Supplementary appendix to reviewers

Simulations of the feature percolation symmetry prediction

Feature percolation accounts of agreement attraction predict that ungrammatical sentences containing a plural attractor should sometimes be judged as grammatical, and that grammatical sentences containing a plural attractor should just as often be judged as ungrammatical. In this appendix we test whether this symmetric shift in the perception of grammaticality leads to a symmetric response in mean RTs. Response times have a characteristically positively-skewed distribution and, for this reason, one anonymous reviewer wondered whether the shape of these distributions might mean than underlyingly symmetric shifts in grammaticality would not be reflected by symmetric shifts in mean RTs. Analytically we did not expect this to be the case, as we note on page 31 of the manuscript. However, we also simulated the size and variability of the RT response to attraction in both grammatical and ungrammatical sentences by modeling participant RTs to agreement licensing at the single trial level. The results of 3 simulation scenarios are reported below which show that symmetric changes in the underlying distribution of grammaticality lead to symmetric shifts in the mean. We believe reporting these simulations goes beyond the scope of the current paper. However we wanted to report the outcomes of our attempt at addressing this concern.

We defined two random variables, **G**, corresponding to the distribution of RTs resulting from an individual's response to grammatical agreement; and **U**, corresponding to ungrammatical agreement. Both **G** and **U** were generated with ex-Gaussian density functions, a convolution of the normal and exponential density functions which accurately models RT distributions (Luce, 1986). Ex-Gaussian distributions have three parameters: μ, the normal mean; σ, the normal variance; and τ, the exponential mean. The mean of the ex-Gaussian is simply $\mu + \tau$; and its variance $\sigma^2 + \tau^2$. A population of fifty-six participants was created whose parameters μ, σ, τ were drawn from a normal distribution, constrained in particular ways in each of the three simulation scenarios below. For each participant, 24 experimental trials were simulated, corresponding to six trials for each of the four conditions in our Experiment 4: Sg attractor, Grammatical and Ungrammatical; Pl attractor, Grammatical and Ungrammatical. For trials involving a singular attractor, the RT for a single trial was drawn from that participant's **G**, if agreement was grammatical, or **U**, if it was ungrammatical. For trials involving a plural attractor, **G** and **U** were sampled at the rate of percolation, p. For grammatical trials, RTs were drawn from **U** p% of the time; for ungrammatical trials, RTs were drawn from **G** $p\%$ of the time.

Because the parameter space for this simulation was so large, we had to restrict our consideration to three scenarios which we considered most germane to the prediction of symmetry. In simulation one, the population parameters are estimated from actual experimental data, and a range of percolation rates is considered. In simulation two, percolation rate is held constant, and the mean parameters are manipulated to assess the effect of concentrating the grammaticality effect in the tail of the distribution. In simulation three, low percolation rates are examined. For each simulation scenario, 100 experimental runs were generated (with a new population of participants each time). The mean and standard deviation over the difference between attractor conditions is summarized below.

<u>Simulation 1</u> In simulation one, population parameters for **G** and **U** were estimated from RT data collected in Experiment 5, Region 7. An ex-Gaussian function was fit to both the singular-attractor, grammatical aggregate data, to estimate the population mean of **G**; and the singular-attractor ungrammatical aggregate data, to estimate the population mean of **U**. Variation in the population parameters was set at 20 ms standard deviation for $\boldsymbol{\mu}$ and $\boldsymbol{\tau}$ and 10 ms for $\boldsymbol{\sigma}$. It would have been desirable to estimate distribution parameters for each participant, and thus empirically estimate both the location and the shape of the parameter distributions. Unfortunately, the number of trials collected per experimental condition in our experiment (6) and in most sentence processing experiments we are aware of are simply too few to collect robust estimates.

Five percolation rates (*p*) were considered, from 0.10 to 1.0. Table I reports the mean RTs for Sg attractor conditions (reported once, as they do not change with percolation rate), and then the differences between those conditions and the attractor conditions for each of the percolation rates. The results are clear: the mean RT for Pl attractor grammatical condition shifts 1:1 with the mean RT for Pl attractor ungrammatical conditions. The size of this shift corresponds to approximately *p* times the difference in means between **G** and **U**. Note that the distribution of ungrammatical mean differences does show greater variability. This is expected since variation in **U** is proportional to $\boldsymbol{\tau}^2$ and correspondingly the difference between variability in grammatical and ungrammatical effects depends on the number of observations drawn from **U** (i.e., *p* for grammatical comparisons, and (1-*p*) for ungrammatical ones).

Based on this simulation (and the estimates of Pearlmutter, Garnsey, & Bock, 1999), the percolation rate would have to be larger in comprehension than in production, to account for the size of the mean RT shifts observed in our experiments 4 and 5.

