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Modelling dependency completion in sentence comprehension as a Bayesian hierarchical mixture process: A case study involving Chinese relative clauses

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Abstract

We present a case-study demonstrating the usefulness of Bayesian hierarchical mixture modelling for investigating cognitive processes. In sentence comprehension, it is widely assumed that the distance between linguistic co-dependents affects the latency of dependency resolution: the longer the distance, the longer the retrieval time (the distance-based account). An alternative theory, direct-access, assumes that retrieval times are a mixture of two distributions: one distribution represents successful retrievals (these are independent of dependency distance) and the other represents an initial failure to retrieve the correct dependent, followed by a reanalysis that leads to successful retrieval. We implement both models as Bayesian hierarchical models and show that the direct-access model explains Chinese relative clause reading time data better than the distance account.

Keywords: Bayesian Hierarchical Finite Mixture Models; Psycholinguistics; Sentence Comprehension; Chinese Relative Clauses; Direct-Access Model; K-fold Cross-Validation

Introduction

Bayesian cognitive modelling (Lee & Wagenmakers, 2014), using probabilistic programming languages like JAGS (Plummer, 2012), is an important tool in cognitive science. We present a case study from sentence processing research showing how hierarchical mixture models can be profitably used to develop probabilistic models of cognitive processes. Although the case study concerns a specialized topic in psycholinguistics, the approach developed here will be of general interest to the cognitive science community.

In sentence comprehension research, dependency completion is assumed by many theories to be a key event. For example, consider a sentence such as (1):

- (1) a. The man (on the bench) was sleeping

In order to understand who was doing what, the noun *The man* must be recognized to be the subject of the verb phrase *was sleeping*; this dependency is represented here as a directed arrow. One well-known proposal (Just & Carpenter, 1992), which we will call the *distance account*, is that dependency distance between linguistically related elements partly

determines comprehension difficulty as measured by reading times or question-response accuracy. For example, the Dependency Locality Theory (DLT) by Gibson (2000) and the cue-based retrieval account of Lewis and Vasishth (2005) both assume that the longer the distance between two co-dependents such as a subject and a verb, the greater the retrieval difficulty at the moment of dependency completion. As shown in (1), the distance between co-dependents can increase if a phrase intervenes.

As another example, consider the self-paced reading study in Gibson and Wu (2013) in Chinese subject and object relative clauses. The dependent variable here was the reading time at the head noun (*official*). As shown in (2), the distance between the head noun and the gap it is coindexed with is larger in subject relatives compared to object relatives.¹ Thus, the distance account predicts an object relative advantage. For simplicity, we operationalize distance here as the number of words intervening between the gap inside the relative clause and the head noun. In the DLT, distance is operationalized as the number of (new) discourse referents intervening between two co-dependents; and in the cue-based retrieval model, distance is operationalized in terms of decay in working memory (i.e., time passing by).

- (2) a. Subject relative

[GAP_i yaoqing fuhao de] guanyuan_i

GAP invite tycoon DE official
xinhuaibugui

have bad intentions

‘The official who invited the tycoon has bad intentions.

- b. Object relative

¹The dependency could be equally well be between the relative clause verb and the head noun; nothing hinges on assuming a gap-head noun dependency.

[fuhao yaoqing GAP_i de] guanyuan_i
 tycoon invite GAP DE official
 xinhuaibugui
 have bad intentions
 ‘The official who the tycoon invited has bad intentions.

In the Gibson and Wu study, reading times were recorded using self-paced reading in the two conditions, with 37 subjects and 15 items, presented in a standard Latin square design. The experiment originally had 16 items, but one item was removed in the published analysis due to a mistake in the item. We coded subject relatives as $-1/2$, and object relatives as $+1/2$; this implies that an overall object relative advantage would show a negative coefficient. In other words, an object relative advantage corresponds to a negative sign on the estimate.

