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Response time distributional evidence for distinct varieties of number attraction

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ABSTRACT

Speakers are known to make subject–verb agreement errors both when a number-mismatching noun intervenes between the head of the subject phrase and the verb (e.g., **The key to the cabinets are on the table*) and in configurations in which there is a number-mismatching noun that does not intervene (e.g., **The cabinets that the key open are on the second floor*). Using a two-choice response time (RT) paradigm, Staub (2009) found that correct agreement decisions were also slowed in both cases. The present article reports a new experiment designed to explore whether these two RT effects are qualitatively similar or different. Fitting of the ex-Gaussian distribution (Ratcliff, 1979) to individual subjects' RT data, in each condition, demonstrated that the effect of an intervening number attractor on correct RT is due to both a shifting of the distribution to the right and to increased skewing, while the effect of a non-intervening attractor is almost entirely a skewing effect. A non-parametric vincentizing procedure supported these conclusions. These findings are taken to support the view that these two types of number attraction involve distinct processing mechanisms.

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1. Introduction

Speakers frequently make subject–verb agreement errors when a noun intervenes between the agreement controller and the verb, and this intervening noun has a different number from the agreement controller, as in example (1a) (Bock & Miller, 1991). This phenomenon, known as *number attraction*, is well-established in a range of languages (e.g., Hartsuiker, Schriefers, Bock, & Kikstra, 2003; Vigliocco, Butterworth, & Semenza, 1995; Vigliocco, Hartsuiker, Jarema, & Kolk, 1996), and has an analogue in comprehension, as subject–verb agreement violations are less salient in the presence of an intervening number attractor (e.g., Nicol, Forster, & Veres, 1997; Pearlmutter, Garnsey, & Bock, 1999; Wagers, Lau, & Phillips, 2009). Interestingly, speakers also make number agreement errors when producing a verb within a relative clause, if the matrix subject differs in number from the relative clause subject, as in (1b) (Bock & Miller, 1991; Franck, Lassi, Frauenfelder, & Rizzi, 2006; cf. Kimball & Aissen, 1971). It has recently been shown that there is a comprehension analogue of this effect, as well (Wagers et al., 2009).

1a **The key to the cabinets are on the table.*
1b **The cabinets that the key open are on the second floor.*

The question addressed here is how similar these two phenomena (hereafter referred to as *intervening* and *non-intervening* attraction) actually are. Theoretical accounts that unify these two types of attraction have been articulated, in different ways, by Franck et al. (2006) and by Wagers et al. (2009). Franck et al. propose that a number attractor has its influence on the computation of agreement at the level of an underlying syntactic representation, rather than at the level of surface structure (see also Vigliocco & Nicol, 1998), they suggest that a non-intervening attractor does intervene at the relevant level. Wagers

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et al. suggest that both intervening and non-intervening attraction arise from a memory retrieval process that occasionally identifies the incorrect noun as the head of the subject phrase, and that an intervening and non-intervening attractor are both visible to this retrieval mechanism. On the other hand, Bock and Miller (1991), and more recently, Eberhard, Cutting, and Bock (2005), have proposed that the two types of attraction may have genuinely distinct causes. They suggest that while intervening attraction results from a spreading activation process by which the attractor's number feature modulates the number information associated with the subject phrase, non-intervening attraction results from occasional confusion about which noun is the relative clause subject and which is the matrix subject, perhaps due to the complexity of the object relative clause structure. Bock and Miller (1991) pointed out that when their participants made errors in the non-intervening configuration, the actual content of their errors was consistent with such confusion, and overlap of semantic features between the two critical nouns exacerbated the effect. Eberhard et al. (2005, p. 555) suggested that this phenomenon, which they called "predication confusion," can "mimic" ordinary attraction, but is likely to arise under cognitively taxing circumstances, as when an experimental task is especially difficult.

