they mismatched, i.e., a prediction advantage. Here, we provide an explanation of this prediction advantage by modeling the eye-tracking experiments of Stone et al. (2021). Our model uses the sentence processing mechanism in the CBR theory and the principles of ACT-R. By doing this, the model extends the CBR architecture and further proposes that the prediction advantage is due to similarity-based interference during the antecedent retrieval process.

Data: Stone et al. (2021), Experiment 2

Stone et al. (2021) reported two visual world eye tracking studies. We first describe and model the second experiment (Experiment 2), and then extend the model to the first experiment (Experiment 1). We proceed in this order because Experiment 2 had a simpler experimental design and a larger sample size than Experiment 1, which likely yielded more precise estimates. Experiment 2 was performed by seventy-four German native speakers. At the beginning of the experiment, participants were introduced to two characters, *Martin* and *Sarah*, whose faces were displayed on screen. Participants' task was to help Martin and Sarah tidy up their house by finding their belongings before their parents arrived. They were told that they would see images and hear instructions, and that their task was to click on the object mentioned in the instruction as quickly and accurately as possible.

During the experimental trials, participants heard an auditory instruction and saw a visual display with a target object (e.g. a blue button.MASC) and a color competitor of different gender (e.g. a blue bottle.FEM). Each object had one of four colors: red, green, blue, or yellow. There were 96 items distributed across two conditions. In the MATCH condition, shown in (1a), the possessor and target noun in the auditory instruction had the same gender, i.e, both were masculine or both were feminine. In the MISMATCH condition, show in (1b), the possessor mismatched in gender with the target object but matched with the competitor.

(1) a. **MATCH condition**
Klicke auf <u>seinen</u> blauen Knopf!
Click on his.MASC blue.MASC button.MASC

b. **MISMATCH condition**
Klicke auf <u>ihren</u> blauen Knopf!
Click on her.MASC blue.MASC button.MASC

Stone et al. (2021) used a Bayesian bootstrapping procedure to estimate the earliest point in time at which participants' fixations to the target object increased compared to those to the color competitor. This point, together with a 95% credible interval was taken as the prediction effect onset. The comparison of the predictive onset in the MATCH vs. MISMATCH condition showed that predictions were 307 [262, 352] ms earlier in the MATCH condition (Figure 1, top row). This difference indicates that predictions arose earlier when the antecedent of the possessive matched in gender with its target object, despite the fact that the antecedent gender was syntactically irrelevant for the target noun prediction.

Prediction advantage as retrieval interference

We propose that the prediction advantage observed in Experiment 2 is a consequence of interference due to a partial-cue match during retrieval, a kind of similarity-based interference (Vasishth et al., 2008). Interference occurs during the antecedent retrieval triggered by the possessive pronoun — the gender cue used in the retrieval of the antecedent in the MATCH condition boosts the activation of the gender-matching target object, but the gender cue in the MISMATCH condition boosts the activation of the competitor object. During the prediction stage, this higher activation of the target object compared to the competitor object in the MATCH condition enables a faster prediction of the target. By contrast, the higher activation of the competitor in the MISMATCH condition delays the prediction of the target object.

Next, we illustrate a model of the two experiments described in Stone et al. (2021). The model is an extension of the sentence processing mechanism from CBR that is tailored to the task of selecting the target object on screen after processing an input sentence. We use the ACT-R architecture to model non-linguistic processes. Note that we do not explicitly model eye movement processes or visual search processes as, for example, in EMMA (Salvucci, 2001) or other aspects of the visual system as, for example, in PAAV (Nyamsuren & Taatgen, 2013). The goal here is to provides an explicit proposal of how top-down psycholinguistic processes, such as antecedent retrieval and prediction, could influence the activation of elements in memory and how these activation levels could impact visual attention and fixation probabilities. We are able to model fixation patterns as they unfold in real-time, thus going beyond previous CBR models on pronoun resolution, which have solely focused on average reading time effects (Patil, Vasishth, & Lewis, 2016; Parker & Phillips, 2017; Engelmann et al., 2019).

Model of Experiment 2 from Stone et al. (2021)

The model combines the cue-based retrieval model of antecedent retrieval (Patil, Vasishth, & Lewis, 2016) and the ACT-R model for predicting the target picture matching the sentence (Patil, Hanne, Burchert, De Bleser, & Vasishth, 2016). To model the dual-task in Experiment 2, we modified the values of three ACT-R parameters (Table 1) and made the following new assumptions.