The distance account’s predictions can be evaluated by fitting the hierarchical linear model shown in (1). Assume that (i) i indexes participants, $i = 1, \dots, I$ and j indexes items, $j = 1, \dots, J$; (ii) y_{ij} is the reading time in milliseconds for the i -th participant reading the j -th item; and (iii) the predictor X is sum-coded ($\pm 1/2$), as explained above. Then, the data y_{ij} (reading times in milliseconds) are defined to be generated by the following model:

$$y_{ij} = \beta_0 + \beta_1 X_{ij} + u_i + w_j + \varepsilon_{ij} \quad (1)$$

where $u_i \sim Normal(0, \sigma_u^2)$, $w_j \sim Normal(0, \sigma_w^2)$ and $\varepsilon_{ij} \sim Normal(0, \sigma_e^2)$; all three sources of variance are assumed to be independent. The terms u_i and w_j are called varying intercepts for participants and items respectively; they represent by-subject and by-item adjustments to the fixed-effect intercept β_0 . Their variances, σ_u^2 and σ_w^2 represent between-participant (respectively item) variance.

This model is effectively a statement about the generative process that produced the data. If the distance account is correct, we would expect to find evidence that the slope β_1 is negative; specifically, reading times for object relatives are expected to be shorter than those for subject relatives. As shown in Table 1, this prediction appears, at first sight, to be borne out. Subject relatives are estimated to be read 120 ms slower than object relatives, apparently consistent with the predictions of the distance account.

	Estimate	Std. Error	t value
$\hat{\beta}_0$	548.43	51.56	10.64*
$\hat{\beta}_1$	-120.39	48.01	-2.51*

Table 1: A linear mixed model using raw reading times in milliseconds as dependent variable, corresponding to the reported results in Gibson and Wu 2013. Statistical significance is shown by an asterisk.

The object relative advantage shown in Table 1 was origi-

nally presented in Gibson and Wu (2013) as a repeated measures ANOVA.

To summarize, the conclusion from the above result would be that in Chinese, subject relatives are harder to process than object relatives because the gap inside the relative clause is more distant from the head noun in subject vs. object relatives. This makes it more difficult to complete the gap-head noun dependency in subject relatives. This distance-based explanation of processing difficulty is plausible given the considerable independent evidence from languages such as English, German, Hindi, Persian and Russian that dependency distance can affect reading time (see review in Safavi, Husain, and Vasishth (2016)).

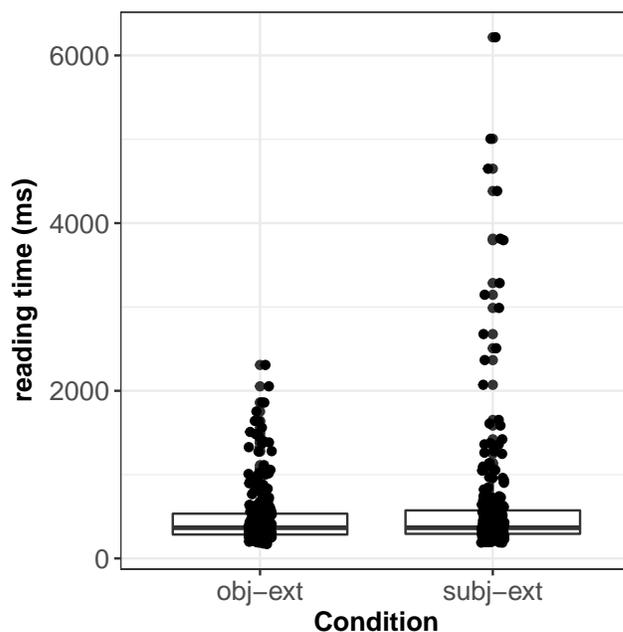


Figure 1: Boxplots showing the distribution of reading times by condition of the Gibson and Wu (2013) data.

