Fast visual generation: Its nature and chronometrics

DAVID B. BOLES

Rensselaer Polytechnic Institute, Troy, New York

The fast-generation model for the matching of mixed-case letter pairs (e.g., Aa, Ab) states that one or both members of a pair activate visual representations in memory of the opposite case, supporting "same" or "different" responses through crossmatching to representations of the pair members themselves. Here the reaction time and error results of three experiments using simultaneous matches support a specific variant of the model in which generation proceeds from the uppercase letter. Furthermore, a manipulation of stimulus onset asynchrony in a fourth experiment using near-simultaneous matches indicates that fast generation produces a visual representation that occurs within 67 msec of initiation and that decays within 200 msec. A fifth experiment contrasts simultaneous and successive matches and in the case of successive matches finds evidence in support of a regeneration process acting after an initial decay. Models of mixed-case matching that are based on the phonetic representation of letter names, or on abstract-letter identities, completely fail to account for the results. Fast generation is distinguishable from slow generation in that it shows fast (vs. slow) dynamics, rapid decay (vs. maintainability), no imagery (vs. imagery), and (probably) automatic (vs. controlled) processing.

A prevalent view of letter matching is that when two letters have the same shape (e.g., AA), they are matched according to a visual representation or physical code. By contrast, when two letters have the same name but not the same shape (e.g., Aa), it has often been assumed that they are matched according to a phonetic representation of the letter name, or name code (Posner, 1978). Given this view, the difference in the two letter-matching tasks has been treated as bearing on a number of important issues: notably, on levels of processing or mental representation (Posner, 1978), on individual differences in the use of those representations (Hunt, 1978), and on differences in hemispheric processing (Davis & Schmit, 1973; Geffen, Bradshaw, & Nettleton, 1972).

However, Boles and Eveland (1983) reported the results of five experiments that cast substantial doubt on the contribution of phonetic or name coding to letter matching. In some of the experiments, mixed-case letter pairs were matched, with random intermixing of *same* pairs (e.g., Aa) and *different* pairs (e.g., Ab). Within the *different* pairs, phonetic similarity was varied by selecting stimuli from a phonetic confusion matrix to be either phonetically similar (e.g., Aj) or not (e.g., Az). No reaction time (RT) difference was found between the two sets of *different* pairs. This null result was obtained for both simultaneous and successive presentation of pair members and

was found even when the same letters were used in the two sets but paired so as to be similar or dissimilar. Thus, no evidence was found for the use of phonetic representations in mixed-case letter matching. Other work has come to the same conclusion (Besner, Coltheart, & Davelaar, 1984; Boles, 1986; Boles & Hellige, 1984; Carrasco, Kinchla, & Figueroa, 1988).

If phonetic representations of letter names are not used, what is the alternative? Boles and Eveland (1983) reported a robust experimental finding that indicated that some type of visual matching is employed. Specifically, we found that pairs like "Qg," in which each member resembles the alternate case of the other ("Q" resembles "G," and "g" resembles "q"), increased RTs by 50–100 msec over pairs without such resemblance. The elevation in RT applied to both simultaneous and successive matches and persisted even when similar and dissimilar pairs were matched for the degree of veridical visual similarity between the pair members as displayed (e.g., between "Q" and "g").

To account for this phenomenon, Boles and Eveland (1983) devised the fast-generation model of mixed-case matching. The model accounts for the confusion effect by proposing that one or both members of a letter pair activate memory representations not only of themselves but of their opposite cases ("generated" representations). For example, a pair like "Qg" might produce generated representations of each opposite case ("q" and "G"), in addition to representations of the stimulus letters themselves ("Q" and "g"). Matching proceeds by comparing the generated representations to the stimulus representations. In this example, confusion results from the visual similarity of the two types of representations. Thus, "Q"

I wish to thank David Rundus, Michael Rowe, Lori Cohan, and Jonathan Wolfman for running subjects and Lew Harvey and the Department of Psychology, University of Colorado at Boulder, for making facilities available for the fourth experiment. Correspondence should be directed to D. B. Boles, Department of Psychology, Rensselaer Polytechnic Institute, Troy, NY 12180; e-mail: userbw1@rpi.smts.bitnet.

resembles "G," and "q" resembles "g." Such pairs mimic *same* pairs, and accordingly they could produce RT elevation for "different" responses.

However, one weakness of the generation model, as stated at the time, was its notable lack of specificity. No statement was made regarding the number of letters generated. Theoretically, generation could proceed from both stimulus letters or from only one of them. Furthermore, single-letter generation alternatives include generation from (1) the first letter, (2) the second letter, (3) the uppercase letter, which could be in either the first or second positions, and (4) the lowercase letter, for which the same is true. There are accordingly five possible variants of the generation model, and all are equally capable of handling the confusion data produced by Boles and Eveland (1983) and Boles (1986).

A preliminary aim of the present experiments is to provide a comparative test of the five variants of the generation model. Having established the success of one specific model, the research then investigates the chronometrics of the generation process. On an *a priori* basis, this type of generation must be very fast, for mixed-case letter pairs are matched at latencies that are typically less than 100 msec longer than the latencies for pure-case letter pairs (Boles & Eveland, 1983; Boles & Hellige, 1984; Posner, 1978). Since pure-case pairs do not require generation, it seems reasonable to expect that generation can be accomplished in less than 100 msec, with some indeterminacy due to other potential disparities in the processes involved. How much less will be a matter for empirical determination.

