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Serial Processing in Reading Aloud: Reply to Zorzi (2000)

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K. Rastle and M. Coltheart (1999; see also M. Coltheart & K. Rastle, 1994) reported data demonstrating that the cost of irregularity in reading aloud low-frequency exception words is modulated by the position of the irregularity in the word. They argued that these data implicated a serial process and falsified all models of reading aloud that operate solely in parallel, a conclusion that M. Zorzi (2000) challenged by successfully simulating the position of irregularity effect with such a model. Zorzi (2000) further claimed that a reanalysis of K. Rastle and M. Coltheart's (1999) data demonstrates sensitivity to grapheme–phoneme consistency (which he claimed was confounded across the position of irregularity manipulation) rather than the use of a serial process. Here, the authors argue that M. Zorzi's (2000) reanalyses were inappropriate and reassert that K. Rastle and M. Coltheart's (1999) findings are evidence for serial processing.

In his observation, Zorzi (2000) made two arguments. We agree with one of these arguments and dispute the other.

Zorzi's (2000) first argument is that strong claims about the sufficiency of computational models should be avoided until simulations have been conducted. He illustrated this point by presenting a successful simulation of the position of irregularity effect (an effect that we, Rastle & Coltheart, 1999, claimed falsified all models that translate orthography to phonology solely in parallel) with the dual-process model (a model that operates solely in parallel; Zorzi, Houghton, & Butterworth, 1998). We agree with Zorzi's claims regarding our rather premature conclusions and applaud his careful analysis of the dual-process model in discovering an explanation for the effect alternative to the one we provided.

Zorzi's (2000) second argument is that the effect of position of irregularity that we observed reflected not a serial processing mechanism but rather sensitivity to grapheme–phoneme consistency, which was confounded across the position of irregularity manipulation. We do not agree with this assessment, and we argue that Zorzi's reanalyses of our data were inappropriate.

The Position of Irregularity Effect

We (Coltheart & Rastle, 1994; Rastle & Coltheart, 1999) have reported data showing that the irregularity disadvantage on naming latency is modulated by the position in the word at which the irregularity occurs. Words with early irregularities (e.g., *chef*) are named more slowly relative to matched regular controls (e.g., *shed*) than are words with late irregularities (e.g., *glow* vs. *grab*). Our early work using disyllabic stimuli (Coltheart & Rastle, 1994) showed a monotonic and linear decrease in the cost of irregularity over five positions of irregularity, with no effect of irregularity when it occurred in the third grapheme–phoneme correspondence or later. In an experiment using monosyllabic stimuli controlled for consistency averaged across five orthographic segments (head, nucleus, body, antibody, and coda), we obtained similar results: The cost of irregularity declined monotonically and linearly over three positions of irregularity, with no irregularity disadvantage for words with irregularities in the third grapheme–phoneme correspondence (Rastle & Coltheart, 1999).

We argued that these data implicate a serial procedure in the translation of orthography to phonology, and we provided a successful simulation of the monosyllabic results with the dual-route cascaded (DRC) model, an implementation of the dual-route theory of reading (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart & Rastle, 1994). The specific locus of the effect in the DRC model is as follows:

> (a) The model translates orthography to phonology via two processing routes, a lexical (addressed) route and a nonlexical (rule-based) route;
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> (b) words that violate spelling–sound correspondence rules are translated correctly via the lexical route but are regularized by the nonlexical route, which disrupts processing when information from both routes is combined in a shared phoneme system;
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> (c) the nonlexical route translates orthography to phonology serially, letter by letter, from left to right;
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> (d) incorrect nonlexical information about words with early irregularities has a greater propensity to disrupt correct lexical processing of irregular words than does incorrect nonlexical information about words with late irregularities; correct lexical processing is often complete before nonlexical information about late irregularities arrives at the phoneme system.

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Contrary to Rastle and Coltheart's (1999) claim that this effect in principle falsified any model that translates orthography to phonology in a strictly parallel fashion, Zorzi (2000) presented a successful simulation of the effect in the dual-process model (Zorzi et al., 1998), a dual-route connectionist model of reading aloud, which does not contain a serial component. Zorzi (2000) provided an alternative explanation for the position of irregularity effect based on a detailed analysis of the effect in the "nonlexical" component of the dual-process model (the two-layer network of phonological assembly, henceforth, the TLA network).