However, the distributions of the reading times for the two conditions show an interesting asymmetry that cannot be straightforwardly explained by the distance account. At the head noun, the reading times in subject relatives are much more spread out than in object relatives. This is shown in Figure 1, where reading times are shown on the log scale. Although this spread was ignored in the original analysis, a standard response to heterogeneous variances (heteroscedasticity) is to delete “outliers” based on some criterion; a common criterion is to delete all data lying beyond $\pm 2.5SD$ in each condition.² This procedure assumes that the data points identified as extreme are irrelevant to the question being investigated. An alternative approach is to not delete data but to downweight the extreme values by applying a variance stabilizing transform (Box & Cox, 1964). Taking a log-transform

²In the published paper, Gibson and Wu (2013) did not delete any data, leading to the results shown in Table 1.

of the reading time data, or a reciprocal transform, can reduce the heterogeneity in variance; see Vasishth, Chen, Li, and Guo (2013) for analyses of the Gibson and Wu data using a transformation.

One might think that if subject and object relatives are generated by LogNormal distributions with different means, then modelling the data as being generated by LogNormals would adequately explain the data. Table 2 shows that if we assume such a model, there is no longer a statistically significant object relative advantage: the absolute t-value for the estimate of the β_1 parameter is smaller than the critical value of 2 (Bates, Maechler, Bolker, & Walker, 2015). Thus, assuming that the data are generated by LogNormal distributions with different means for the subject and object relatives leads to the conclusion that there isn't much evidence for the distance account.

	Estimate	Std. Error	t value
$\hat{\beta}_0$	6.06	0.07	92.64*
$\hat{\beta}_1$	-0.07	0.04	-1.61

Table 2: A linear mixed model using log reading times in milliseconds as dependent variable in the Gibson and Wu, 2013, data.

Consider next the possibility that the heteroscedasticity in subject and object relatives in the Gibson and Wu data reflects a systematic difference in the underlying generative processes of reading times in the two relative clause types. We investigate this question by modelling the extreme values as being generated from a mixture distribution.

Using the probabilistic programming language Stan (Stan Development Team, 2016), we show that a hierarchical mixture model provides a better fit to the data (in terms of predictive accuracy) than several simpler hierarchical models. As Nicenboim and Vasishth (2017) pointed out, the underlying generative process implied by a mixture model is consistent with the direct-access model of McElree, Foraker, and Dyer (2003). We therefore suggest that, at least for the Chinese relative clause data considered here, the direct-access model may be a better way to characterize the dependency resolution process than the distance account.

We can implement the direct-access model as a hierarchical mixture model with retrieval time assumed to be generated from one of two distributions, where the proportion of trials in which a retrieval failure occurs (the mixing proportion) is p_{sr} in subject relatives, and p_{or} in object relatives. The expectation here is the extreme values that are seen in subject relatives are due to p_{sr} being larger than p_{or} .

Subject relatives

$$y_{ij} \sim p_{sr} \cdot \text{LogNormal}(\beta + \delta + u_i + w_j, \sigma_e^2) + (1 - p_{sr}) \cdot \text{LogNormal}(\beta + u_i + w_j, \sigma_e^2) \quad (2)$$

Object relatives

$$y_{ij} \sim p_{or} \cdot \text{LogNormal}(\beta + \delta + u_i + w_j, \sigma_e^2) + (1 - p_{or}) \cdot \text{LogNormal}(\beta + u_i + w_j, \sigma_e^2)$$

Here, the terms u_i and w_j have the same interpretation as in equation 1.

Model comparison

Bayesian model comparison can be carried out using different methods. Here, we use Bayesian k-fold cross-validation as discussed in Vehtari, Gelman, and Gabry (2016). This method evaluates the predictive performance of alternative models, and models with different numbers of parameters can be compared (Vehtari, Ojanen, et al., 2012; Gelman, Hwang, & Vehtari, 2014).