Model assumptions

(1) At each input word, the model tries to predict the target object (the possessum) based on the information in the sentence encountered up to that point in time. This configuration seeks to replicate participants' goal during the experiment, since their task was to click on the target object as quickly as possible. Thus, we assume that they would try to predict the target object with each new bit of linguistic information.
(2) We assume that the objects on screen are stored as referents in declarative memory. This means that the memory representations of, for example, *Martin*, *Sara*, *button* and *bottle* are referents that are accessible during sentence processing.
(3) The prediction of the target object is implemented as a retrieval of the memory representation of its referent. This is motivated based on the model of sentence-picture matching task in Patil, Hanne, et al. (2016). Additionally, the prediction steps weight color cues higher than linguistic cues (see Parker, Shvartsman, & Dyke, 2017 for similar cue-weighting proposals). This was done to model the saliency of visual features over linguistic features in a visual world task (Coco & Keller, 2015).
(4) When processing the possessive pronoun, the antecedent retrieval precedes the target prediction. This reflects the linear order of the two agreement morphemes in the possessive.
(5) The probability of fixating an object is modeled through the activation of the memory representations of the object — higher activation means higher probability of fixation. This is also based on the model in Patil, Hanne, et al. (2016).

Table 1: List of ACT-R parameter values that were modified during model fitting in Model 1. The parameters were modified to improve model fit. All other parameters had their default values or values used in earlier CBR model.

ACT-R parameter	Default	New
Activation noise (ANS)	0.2	0.15
Maximum associative strength (MAS)	1	3
Match Scale (MP)	1	0.2

Results and discussion

The model predictions for the MATCH and MISMATCH conditions are illustrated in Figure 1 (bottom row). The object with higher activation is predicted to be the object that is fixated. The activation values for objects are sampled after every temporal event, such as production firing or memory retrieval. This is done because the increment of time and memory retrievals cause the activation to change which influences the decision to fixate an object (see assumption (5) in 'Model assumptions'). The predicted fixation curves are smooth because they are binned averaged fixation probabilities (bin size = 200 ms) across 10000 simulations. Vertical red bars denote the divergence points between the two curves predicted by the model. The divergence onset was predicted to be 400 ms earlier in the MATCH conditions compared to the MISMATCH.

The predicted fixation probabilities capture the two key effects in the empirical data. First, the prediction of the target object before hearing its name, which in the empirical data emerged as a 66 [64, 68]% target-over-competitor advantage over the entire predictive window. The model captures this effect by using the gender and color features of the possessive and the adjective to retrieve the target object (e.g. "masculine" and "blue"). Second, the model captures the earlier prediction onset in the MATCH than MISMATCH condition, which was on average 307 [262, 352] ms in the empirical data. The model captures this effect through an interaction between retrieval and prediction processes, on the one hand, and similarity-based interference, on the other. Specifically, the gender cue (masculine for the stem "sein-") in the antecedent retrieval in the MATCH condition boosts the activation of gender-matching objects in memory, which includes the memory representation of the target object (the button, "Knopf.MASC"). Meanwhile, the gender cue in the antecedent retrieval in the MISMATCH condition (feminine for the stem "ihr-") boosts the activation of the memory representation of the competitor object (the bottle, "Flasche.FEM") relative to the target object. This difference in the activation of the target and the competitor during the antecedent retrieval process leads to a faster prediction of the target in the MATCH condition.

Model of Experiment 1 from Stone et al. (2021)

The goal of this model is to test the predictions made by the previous model with new data, without making any new assumptions. With this goal, we modeled the data from Experiment 1 in Stone et al. (2021). Experiment 1 was also performed by seventy-four German native speakers and it was similar to Experiment 2, with a couple of exceptions. First, Experiment 1 featured four objects on screen: in addition to the target and color competitor ('button' and 'bottle', as in Experiment 2) there were two additional objects: a "gender competitor", which matched the target object in gender but not in color (e.g., 'the balloon.MASC'), and a "distractor", which mismatched the target in both color and gender ('the flower.FEM'). Due to the presence of these differently colored objects on screen, the target object was only predictable after the onset of the color adjective (e.g., 'blue'), because both color and gender were necessary to identify the target.