<table>
<tr><td rowspan="2"><u>Simulation 1</u>
Parameters estimated from Experiment 5, Region 7, group distributions

Experimental runs: 100</td><td colspan="5">Mean simulation parameters (s.d. in parentheses)
per run: 56 participants, 6 trials/per condition</td></tr>
<tr><td colspan="3">Grammatical RT
μ: 218 ms (20 ms)
σ: 47 ms (10 ms)
τ: 96 ms (20 ms)</td><td colspan="2">Ungrammatical RT
μ: 181 ms (20 ms)
σ: 21 ms (10 ms)
τ: 229 ms (20 ms)</td></tr>
<tr><td colspan="6">Basic grammaticality effect
[Sg Sg] Grammatical: 314 ± 6 ms
[Sg Sg] Ungrammatical: 410 ± 14 ms</td></tr>
<tr><td rowspan="2">Attraction effects</td><td colspan="5">Percolation rate (p)</td></tr>
<tr><td>0.10</td><td>0.25</td><td>0.5</td><td>0.75</td><td>1.0</td></tr>
<tr><td>Grammatical:
[Sg Pl]-[Sg Sg]</td><td>11 ms
± 10 ms</td><td>25 ms
± 13 ms</td><td>49 ms
± 14 ms</td><td>72 ms
± 15 ms</td><td>99 ms
± 15 ms</td></tr>
<tr><td>Ungrammatical:
[Sg Sg]-[Sg Pl]</td><td>8 ms
± 22 ms</td><td>24 ms
± 19 ms</td><td>50 ms
± 19 ms</td><td>72 ms
± 17 ms</td><td>96 ms
± 15 ms</td></tr>
</table>

Table I **Effect of different percolation proportions on mean RT differences**
RT distribution parameters estimated from the experimental group distributions: Experiment 5, Region 7, singular attractor conditions. The standard deviation of simulation means is reported.

<u>Simulation 2</u> The overall mean of an ex-Gaussian distribution depends on the means of its generating distributions, the normal and exponential means. In this simulation, we held the mean difference between **G** and **U** constant, but investigated the trade-off between locating that difference entirely in the $\boldsymbol{\tau}$ parameter, or in the $\boldsymbol{\mu}$ parameter. $\boldsymbol{\mu}_{\mathbf{Gram}}$, $\boldsymbol{\tau}_{\mathbf{Gram}}$, $\boldsymbol{\sigma}$ and *p* were held constant. $\mathbf{(\Delta\mu + \Delta\tau)}$, the difference between **G** and **U** parameters, was constrained to 75 ms, thus holding the basic grammaticality effect constant.

The results are reported in Table II. As in simulation 1, the mean RT difference in both grammatical and ungrammatical attractor conditions is nearly identical, and does not depend on the size of $\mathbf{\Delta\tau}$**.** Across the board the effect is approximately $p \bullet \mathbf{(\Delta\mu + \Delta\tau)}$ (= 18.75 ms). For higher $\mathbf{\Delta\tau}$, slightly more variability is observed in ungrammatical comparisons.

<u>Simulation 2</u> Grammaticality effect constrained to be 75 ms *Experimental runs:* 100	**Mean simulation parameters** (s.d. in parentheses) *per run:* 56 participants, 6 trials/per condition $\mathbf{(\Delta\mu + \Delta\tau)}$ = 75 ms; $\boldsymbol{\mu}_{\mathbf{Gram}}$**:** 200 ms (20 ms)**;** $\boldsymbol{\mu}_{\mathbf{Ungram}}$**:** $\boldsymbol{\mu}_{\mathbf{Gram}} + \mathbf{\Delta\mu}$ $\boldsymbol{\tau}_{\mathbf{Gram}}$**:** 50 ms (20 ms); $\boldsymbol{\tau}_{\mathbf{Gram}}$**:** $\boldsymbol{\tau}_{\mathbf{Gram}} + \mathbf{\Delta\tau}$ $\boldsymbol{\sigma}$**:** 35 ms (10 ms) Percolation rate constant: 0.25					
Basic grammaticality effect [Sg Sg] Grammatical: 250 ms ± 3 ms [Sg Sg] Ungrammatical: 326 ± (3-6) ms (higher s.d.s observed for higher $\boldsymbol{\tau}$)						
Attraction effects	$\mathbf{\Delta\tau}$					
	75 ms	60 ms	45 ms	30 ms	15 ms	0 ms
Grammatical: [Sg Pl]-[Sg Sg]	19 ms ± 6 ms	20 ms ± 6 ms	20 ms ± 6 ms	17 ms ± 5 ms	18 ms ± 5 ms	19 ms ± 4 ms
Ungrammatical: [Sg Sg]-[Sg Pl]	19 ms ± 10 ms	19 ms ± 10 ms	18 ms ± 7 ms	18 ms ± 6 ms	19 ms ± 7 ms	18 ms ± 5 ms

Table II **Effect of the RT distribution tail parameter on mean RT differences**
The size of the grammaticality effect is held constant at 75 ms by constraining the parameters the μ and τ parameters. Higher $\mathbf{\Delta\tau}$s correspond to scenarios in which most of the difference between ungrammatical and ungrammatical distributions in borne by the tail. The standard deviation of simulation means is reported.