The k-fold cross-validation algorithm is as follows:

1. Split data pseudo-randomly into K held-out sets $\mathbf{y}_{(k)}$, where $k = 1, \dots, K$ that are a fraction of the original data, and K training sets, $\mathbf{y}_{(-k)}$. Here, we use $K = 10$, and the length of the held-out data-vector $\mathbf{y}_{(k)}$ is approximately $1/K$ -th the size of the full data-set. We ensure that each participant's data appears in the training set and contains an approximately balanced number of data points for each condition.
2. Sample from the model using each of the K training sets, and obtain posterior distributions $p_{\text{post}(-k)}(\theta) = p(\theta | \mathbf{y}_{(-k)})$, where θ is the vector of model parameters.
3. Each posterior distribution $p(\theta | \mathbf{y}_{(-k)})$ is used to compute predictive accuracy for each held-out data-point y_i :

$$\log p(y_i | \mathbf{y}_{(-k)}) = \log \int p(y_i | \theta) p(\theta | \mathbf{y}_{(-k)}) d\theta \quad (3)$$

4. Given that the posterior distribution $p(\theta | \mathbf{y}_{(-k)})$ is summarized by $s = 1, \dots, S$ simulations, i.e., $\theta^{k,s}$, log predictive density for each data point y_i in subset k is computed as

$$\widehat{\text{elpd}}_i = \log \left(\frac{1}{S} \sum_{s=1}^S p(y_i | \theta^{k,s}) \right) \quad (4)$$

5. Given that all the held-out data in the K subsets are y_i , where $i = 1, \dots, n$, we obtain the $\widehat{\text{elpd}}$ for all the held-out data points by summing up the $\widehat{\text{elpd}}_i$:

$$\widehat{\text{elpd}} = \sum_{i=1}^n \widehat{\text{elpd}}_i \quad (5)$$

The difference between the \widehat{elpd} 's of two competing models is a measure of relative predictive performance. We can also compute the standard deviation of the sampling distribution (the standard error) of the difference in \widehat{elpd} using the formula discussed in Vehtari et al. (2016). Letting \widehat{ELPD} be the vector $\widehat{elpd}_1, \dots, \widehat{elpd}_n$, we can write:

$$se(\widehat{elpd}_{m0} - \widehat{elpd}_{m1}) = \sqrt{n\text{Var}(\widehat{ELPD})} \quad (6)$$

When we compare the model (1) with (2), if (2) has a higher \widehat{elpd} , then it has a better predictive performance compared to (1).

The quantity \widehat{elpd} is a Bayesian alternative to the Akaike Information Criterion (Akaike, 1974). Note that the relative complexity of the models to be compared is not relevant: the sole criterion here is out-of-sample predictive performance. As we discuss below (Results section), increasing complexity will not automatically lead to better predictive performance. See Vehtari et al. (2012); Gelman, Hwang, and Vehtari (2014) for further details.³

The data

The evaluation of these models was carried out using two separate data-sets. The first was the original study from Gibson and Wu (2013) that was discussed in the introduction. The second study was a replication of the Gibson and Wu study that was published in Vasishth et al. (2013). This second study served the purpose of validating whether independent evidence can be found for the mixture model selected using the original Gibson and Wu data.

Results

In the models presented below, the dependent variable is reading time in milliseconds. Priors are defined for the model parameters as follows. All standard deviations are constrained to be greater than 0 and have priors Cauchy(0, 2.5) (Gelman, Carlin, et al., 2014); probabilities have priors Beta(1, 1); and all coefficients (β parameters) have priors Cauchy(0, 2.5).

Fake-data simulation for validating model

Before evaluating relative model fit, we first simulated data from a mixture distribution with known parameter values, and then sampled from the models representing the distance account and the direct-access model. The goal of fake-data simulation was to validate the models and the model comparison method: with reference to the simulated data, we asked (a) whether the 95% credible intervals of the posterior distributions of the parameters in the mixture model contain the true parameter values used to generate the data; and (b) whether k-fold cross validation can identify the mixture model as the correct one when the underlying generative process matches the mixture model.

³We also used a simpler method than k-fold cross-validation to compare the models; this method is described in Vehtari et al. (2016). The results are the same regardless of the model comparison method used.

The answer to both questions was “yes”. This raises our confidence that the models can identify the underlying parameters with real data. The fake-data simulation also showed that when the true underlying generative process was consistent with the distance account but not the direct access model, the hierarchical linear model and the mixture model had comparable predictive performance. In other words, the mixture model furnished a superior fit only when the true underlying generative process for the data was in fact a mixture process. Further details are omitted here due to lack of space.