The TLA network learns regularities in the English spelling–sound mapping, so it generally produces regularized phonologies for irregular words. In a word like *chef*, for example, the most active phoneme in the first position will not be /S/ but rather /tS/. Zorzi (2000) ran each word in the Rastle and Coltheart (1999) stimulus list through the TLA network, and at the phoneme position corresponding to each word's irregularity (or for regular words, the phoneme position corresponding to the vowel) compared the activation of the correct phoneme with the activation of the most highly activated competitor phoneme. For regular words, the activation difference between the correct phoneme and the highest competitor phoneme was a high positive number; for irregular words, this activation difference was generally a negative number. Critically, Zorzi found that this negative activation difference was greatest for first-position irregular words and decreased over position of irregularity. Thus, the position of irregularity effect in the dual-process model is due to its sensitivity to grapheme–phoneme consistency, and in particular, greater grapheme–phoneme inconsistency in the set of first-position irregular words used by Rastle and Coltheart (1999) than in the set of second- or third-position irregular words (relative to matched regular controls).

In order to determine whether the locus of the position of irregularity effect in human participants was the result of a confound of grapheme–phoneme consistency across position of irregularity, Zorzi (2000) reran the analyses reported by Rastle and Coltheart (1999) but used head consistency and nucleus consistency (as measured by those authors) as covariates. This analysis showed a greatly reduced interaction between position of irregularity and regularity that was no longer statistically reliable (p = .07). Zorzi concluded that the results reported by Rastle and Coltheart (1999) reflected participant sensitivity to differing levels of grapheme–phoneme consistency, not a nonlexical serial process. He wrote, "the supposed serial effect can be reduced to a position-specific grapheme–phoneme consistency effect . . . the position-of-irregularity effect vanishes when the experimental data are reanalyzed using grapheme–phoneme consistency as the covariate" (Zorzi, 2000, p. 847).

We argue that Zorzi's (2000) reanalysis was inappropriate and further wish to dispute his conclusion that the serial effect we reported can be reduced to a position-specific grapheme–phoneme consistency effect. Rather, we argue that our findings (Rastle & Coltheart, 1999) represent a genuine example of serial processing.

Zorzi's Reanalysis

In this section, we consider carefully the analysis of covariance described by Zorzi (2000) and demonstrate clearly why it is not a sensible analysis. As described, Zorzi carried out an analysis of covariance that examined naming latency as a function of regularity (two levels) and position of irregularity (three levels), and covaried neighborhood size, head consistency, and nucleus consistency. What exactly is the effect of covarying head consistency and nucleus consistency in this analysis?

Let us first consider head consistency. Entering head consistency into the analysis of covariance has the effect of adjusting the naming latency means in all six cells as if to equate those six cells' values of head consistency. Table 1 shows values of head consistency and nucleus consistency, calculated by Rastle and Coltheart (1999), for each of the six cells; values range from +1 indicating perfect consistency to −1 indicating perfect inconsistency.

As can be seen from Table 1, head consistency is not confounded with either position or regularity but rather first-position irregularity. Five of the six cells have extremely high positive values of head consistency; the cell of first-position irregular items has a moderately negative value of head consistency. For items with irregularities in the first position, the only instances in which regularity is not perfectly confounded with head consistency are for three items that do not have any head neighbors (e.g., *chrome*). These items are perfectly head consistent (since there are no other items that share the head segment) yet are irregular. Zorzi (2000), however, excluded these three items from his analyses.

Thus, in the set of items reanalyzed by Zorzi (2000), those items that were head inconsistent also had irregularities in the first position. This relationship was not *generally* the case but rather was *always* the case. Therefore, by statistically removing the effect of head inconsistency on naming latency in the set of items used by Rastle and Coltheart (1999), Zorzi effectively removed the effect of first-position irregularity.

Nucleus consistency was also entered into the analysis of covariance as a covariate. Here again, naming latencies are statistically adjusted in the analysis of covariance as if to equate values of nucleus consistency across all six cells. As can be seen from Table 1, nucleus consistency values are generally lower than head consistency values, which is consistent with other observations that vowels are generally less consistent than consonants (e.g., Berndt, Reggia, & Mitchum, 1987). However, again, nucleus consistency values do not range freely over the variables of regularity and position of irregularity. Rather, the highly nucleus inconsistent items are those with irregularities in the second and third positions. Although first-position irregular items are also somewhat nucleus inconsistent, there is a clear interaction between regularity and position of irregularity on nucleus consistency val-

Table 1
Head Consistency and Nucleus Consistency Values as a Function of Regularity and Position of Irregularity