It is hard to say what the real balance between Δτ and Δμ might be in the population. A conclusion cannot be drawn from the group distributions. We subsequently examined the Experiment 1 data, in which more trials were collected per condition and consequently more stable parameter fits could be done on a per-subject basis. There we found great variability in whether ungrammatical conditions led to shifts in μ, τ, or both. It therefore seems reasonable to suppose that, at the individual level, **G** and **U** may differ in both parameters and that ungrammatical responses are not confined entirely to the tail.

Simulation 3 The previous two simulations revealed that ungrammatical attraction effects are the same in size to grammatical attraction effects. For low percolation rates, or high $\Delta\tau$, there is greater variability in the ungrammatical effect size. In this final simulation, we consider only low percolation rates ($p \leq 0.25$) to better assess the difference in variability. μ and σ are held constant: the difference between **G** and **U** is modeled entirely as a difference in τ, which is set here at 75 ms.

Table III reports the results. As is expected, the mean differences between grammatical and ungrammatical conditions are virtually identical. For $p \leq 0.10$, variability of in the population mean for ungrammatical comparisons is roughly 3 times higher than for grammatical comparisons; the ratio drops to 2 for $0.10 \leq p \leq 0.25$.

<table>
<tr><td colspan="2">Simulation 3
Tail-shift only, low mixing proportions

Experimental runs: 100</td><td colspan="5">Mean simulation parameters (s.d. in parentheses)
per experimental run: 56 participants, 6 trials/per condition
μ: 200 ms (20 ms)
τ_{Gram}: = 50 ms (20 ms); τ_{Ungram}: = 125 ms (20 ms)
σ: 35 ms (10 ms)</td></tr>
<tr><td colspan="7">Basic grammaticality effect
[Sg Sg] Grammatical: 250 ms ± 3 ms
[Sg Sg] Ungrammatical: 325 ± 7 ms</td></tr>
<tr><td rowspan="2">Attraction effects</td><td colspan="6">Percolation rate</td></tr>
<tr><td>0</td><td>0.05</td><td>0.10</td><td>0.15</td><td>0.20</td><td>0.25</td></tr>
<tr><td>Grammatical:
[Sg Pl]-[Sg Sg]</td><td>0 ms
± 4 ms</td><td>8 ms
± 6 ms</td><td>14 ms
± 6 ms</td><td>10 ms
± 6 ms</td><td>14 ms
± 5 ms</td><td>18 ms
± 6 ms</td></tr>
<tr><td>Ungrammatical:
[Sg Sg]-[Sg Pl]</td><td>-1 ms
± 11 ms</td><td>6 ms
± 18 ms</td><td>16 ms
± 18 ms</td><td>10 ms
± 11 ms</td><td>15 ms
± 10 ms</td><td>18 ms
± 10 ms</td></tr>
</table>

Table III Effect of low percolation proportions on mean RT differences

The relationship between percolation proportion and mean RT differences is simulated. The difference between grammatical and ungrammatical distributions is borne entirely by the tail of the distribution. The standard deviation of simulation means is reported.

Summary The results of the three simulations reported show that, despite the positive skew in RT distributions, an underlying symmetric shift in distributions of grammaticality leads to a symmetric shift in mean RTs. Therefore, the prediction of symmetric RT shifts in the self-paced reading experiments in our study defines a fair test of feature percolation accounts.

For low values of p or high values of $\Delta\tau$, we did find greater variability in the ungrammatical comparisons. This raises the possibility that finding an asymmetry would be not be inconsistent with the feature percolation account (in the sense that, the wider the distribution of effect sizes, the more likely they will be discrepant). However it is important to note three things: First, it is as likely we would observe smaller effects for ungrammatical comparisons, as for larger ones. Secondly, the lower variability in the grammatical effect sizes leads us to have more confidence in expecting a non-null result for grammatical comparisons than for ungrammatical ones. Thirdly, the size of the actual ungrammatical attractor effects we observe in Experiments 2-5 and 7 suggests that the percolation rate cannot be very low.