Experiment 1 had only 24 experimental trials, a smaller number than the 96 trials of Experiment 2. The experimen-

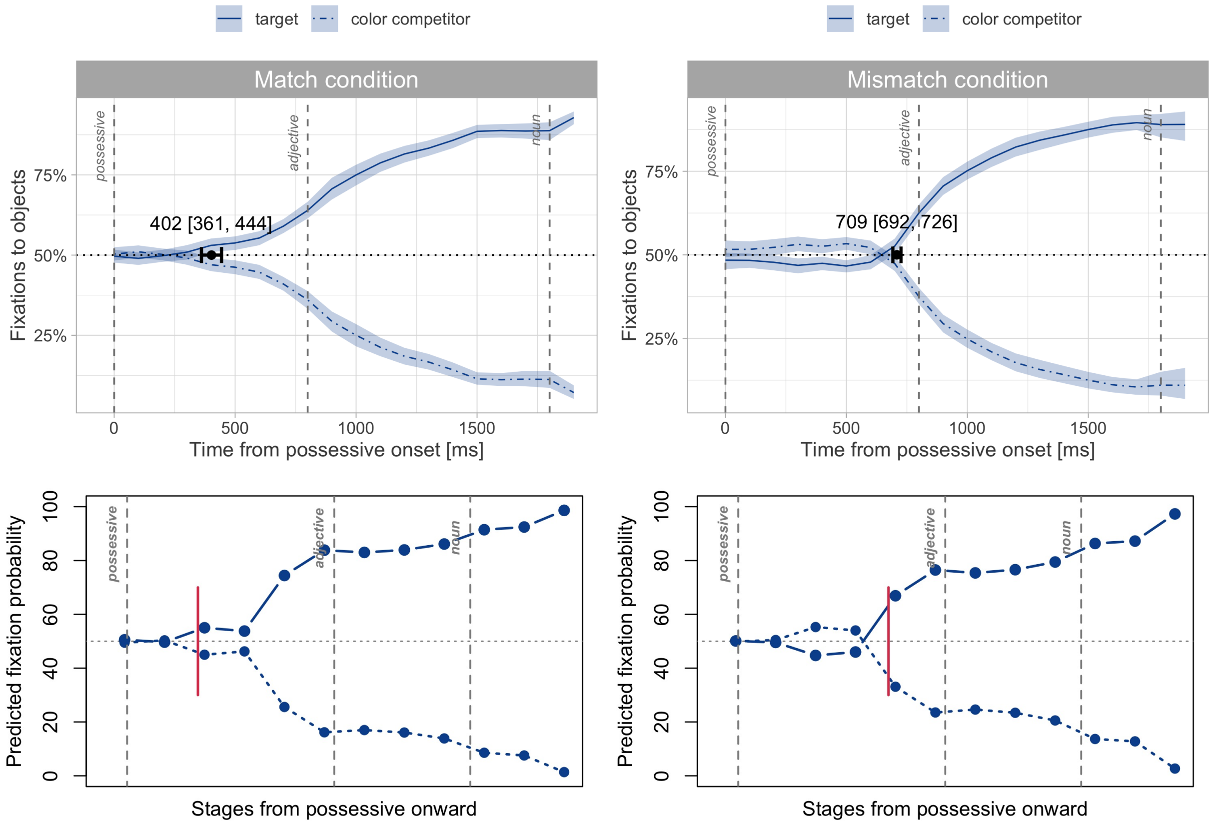

Figure 1: **Top row** (behavioral data): Fixation curves to the two objects averaged across items and participants in Experiment 2. The predictive window extended from the onset of the possessive to the onset of the noun, adding 200 ms for saccade planning (Salverda et al., 2014). The x-axis is time-locked to the possessive. Estimated prediction onsets and their 95% credible intervals are overlaid on the fixation curves in each condition. **Bottom row** (model): Predictions of the model for fixation probabilities to the target and competitor object (the button and bottle, respectively). Red bars denote the predicted divergence points between the two curves.

tal conditions were identical to Experiment 1 and featured a MATCH and a MISMATCH condition. The results were consistent with those of Experiment 1 (Figure 2, top row). First, a 59 [53, 66]% target-over-competitor advantage was observed across the whole predictive window. Second, the onset of the prediction effect was 106 ms [-56, 268] ms earlier in the MATCH than in the MISMATCH conditions. The direction of the effect suggested earlier predictions when the antecedent of the possessive matched in gender with the target object, despite the fact that the antecedent gender was syntactically irrelevant for prediction purposes. However, the magnitude of the between-condition difference was smaller than in Experiment 2 (106 vs. 307 ms on average).

The assumptions of our model were kept constant in terms of modeling the task. We also generate the predicted fixation probabilities in the same manner. The only difference is that declarative memory in the current model includes two extra referents corresponding to the two additional objects shown on screen: one for the gender competitor object (e.g. the balloon) and one for the distractor object (e.g. the flower). We examined whether the model was able to predict the effects observed in Experiment 1 without additional assumptions.