In a recent article, Staub (2009) reported response time (RT) data suggesting important differences between the two types of attraction. Participants made a speeded choice between singular and plural verb forms (e.g., IS/ARE) after reading a subject phrase presented in rapid serial visual presentation (RSVP) format; the task was simply to select the grammatical sentence continuation. The presence of an intervening number attractor reliably induced errors and reliably slowed correct responses. Across several experiments these two effects were tightly coupled, with more slowing of correct responses in conditions that also induced more errors. However, in an experiment comparing intervening and non-intervening attraction, a non-intervening attractor induced almost as many errors as an intervening attractor (a nonsignificant difference of 17% vs. 20%), but significantly less slowing of correct responses (49 ms RT penalty vs. 125 ms penalty). In addition, error responses were significantly slower than correct responses only when the attractor was of the non-intervening variety. On the basis of these RT patterns, Staub suggested that while an intervening attractor has a general effect on the difficulty of agreement computation, a non-intervening attractor has an effect on only a subset of trials, which are disproportionately trials that result in error responses.

The present article reports an experiment designed to test additional RT predictions of an account according to which only intervening attraction results in general difficulty, while non-intervening attraction has a more sporadic effect. This hypothesis predicts that not only should the effect of a non-intervening attractor on correct RT be smaller than the effect of an intervening attractor (as reported by Staub (2009)), the two RT effects should also be qualitatively different. The effect of an intervening attractor on correct RT should be an effect on most or all trials. In distributional terms, this pattern would be manifested in a shift of the entire RT distribution to the right. On the other hand, the effect of a non-intervening attractor on correct RT should reflect a substantial RT penalty on a subset of trials, with little or no penalty on other trials. In distributional terms, this would take the form of increased skewing.

To test these predictions, new data were collected using the paradigm employed by Staub (2009), and these data were analyzed by fitting the ex-Gaussian distribution (Ratcliff, 1979) to each individual subject's data, in each experimental condition. A sizable literature has used the ex-Gaussian distribution to explore effects of various experimental manipulations on visual word recognition (Andrews & Heathcote, 2001; Balota & Spieler, 1999; Balota, Yap, Cortese, & Watson, 2008; Plourde & Besner, 1997; Staub, White, Drieghe, Hollway, & Rayner, in press; Yap & Balota, 2007; Yap, Balota, Cortese, & Watson, 2006; Yap, Balota, Tse, & Besner, 2008) and on selective attention and inhibitory control (Heathcote, Popiel, & Mewhort, 1991; Spieler, Balota, & Faust, 1996, 2000). The ex-Gaussian is the convolution of a normal distribution with parameters (μ, σ) and an exponential distribution with single parameter τ. (See Van Zandt (2000), for discussion of a range of other parameterizations of empirical RT distributions.) An experimental manipulation that shifts each subject's RT distribution to the right, adding an interval to every trial, will affect primarily the μ parameter. On the other hand, a manipulation that increases skewness, by making relatively long RTs even longer, will affect the τ parameter. The present study tests the prediction that the effect of an intervening attractor on correct RT involves an effect on μ, while the effect of a non-intervening attractor is primarily an effect on τ. Vincentile plots (Ratcliff, 1979; Vincent, 1912) are also used as a non-parametric means of confirming the ex-Gaussian findings; this procedure is described below.

2. Methods

2.1. Participants

In exchange for course credit, 32 undergraduates at the University of Massachusetts Amherst participated in the experiment. All were native speakers of English and naïve to the experimental hypotheses.

2.2. Materials

The materials for this experiment consisted of 160 items, with eight versions of each, adapted from items used by Staub (2009). Three factors were manipulated: the number of the agreement controller (singular vs. plural), the number of the attractor (matching or mismatching the controller in number), and whether the attractor was intervening or non-intervening. An example set is shown in Table 1. Each participant viewed two versions of each of the 160 stimulus sets, one intervening and one non-intervening, for a total of 320 trials, 40 in each of the eight experimental conditions. The 320 trials were presented in an individually randomized order, following 12 practice trials.

Table 1
Sample stimulus set used in the experiment.