	Position		
Consistency	1	2	3
Head			
Irregular	−.499	.986	.991
Regular	.992	.992	.966
Nucleus			
Irregular	.063	−.695	−.698
Regular	.745	.757	.734

ues, $F(2, 170) = 14.40$, $p < .001$, $MSE = 0.156$, such that the difference between nucleus consistency values for regular and irregular words is greater for Position 2 and 3 items than it is for Position 1 items. Out of the 68 second- and third-position irregular words used by Rastle and Coltheart (1999), only two of those items had positive values of nucleus consistency (*quay,* which was removed from Zorzi's analysis, and *hose,* which is not irregular in the nucleus). Thus, by statistically eliminating the effect of nucleus consistency on naming latency, Zorzi (2000) also effectively eliminated the effect of Position 2 and Position 3 irregularity; because nucleus consistency and regularity are completely confounded at these positions of irregularity (with only one exception—*hose*), removing the effect of one variable removes the effect of the other.

Thus, in his reanalysis of the Rastle and Coltheart (1999) data, Zorzi (2000) statistically removed the regularity–consistency effect at Position 1 (by covarying head consistency), then removed the regularity–consistency effect at Positions 2 and 3 (by covarying nucleus consistency). It is thus no wonder that the interaction between regularity and position of irregularity disappeared. Zorzi (2000) effectively examined the effect of position of irregularity when the position of irregularity variable was removed.

Zorzi (2000) subsequently reported a regression analysis designed to assess the unique contribution of each of several factors on naming latency—head consistency, nucleus consistency, neighborhood size, and regularity. He found that all four factors accounted for significant portions of variance in naming latency. He concluded from this that "positional grapheme–phoneme consistency makes an independent contribution to the naming latencies. This is not surprising, because the dichotomous description of regular versus exception does not capture the more fine-grained degree of irregularity" (p. 853).

The problem with the regression analysis that Zorzi (2000) reported is similar to the problem with the analysis of covariance that he reported. It is no surprise given our (Rastle & Coltheart, 1999) results that regularity is not the only significant contributor to naming latency. Indeed, we argue this explicitly—that there is another factor critical to naming latency that is even more important than regularity: position of irregularity. In his regression analysis, Zorzi (2000) cast this variable in terms of "head consistency" and "nucleus consistency." As explained, head inconsistent items are those with first-position irregularities and nucleus inconsistent items are those with second- and third-position irregularities. Thus, by finding that head consistency makes a unique contribution to naming latency over and above simple regularity across the whole set of items, what Zorzi may really be finding is that in fact *first-position irregularity* makes a unique contribution to naming latency over and above simple regularity.

A Thought Experiment

In order to illustrate further why the reanalysis carried out by Zorzi (2000) was not appropriate, consider how else we might adjudicate between the "grapheme–phoneme consistency" explanation of the position of irregularity effect and the "serial processing" explanation of the effect. Imagine that we did not want to control for grapheme–phoneme consistency statistically but wanted to control for the head consistency and nucleus consistency variables in a new experiment that examined the interaction between regularity and position of irregularity. As in the Rastle and Coltheart (1999) study, we would vary regularity (two levels) and position of irregularity (three levels) but would hold head and nucleus consistency constant across each of the six cells. What types of stimuli would meet these requirements? In fact, the only items that would meet these criteria are ones that are perfectly head and nucleus consistent, for that is the only way that consistency can be equated across the regularity comparison and that head and nucleus consistency can be equated across the position of irregularity comparison. This constraint leaves only "hermit"-type items in the irregular conditions—items that do not have any head or nucleus neighbors and so are perfectly consistent.

This thought experiment shows that it would be impossible to do an experiment that disentangled the position of irregularity variable and the head–nucleus consistency variables and should, therefore, reinforce our assertions that trying to disentangle these variables statistically in the way that Zorzi attempted is not sensible.

Does Position of Irregularity Play a Role in Naming Latency?

So far, we have shown that head and nucleus consistencies are confounded with particular positions of irregularity in the stimulus set used by Rastle and Coltheart (1999). And we have argued that because of the *perfect* confound between head consistency and first-position irregularity and the *near-perfect* confound between nucleus consistency and second- and third-position irregularity, Zorzi's statistical treatment of the Rastle and Coltheart (1999) data was inappropriate. Is it possible to draw any conclusions at all, then, regarding whether the relevant variable in reading is positional regularity (proposed by Coltheart & Rastle, 1994, and Rastle & Coltheart, 1999) or grapheme–phoneme consistency (proposed by Zorzi, 2000)?