Results and discussion

The model predictions are illustrated in Figure 2 (bottom row). The predictions are generated using the same procedure as in the previous model, with the only difference being that here the predictions are generated also for the two additional objects. The predicted fixation probabilities for the two conditions show patterns comparable to those in the data. The model partially captures the prediction advantage effect in the data: the earlier onset of the target prediction between the MATCH and MISMATCH conditions only when the prediction of target vs. the color competitor is considered. The model captures the other key effect in the data: the prediction of the target object before hearing its name. However, some predictions of the model do not correspond well to the empirical patterns. First, the model predicts similar fixation proportions to the target and gender competitor after the processing of the pronoun. This was not observed in the em-

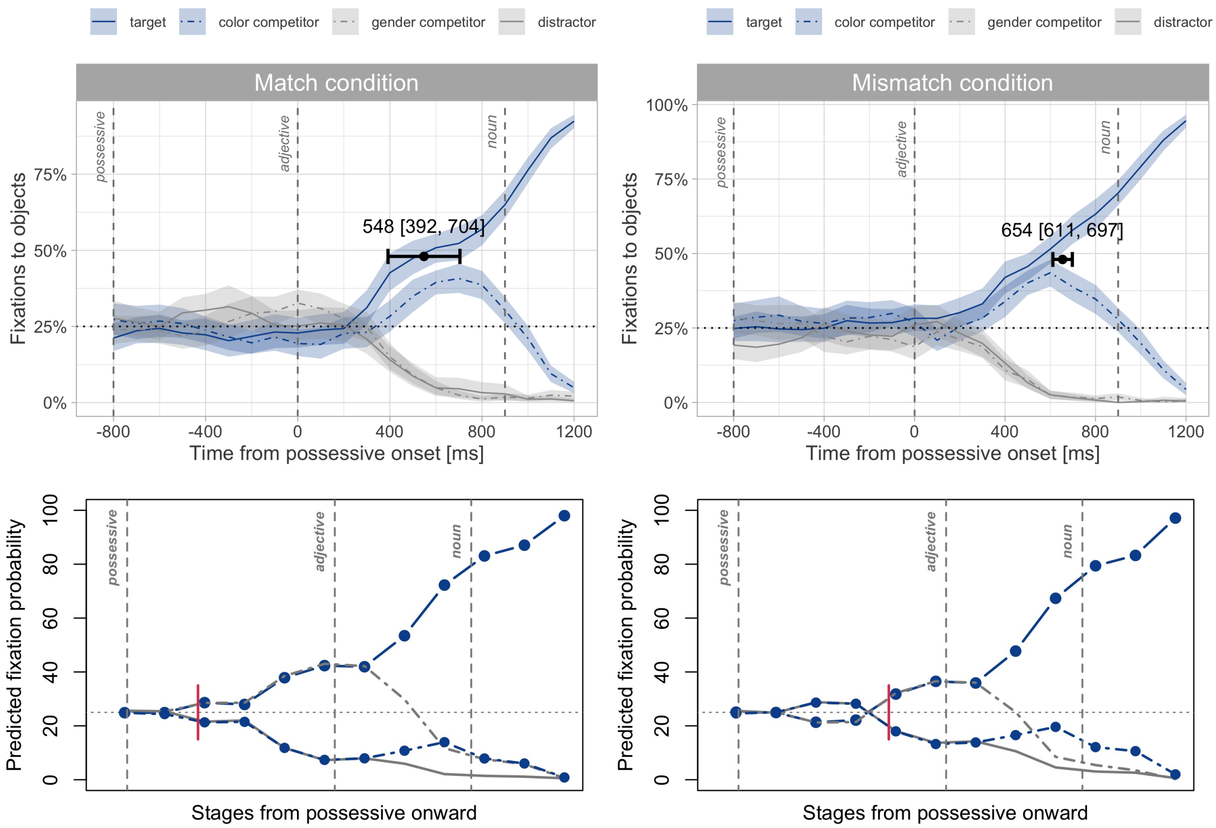

Figure 2: **Top row** (behavioral data): Fixation curves to the four objects averaged across items and participants in Experiment 1. The predictive window extended from the onset of the adjective to the onset of the noun, shifted 200 ms to the right. The x-axis is time-locked to the adjective. Estimated predictive onsets and their 95% credible intervals are overlaid on the fixation curves in each condition. **Bottom row** (model): Predictions of the model for fixation probabilities to the target (the button), the color competitor (the bottle), the gender competitor (the balloon) and the distractor object (the flower). Red bars denote the predicted divergence points between the curve for the target and the color competitor.

pirical data, in which fixations to the gender competitor were very infrequent and patterned with the fixations to the distractor object. Moreover, the magnitude of the prediction advantage (between the target and the color competitor) predicted by the model was higher than in the data. The model predicted a prediction advantage of 400 ms, however, in the data it was only 106 [-56, 268] ms. We discuss these issues in the general discussion.