The original Gibson and Wu study The estimates from the hierarchical linear model (equation 1) and the mixture model (equation 2) are shown in Tables 3 and 4. Note that in Bayesian modelling we are not interested in “statistical significance” here; rather, the goal is inference and comparing predictive performance of two competing models.

	mean	lower	upper
$\hat{\beta}_1$	6.06	5.91	6.20
$\hat{\beta}_2$	-0.07	-0.16	0.02
$\hat{\sigma}_e$	0.52	0.49	0.55
$\hat{\sigma}_u$	0.25	0.18	0.34
$\hat{\sigma}_w$	0.20	0.12	0.33

Table 3: Posterior parameter estimates from the hierarchical linear model (equation 1) corresponding to the distance account. The data are from Gibson and Wu, 2013. Shown are the mean and 95% credible intervals for each parameter.

	mean	lower	upper
$\hat{\beta}_0$	5.85	5.76	5.95
$\hat{\delta}$	0.93	0.73	1.14
$\hat{p}_{sr} - \hat{p}_{or}$	0.04	-0.04	0.13
\hat{p}_{sr}	0.25	0.17	0.34
\hat{p}_{or}	0.21	0.14	0.29
$\hat{\sigma}_{e'}$	0.64	0.54	0.74
$\hat{\sigma}_e$	0.22	0.20	0.25
$\hat{\sigma}_u$	0.24	0.18	0.31
$\hat{\sigma}_w$	0.09	0.05	0.16

Table 4: Posterior parameter estimates from the hierarchical mixture model (equation 2) corresponding to the direct-access model. The data are from Gibson and Wu, 2013. Shown are the mean and 95% credible intervals for each parameter.

Table 4 shows that the mean difference between the probability p_{sr} and p_{or} is 4%; the posterior probability of this difference being greater than zero is 82%. K-fold cross-validation shows that \widehat{elpd} for the hierarchical model is -3761 (SE: 38) and for the mixture model is -3614 (35). The difference between the two \widehat{elpds} is 148 (18). The larger \widehat{elpd} in the hierarchical mixture model suggests that it has better predictive performance than the hierarchical lin-

ear model. In other words, the direct-access model has better predictive performance than the distance model.

The replication of the Gibson and Wu study This dataset, originally reported by Vasishth et al. (2013), had 40 participants and the same 15 items as in Gibson and Wu’s data. Figure 2 shows the distribution of the data by condition; there seems to a similar skew as in the original study, although the spread is not as dramatic as in the original study.

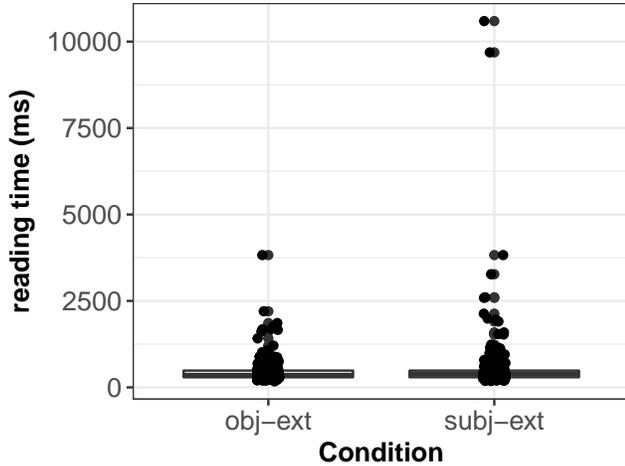


Figure 2: Boxplots showing the distribution of reading times by condition of the replication of the Gibson and Wu data.

Tables 5 and 6 show the estimates of the posterior distributions from the two models. Table 4 shows that the mean difference between the probability p_{sr} and p_{or} is 7%; the posterior probability of this difference being greater than zero is 96%.