Stimulus	Controller	Attractor	Configuration	Abbreviation
The advertisement from the club	Singular	Match	Intervening	SS
The advertisement from the clubs	Singular	Mismatch	Intervening	SP
The advertisements from the clubs	Plural	Match	Intervening	PP
The advertisements from the club	Plural	Mismatch	Intervening	PS
The club that the advertisement	Singular	Match	Non-intervening	SSni
The clubs that the advertisement	Singular	Mismatch	Non-intervening	SPni
The clubs that the advertisements	Plural	Match	Non-intervening	PPni
The club that the advertisements	Plural	Mismatch	Non-intervening	PSni

2.3. Procedure

Because the experimental procedure was essentially as described in Staub (2009), with the exceptions mentioned below, only a brief summary will be given here. Each sentence fragment was presented one word at a time on a computer monitor, with an ISI of 400 ms. After the final word, two response options were presented. For a random half of the items these options were WAS and WERE, and for half they were IS and ARE. In the present experiment (unlike in Staub (2009)), these options were rotated so that for a random half of the items the singular response was on the left, and for the other half it was on the right. Participants were instructed to press a key corresponding to the option that would continue the sentence grammatically; the instructions emphasized both speed and accuracy. The most important difference from Staub (2009) is that a response deadline was not used in the present study, because the right tail of the RT distribution was of particular interest. Error responses resulted in the word ''INCORRECT'' being displayed.

3. Results

3.1. Accuracy and mean RT

Responses longer than 4000 ms or shorter than 200 ms were excluded from analysis, eliminating less than 1.5% of trials overall, and less than 1% of correct responses. (See Staub et al. (in press), for a discussion of outlier trimming in the context of fitting the ex-Gaussian distribution.) Fig. 1 illustrates mean RT for correct responses and for errors in each condition; accuracy in each condition is provided below the corresponding bars. Statistical analysis of the proportion correct used mixed-effects logistic regression (Jaeger, 2008), and analysis of the latency of correct responses used a mixed linear model (Baayen, Davidson, & Bates, 2008), with subjects and items as crossed random factors and with the experimental manipulations, and their interactions, as fixed effects. Analyses were carried out using R, an open-source programming language and environment for statistical computing (R Development Core Team, 2007), and in particular the lme4 package for linear mixed-effects models (Bates, 2005).

The results of the logistic regression on the accuracy data are shown in Table 2. There were significant main effects of controller number and attractor mismatch, qualified by a significant interaction: accuracy was somewhat lower in the PP conditions than in the SS conditions, but was much lower in the SP conditions than in the PS conditions. In other words, a mismatching plural attractor had a much larger effect on accuracy than did a mismatching singular attractor, replicating a result obtained by Staub (2009) and in many other studies (e.g., Bock & Eberhard, 1993; Eberhard, 1997). There was no main effect of configuration on accuracy, and no significant interactions involving configuration.

The results of the analysis of the correct RT data are shown in Table 3. The critical findings are: (a) slower responding in the presence of a mismatching attractor, (b) more pronounced slowing when this mismatching attractor was plural, and (c) a three-way interaction, due to the fact that the SS vs. SP difference (269 ms) was greater than the SSni vs. SPni difference (176 ms). An additional analysis focusing on these four conditions found the interaction to be significant ($p < .02$).

The difference between correct RT and error RT in each condition was analyzed by means of a within-subjects t-test. As in Staub (2009), in several of the conditions with a matching attractor (i.e., the conditions in which errors were relatively rare), errors were significantly or marginally slower than correct responses. Also replicating Staub (2009), errors in the presence of a mismatching attractor noun were slower that correct responses in the non-intervening configurations (SPni: $t(31) = 3.61$, $p < .01$; PSni: $t(31) = 3.46$, $p < .01$), while errors in the SP and PS conditions were not slower than the corresponding correct responses; indeed, in this experiment (unlike in Staub, 2009) errors in the SP condition were faster than correct responses ($t(31) = 3.16$, $p < .01$). In sum, the present experiment replicated the critical data patterns relating to accuracy and mean RT from the Staub (2009) study.