General discussion

This paper reports two modeling experiments that test the hypothesis that the prediction advantage observed in Stone et al. (2021) is due to similarity-based interference during the antecedent retrieval of a possessive pronoun. Stone et al. (2021) reported two dual-task experiments involving sentence processing in the visual world paradigm. Participants listened to German sentences with possessive pronouns and were asked to select an appropriate object on a screen. German possessive pronouns have a bi-directional pattern of gender agreement: their stem encodes agreement with a previously mentioned antecedent but their suffix encodes agreement with a following possessum. Stone et al. (2021) found that participants predicted the target object faster when the possessum and possessor matched in gender (MATCH condition) than when they mismatched (MISMATCH condition).

We hypothesized that the prediction advantage in the MATCH condition was due to the interaction between the antecedent retrieval and the possessum prediction at the pronoun. We tested this hypothesis by modeling the dual-task from Stone et al. (2021). The model is an extension of the cue-based retrieval model of sentence processing in ACT-R. The model captures the key effect of the prediction advantage in MATCH condition in both the experiments. The prediction advantage arises due to retrieval interference during antecedent retrieval at the possessive pronoun — the overlap of the gender feature between the antecedent and the possessum boosts the activation level of the possessum which later helps in predicting it faster.

Stone et al. (2021) also observed that the prediction advantage is smaller and happens at a later stage when the visual scene contains two extra objects, a gender competitor and a distractor object as in Experiment 1. The model only partially captures this effect — it captures the prediction advantage effect between the target and color competitor, but not between the target and the gender competitor. The model uses all the information present in the input immediately but sequentially to predict the target: first, the gender information encoded in the suffix of the possessive pronoun to rule out the color competitor, and then, the color information encoded in the adjective to rule out the gender competitor. By contrast, in Experiment 1, participants seem to delay the prediction decision until after they have heard the adjective. We acknowledge that this is a limitation of the model and needs to be investigated further. One possible way to improve the predictions of the model for Experiment 1 could be using different combinations of weights for linguistic and visual cues. However, since the size of the data in Experiment 1 was substantially smaller than in Experiment 2, we also consider that the process of adjusting parameters should be deferred until the effects in Experiment 1 are replicated using a larger sample size.

By modeling the prediction advantage in Stone et al. (2021) data, we have also created a preliminary working model of: (1) prediction in terms of retrieval, and, (2) how psycholinguistic processes might influence visual attention. This is supported by the effect that the model captures across the MATCH and MISMATCH conditions: the prediction of the target object before hearing its name. Since this effect emerged due to interactions between linguistic, visual and predictive processing, we suggest that our model is a good starting point for implementing a full-fledged model of sentence processing in the visual world paradigm. A next step towards such a full-fledged model would be to combine our model with a model that can relate higher level cognitive processes with lower-level eye movement processes and visual search, such as EMMA (Salvucci, 2001) which is an extension of ACT-R's vision module. Such an extension should also be useful for studying how the visual system could influence declarative memory and, in effect, language processing.

It has been proposed that prediction can be conceived of as a memory retrieval, but without any implemented model of this proposal (Chow, Momma, Smith, Lau, & Phillips, 2016). The current model fills this gap by demonstrating that prediction and memory retrieval do not have to be thought of as two separate or encapsulated cognitive processes. If this were the case, then interference at retrieval should not have affected prediction speed. Instead, our results show that prediction and retrieval processes interact in comprehension, either because they act on the same memory representations, or because they draw from a shared set of resources. Our model captures the prediction effect without having to posit any special prediction mechanism.

Our model converges with psycholinguistic accounts that view prediction as a memory retrieval problem, in which the linguistic and non-linguistic context are used to access representations in working memory, with the goal of inferring which words are likely to come next (Chow et al., 2016). In this account, previously encountered words and predicted words are held in the same working memory space, with their activation levels being modulated by factors such as recency and frequency of use. Within the larger framework of cognitive science, such an account is more compatible with unified models of memory (e.g., Cowan, 1988; McElree, 2000; Oberauer, 2002) than with multistore models (e.g., Baddeley, 2000) or models that posit a specialized memory system for the storage of predictions ("prospective memory", e.g., Zogg et al., 2012).

Funding information & data

Umesh Patil and Sol Lago were supported by the German Research Foundation (project numbers 248411105 and 317308350, respectively). The model code and supplementary files are available at: `https://osf.io/fsbzw/`

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