Recall that Rastle and Coltheart (1999) observed a significant regularity effect for words with irregularities in the second position (e.g., *pint*) yet no such effect for words with irregularities in the third position (e.g., *crepe*). In almost all cases, irregularities in the Position 2 and Position 3 items occurred in the vowel. Therefore, if the grapheme–phoneme consistency account put forth by Zorzi (2000) is correct, then the variation in the size of the regularity effect across Positions 2 and 3 should be accountable for in terms of nucleus consistency (as measured by Rastle & Coltheart, 1999). Specifically, a nucleus inconsistency effect should exist at Position 2 but not at Position 3. Statistical analyses show that this is not the case, however: Randomization tests (as used by Rastle & Coltheart, 1999) reveal significant nucleus inconsistency effects at both Position 2 ($p < .0001$) and Position 3 ($p < .0001$). Indeed, there is no difference in the level of nucleus consistency across these positions, $F(1, 132) = 0.032$. We therefore claim that our data (Rastle & Coltheart, 1999) genuinely reflect the use of a serial process.

Summary

Coltheart and Rastle (1994) and subsequently Rastle and Coltheart (1999) reported that the size of the regularity effect is modulated by the position of the irregularity in the exception word. Items with early irregularities produce a larger naming latency disadvantage than do items with later irregularities. Rastle and Coltheart (1999) argued that these data implicate serial processing in the translation of orthography to phonology, and they further claimed that they, in principle, falsify all models that translate orthography to phonology solely in parallel.

Zorzi (2000) challenged these conclusions by demonstrating that the position of irregularity effect could be produced in a model that translates orthography to phonology in a strictly parallel fashion. He further claimed, on the basis of a reanalysis of the Rastle and Coltheart (1999) data, that the factor responsible for the effect in the dual-process model is the factor to which human participants are sensitive.

We have argued here that Zorzi's (2000) reanalyses of our data were inappropriate and inconclusive because of the perfect confounding of head consistency and first-position irregularity and the near-perfect confounding of nucleus consistency and second- and third-position irregularity. We have also shown that while the regularity effect is significant for Position 2 items but not for Position 3 items in the data reported by Rastle and Coltheart (1999), the level of nucleus consistency is constant across these positions of irregularity, a result inconsistent with Zorzi's (2000) account. Thus, we argue that our (Rastle & Coltheart, 1999) data do indeed reflect the use of a serial nonlexical procedure.

We conclude by highlighting the fact that these data are not the only reason for proposing that the nonlexical reading procedure operates serially, from left to right; rather, this proposal is consistent with a number of other results, including

> (a) the interaction between length and lexicality on naming latency, with nonwords showing greater length effects than words (Weekes, 1997);
>
> (b) the position-sensitive Stroop effect. Coltheart, Woollams, Kinoshita, and Perry (1999) showed, first, that color naming of color-unrelated words was facilitated when the word had one phoneme in common with the color name compared with when it had none, second, that this facilitation was larger when the shared phoneme was the first phoneme in the printed word than when it was the last, and, third, that a version of the DRC model to which a color-naming system had been added showed exactly these effects in its color-naming latencies;
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> (c) the effect of filler condition on regular word and nonword naming latency (Rastle & Coltheart, 1999)—regular words and nonwords are named more slowly when fillers are exception words with first-position irregularities than when they are exception words with third-position irregularities;
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> (d) the onset effect in masked-form priming (Forster & Davis, 1991): Naming latency for a target word is reduced when a preceding masked prime has the same initial phoneme as the target word, whereas shared phonemes at any other position have no effect; and
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> (e) when naming of the nonwords used in the study by Weekes (1997) is simulated with computational models of reading, a model in which the nonlexical route operates serially left to right (the DRC model) accounts for a substantial percentage of the variance of human naming latencies, namely, 38%. In contrast, models that have a parallel procedure for reading nonwords do not account for significant percentages of the variance here: the dual-process model accounts for only 0.03%, and the model of Plaut, McClelland, Seidenberg, and Patterson (1996) accounts for only 0.10%.

These five findings, plus the results of Rastle and Coltheart (1999), provide very strong evidence that the reading system contains a nonlexical reading procedure that operates serially, from left to right. Of course, as Zorzi (2000) showed, sometimes simulations produce unexpected results. It remains to be seen whether a model that operates solely in parallel can account for *all* of the data that implicate serial processing.

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