3.2. Distributional analysis

Fitting of the ex-Gaussian distribution to the correct RT data from each subject, in each condition, was carried out using the QMPE software developed by Heathcote, Brown, and Mewhort (2002; Cousineau, Brown, & Heathcote, 2004). The fitting procedure divides the empirical distribution into quantiles (i.e., bins with an equal number of observations in each), then uses maximum likelihood estimation to determine the distributional parameters that come closest to producing the correct quantile boundaries, allowing all three parameters to vary freely. Heathcote et al. (2002; see also Rouder, Lu, Speckman, Sun, & Jiang, 2005) found that the best fits are delivered when the maximum number of possible quantiles is used, i.e., with each

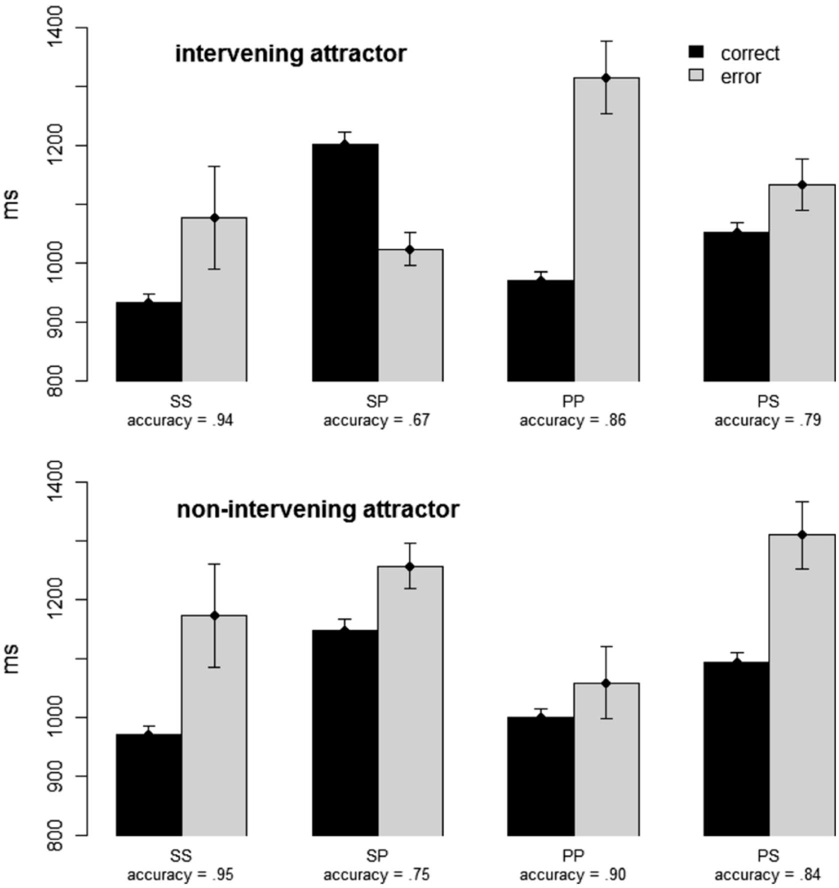

Fig. 1. Mean accuracy, correct RT, and error RT in each experimental condition; error bars represent standard errors.

Table 2
Parameter estimates for fixed effects on accuracy in mixed logistic regression, in log odds, and associated standard errors and probabilities.

Effect	Estimate	SE	*z*-Value	Pr (>|*z*|)
Intercept	3.0187	0.1776	17.000	<.001
Controller: plural	−0.9597	0.1484	−6.468	<.001
Attractor: mismatch	−2.2255	0.1373	−16.205	<.001
Config.: non-intervening	0.1819	0.1842	0.987	.32
Controller: plural × attractor: mismatch	1.6340	0.1764	9.261	<.001
Controller: plural × Config.: ni	0.2237	0.2215	1.010	.31
Attractor: mismatch × Config.: ni	0.2493	0.2019	1.235	.22
Controller: plural × attractor: mismatch × Config.: ni	−0.2582	0.2628	−0.982	.33

Table 3
Parameter estimates for fixed effects on correct RT in mixed linear model, and associated standard errors and *t*-values. The *t*-values denoted with an asterisk are significant at the .05 level.

Effect	Estimate	SE	*t*-Value
Intercept	933.56	45.76	20.401*
Controller: plural	45.78	19.85	2.307*
Attractor: mismatch	260.24	21.39	12.168*
Config.: non-intervening	38.72	20.73	1.867
Controller: plural × attractor: mismatch	−179.05	29.83	−6.002*
Controller: plural × Config.: ni	−20.16	27.89	−0.723
Attractor: mismatch × Config.: ni	−81.70	29.75	−2.746*
Controller: plural × attractor: mismatch × Config.: ni	96.65	41.53	2.327*

data point in a separate bin; this method was used in the present research.