The \widehat{elpd} for the hierarchical model is -3959 (53), and for the hierarchical mixture model, -3801 (38). The difference in \widehat{elpd} is 158 (29). Thus, in the replication data as well, the predictive performance of the mixture model is better than the hierarchical linear model.

	mean	lower	upper
$\hat{\beta}_0$	6.00	5.88	6.12
$\hat{\beta}_1$	-0.09	-0.16	-0.01
$\hat{\sigma}_e$	0.44	0.41	0.47
$\hat{\sigma}_u$	0.25	0.19	0.33
$\hat{\sigma}_w$	0.16	0.10	0.26

Table 5: Posterior parameter estimates from the hierarchical linear model (equation 1) corresponding to the distance account. The data are from the replication of Gibson and Wu, 2013 reported in Vasishth et al., 2013. Shown are the mean and 95% credible intervals for each parameter.

	mean	lower	upper
$\hat{\beta}_0$	5.86	5.78	5.95
$\hat{\delta}$	0.75	0.56	0.97
$\hat{p}_{sr} - \hat{p}_{or}$	0.07	-0.01	0.15
\hat{p}_{sr}	0.23	0.15	0.33
\hat{p}_{or}	0.16	0.09	0.25
$\hat{\sigma}_{e'}$	0.69	0.59	0.81
$\hat{\sigma}_e$	0.21	0.18	0.23
$\hat{\sigma}_u$	0.22	0.17	0.29
$\hat{\sigma}_w$	0.07	0.04	0.12

Table 6: Posterior parameter estimates from the hierarchical linear model (equation 2) corresponding to the direct-access model. The data are from the replication of Gibson and Wu, 2013 reported in Vasishth et al., 2013. Shown are the mean and 95% credible intervals for each parameter.

Discussion

The model comparison and parameter estimates presented above suggest that, at least as far as the Chinese relative clause data are concerned, a better way to characterize the dependency completion process is in terms of the direct-access model and not the distance account implied by Gibson and Wu (2013) and Lewis and Vasishth (2005). Specifically, there is suggestive evidence in the Gibson and Wu (2013) data that a higher proportion of retrieval failures occurred in subject relatives compared to object relatives. In other words, increased dependency distance may have the effect that it increases the proportion of retrieval failures (followed by re-analysis).⁴

There is one potential objection to the conclusion above. It would be important to obtain independent evidence as to which dependency was eventually created in each trial. This could be achieved by asking participants multiple-choice questions to find out which dependency they built in each trial. Although such data is not available for the present study, in other work (on number interference) (Nicenboim, Engelmann, Suckow, & Vasishth, 2016) did collect this information. There, too, we found that the direct-access model best explains the data (Nicenboim & Vasishth, 2017). In future work on Chinese relatives, it would be helpful to carry out a similar study to determine which dependency was completed in each trial. In the present work, the modelling at least shows how the extreme values in subject relatives can be accounted for by assuming a two-mixture process.

Conclusion

The mixture models suggest that, in the specific case of Chinese relative clauses, increased processing difficulty in subject relatives is not due to dependency distance leading to longer reading times, as suggested by Gibson and Wu (2013).

⁴A reviewer suggests that the direct-access model may simply be an elaboration of the distance model. This is by definition not the case: direct access (i.e., distance-independent access) is incompatible with the distance account.

Rather, a more plausible explanation for these data is in terms of the direct-access model of McElree et al. (2003). Under this view, retrieval times are not affected by the distance between co-dependents, but a higher proportion of retrieval failures occur in subject relatives compared to object relatives. This leads to a mixture distribution in both subject and object relatives, but the proportion of the failure distribution is higher in subject relatives.

In conclusion, this paper serves as a case study demonstrating the flexibility of Bayesian cognitive modelling using finite mixture models. This kind of modelling approach can be used flexibly in many different research problems in cognitive science. One example is the above-mentioned work by Nicenboim and Vasishth (2017). Another example, also from sentence comprehension, is the evidence for feature overwriting (Nairne, 1990) in parsing (Vasishth, Jäger, & Nicenboim, 2017).

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