The mean values of all three parameters, in each condition, are shown in Fig. 2. (Note that there were no significant effects on σ, with the exception of increased σ in the mismatch conditions, $F(1, 31) = 6.87$, $p < .02$, which is expected as σ often varies with μ.) There was a significant main effect of attractor mismatch on μ ($F(1, 31) = 22.33$, $p < .001$), as well as a marginally significant interaction of controller number and attractor mismatch ($F(1, 31) = 3.68$, $p = .06$), and a significant interaction of controller number and configuration ($F(1, 31) = 4.28$, $p < .05$). However, these effects are qualified by a three-way interaction ($F(1, 31) = 5.25$, $p < .05$). As can be seen from Fig. 2, the μ parameter is substantially larger in the intervening SP condition than in any other. The pattern for τ is quite different. There was a significant effect of attractor

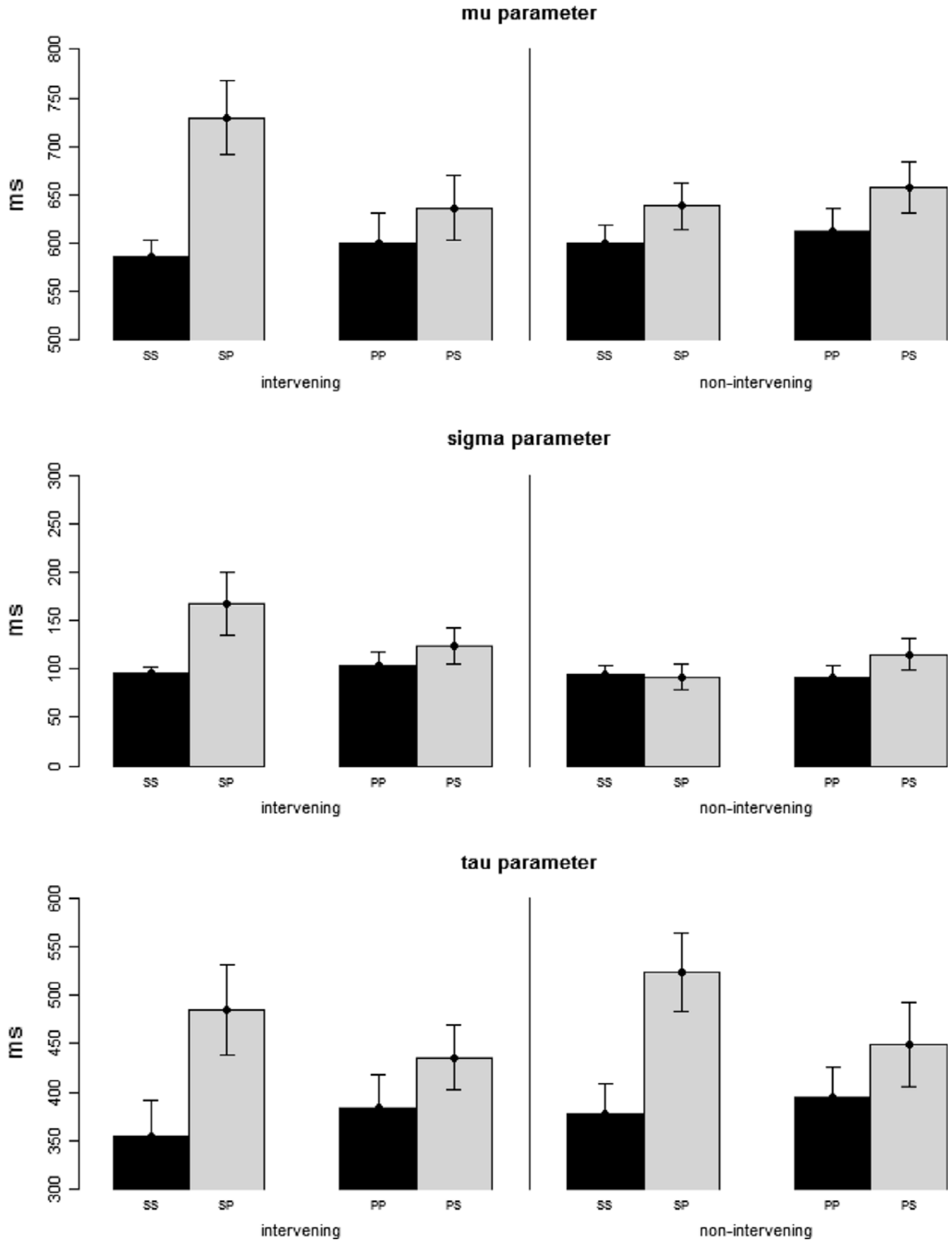

Fig. 2. Mean μ (top panel), σ (middle panel), and τ (bottom panel) ex-Gaussian parameters in each experimental condition. Error bars represent standard errors.

mismatch ($F(1, 31) = 33.73$, $p < .001$) and a marginal interaction of head number and attractor mismatch ($F(1, 31) = 3.75$, $p = .06$), but no hint of a three-way interaction ($F(1, 31) = .04$, $p = .84$).

The critical findings may be summarized as follows. The 269 ms increase in mean correct RT in the intervening SP condition, compared to the corresponding SS condition, was due to nearly equal effects on the μ (144 ms) and τ (130 ms) parameters of the ex-Gaussian distribution. On the other hand, the 176 ms effect on correct RT in the non-intervening SPni condition, compared to the corresponding SSni condition, was due to a very small effect on μ (39 ms), and a large effect on τ (147 ms).[1]

A vincentile plot (Fig. 3) provides a visual representation of the nature of the RT penalty in the SP and SPni conditions.[2] The plot is constructed as follows. The observations

[1] Note that the mean μ and τ effects often do not sum exactly to the effect on mean RT, due to the details of the fitting algorithm.

[2] This non-parametric means of assessing distribution shape is especially important given that the number of observations in each distribution generally fell below the number that has been regarded as providing reliable ex-Gaussian estimates (i.e., about 40; Heathcote et al., 2002).

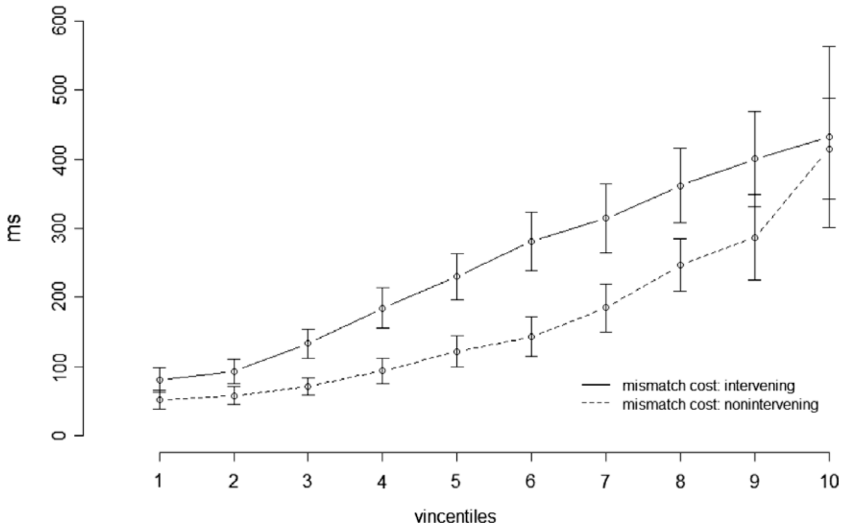

Fig. 3. Vincentile plot of correct RT data comparing SS vs. SP conditions (solid line) and SSni vs. SPni conditions (dashed line).

for each subject, in each condition, are divided into the fastest 10% (vincentile 1), next fastest 10% (vincentile 2), etc. The mean of the observations in each vincentile is computed, and the difference between the condition means, for each subject, is then computed. Finally, the mean of all individual subject differences is computed, for each vincentile, and these values (and standard errors) are displayed as connected points on the plot, with vincentile on the *x*-axis and RT on the *y*-axis. Thus, the plot illustrates the size of the effect of a mismatching attractor as one moves across the RT distribution. An intervening mismatching attractor has an approximately linearly increasing effect on RT, moving from the fastest to the slowest RTs. A non-intervening attractor has a pronounced effect on the slowest RTs, but a substantially smaller effect on fast and medium-speed RTs. These patterns are expected based on the mean ex-Gaussian parameters; the two lines on this plot look, respectively, remarkably like idealized vincentile predictions for an RT effect that is equally divided between μ and τ, and an RT effect that is due to τ only (see, e.g., Balota et al., 2008).

4. Discussion

The critical findings from this experiment are as follows. As in Staub (2009), the effect of a non-intervening number attractor on the error rate was nonsignificantly smaller than the effect of an intervening attractor. However, the experiment replicated the finding of a significantly smaller effect on mean correct RT when the attractor was non-intervening, at least in the conditions in which the attractor was plural (i.e., the conditions that induce the strongest effects). The experiment also replicated the finding that errors are slower than correct responses only when the attractor is non-intervening. The new finding from the present experiment is that the effects of an intervening and non-intervening attractor on correct RT are also different in kind: ex-Gaussian fitting revealed that the effect of a plural intervening attractor on mean RT is both a shift effect and a skew effect, but the effect of a plural non-intervening attractor is almost entirely a skew effect. A non-parametric vincentizing procedure confirmed these patterns.

These results provide further evidence that intervening and non-intervening attraction have different processing characteristics. Taken together, the findings from Staub (2009) and the present experiment suggest that while an intervening attractor affects processing on essentially all trials, whether or not an error is actually made, a non-intervening attractor strongly influences processing in a subset of instances, on many of which an error is made.

In the Introduction, it was suggested that Bock and Miller's (1991) account of non-intervening attraction, according to which errors result from occasional confusion about the identity of the subject, predicts such a pattern. However, it is important to point out that there is an unanswered question here, namely, why this confusion should be only occasional. Why should the complexity of the object relative construction in sentences like (1b) result in difficulty on only some trials? (Relatedly, it is not clear why predication confusion should be restricted to cases in which the attractor is plural.) An interesting question is whether the processing difficulty that is reliably seen in the comprehension of object relative clauses (e.g., King & Just, 1991; Traxler, Morris, & Seely, 2002) has similar characteristics. In addition, it is important to point out that accounts of agreement attraction that offer a common theoretical explanation for intervening and non-intervening attraction (e.g., Franck et al., 2006; Wagers et al., 2009) may be able to account for the RT patterns demonstrated here, depending on the details of how processes such as agreement checking and memory retrieval are computationally implemented. For example, in the word recognition literature, experimental effects on different parameters of RT distributions are sometimes argued to reflect effects on distinct processing stages (e.g., Balota & Spieler, 1999). Thus, the main import of the present data is not to rule out any particular account of attraction, but rather to emphasize a distinction that any account must deal with.

In addition, the nature of the task used here, and in Staub (2009), raises questions about the relative contribution of comprehension and production processes to agreement attraction. This task clearly involves components of both comprehension and production (though so does the standard laboratory production task in which a participant repeats and continues an auditorily-presented fragment). The rate of intervening and non-intervening attraction in truly naturalistic production, in which the speaker is autonomously generating the entire utterance, is not known. However, as discussed in Staub (2009), it is plausible that confusion about the identity of the agreement controller in the object relative construction is more likely to arise in comprehension than in normal production, in which the speaker presumably has access to a message-level representation that defines the roles of the mentioned entities.

More generally, the present results emphasize the importance of examining temporal dependent measures, both at the level of the mean and at the level of distributions, in concert with binary dependent measures. Detailed predictions of competing processing accounts are often best adjudicated by means of such multi-dimensional data. Interestingly, this moral is well-established in some areas of cognitive psychology (e.g., Nosofsky & Stanton, 2005; Ratcliff & McKoon, 2008), but has yet to make a deep impact in psycholinguistics.[3]

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[3] It should be noted that an attempt was made to fit the data presented here using Ratcliff's (1978; Ratcliff & McKoon, 2008) diffusion model. It was found that the model could not reproduce the finding that errors are slower than correct responses in only some conditions. This is consistent with the idea that in at least some conditions, subjects' responses are best thought of as arising from a mixture of two processes, rather than a single diffusion process.

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