One large obstacle to providing a definitive comparison between models has been that available visual-confusion matrices, which are needed to define similar versus dissimilar pairs, have used letter sets differing from those available in software for experimental control. This obstacle has been surmounted by the collection of similarity rating norms for all 2,704 possible pairs of 52 letters (uppercase and lowercase) in a letter set that is widely available for experimental use (Boles & Clifford, 1989). In brief, subjects rated the pairs on a 5-point scale for overall visual similarity, with 5 being highly similar. The mean rating for each pair was used in the present experiments as an index of the amount of similarity present.

The strategy used to test the variants of the generation model is as follows. (1) Samples of mixed-case pairs are selected for use in a matching experiment. (2) RTs are collected for these pairs, and the mean RT is calculated for each. (3) The RTs are then correlated to the amount of generation confusion predicted to be present by each variant of the model. (4) The correlations are then compared to determine whether one variant produces a significantly better fit than the others.

Examples will serve to illustrate how each variant of the generation model makes predictions about the amount of confusion present. Consider the pairs "Rn" and "nR." First-letter generation states that the rated visual similarity between "r" and "n" for the former (3.04) and be-

tween "N" and "R" for the latter (2.17) will be predictive of RT. Second-letter generation states the opposite: predictors should be the similarity between "R" and "N" for the former (2.17) and between "n" and "r" for the latter (3.04). Generation from the uppercase letter, on the other hand, states that the similarity between "r" and "n" (3.04) should be predictive for both pairs, while generation from the lowercase letter states that it is the similarity between "R" and "N" (2.17) that is predictive for both. Finally, generation from both letters states that for each pair, both the uppercase and lowercase similarities should be important, and so the mean of the two values (2.61) should be predictive of RT.

Clearly, by selecting a number of such pairs and correlating the resultant RTs to the values stated by each model to be predictive, it should be possible to arrive at the best-fitting model. Experiments 1-3 follow this strategy.

Although the focus of the present study is primarily on variants of the generation model, a test was also made of a model based on abstract-letter identities. Abstract-letter identities have been proposed to underlie alternative cases of the same letter (Besner et al., 1984; Coltheart, 1981). Basically, two forms of a letter, such as "A" and "a," are assumed to be associated to a single abstract-letter node (an abstract A). *Same* matches are then supported through linkage to a common node. The model is a strong competitor to the fast-generation model because like fast generation, it can handle "Qg"-type confusion. The reason is that each of the original letters resembles a form of the other letter ("Q" resembles "G," and "g" resembles "q"), so that according to the model, both stimulus letters can through visual similarity activate common nodes (the abstract letters Q and G).

The abstract-identity model is difficult to test because it is so abstract as to provide few concrete predictions. However, it does make one prediction not made by the generation model: If convergence by two different stimulus letters on the same nodes is confusing, as it must be in order to account for "Qg"-type confusion, then confusion should also occur if both stimulus letters converge on a *third* node. That is, if both stimulus letters resemble forms of some third letter, then convergence on the abstract identity of that letter should lead to slow "different" responses.

Such pairs do exist. The letters "Vg," for example, show little convergence on the two stimulus letter nodes ("V" does not resemble "G," and "g" does not resemble "v"), but substantial convergence should exist on the abstract letter Y. That is, "V" resembles "Y," and "g" resembles "y." By dint of a third node, the pair should be confused. In contrast, the generation model does not predict confusion, because the generated letters do not resemble the original stimulus letters.

How can one index convergence on a third node? One method is to check the similarity of each original letter to all possible third letters (a process, incidentally, that is greatly facilitated by a computer program). In the case of "Vg," the most similar third letter in the rated letter

set is in fact "Y." The index of similarity is the lesser of the two similarities between "V" and "Y" (3.59) and between "g" and "y" (3.75), or a rating value of 3.59.¹ This is the value stated by the abstract-letter-identity model to be predictive of RT.

Parenthetically, it is not the case that all letter pairs are closely related through some third letter. The pair "Ql," for example, produces poor convergence: indeed, in the rated letter set, the most similar third letter was "J"! The similarity value of 2.34 for the convergence is far below that for the convergence of "Vg" on the abstract letter Y (3.59).

A potential complication in the calculation of convergence values should be mentioned. Namely, the set of possible "third" letters must include the original letters themselves, since convergence on either of these nodes could be stronger than convergence on any third letter. This possibility is allowed in calculations made for the present experiments.

EXPERIMENTS 1, 2, AND 3

Although run as separate studies, Experiments 1-3 had similar designs and produced similar results. Therefore, they are described together.

Method

Subjects. Ten subjects participated in Experiment 1, 15 in Experiment 2, and 16 in Experiment 3. All were student volunteers from Rensselaer Polytechnic Institute.

Apparatus. Stimuli were presented either on a black-and-white monitor at a luminance of 1.9 cd/m² (Experiments 1 and 3) or on a color monitor in blue at a luminance of 5.0 cd/m² (Experiment 2); the presentations were controlled by the Apple-Psych system for experimental control (Barnes & Burke, 1988; Osgood, 1988). A chinrest was used to enforce a constant viewing distance of 50 cm.

Stimuli. The stimuli were standard software characters in the Apple-Psych system. Experiments 1, 2, and 3 used 27, 24, and 16 mixed-case *different* pairs, respectively. For Experiment 1, the pairs were Da, Do, Ga, Gl, Gs, Il, Oa, Oc, Og, Oq, Ov, Qa, Qc, Qf, Qg, Ra, Se, Sq, Tf, Tg, Tv, Yc, Yf, Yl, Yq, Yt, and Yv. For Experiment 2, they were Ah, Fa, Fq, Fv, Fy, Jg, Mh, My, Oa, Oj, On, Ov, Ow, Oy, Ph, Pw, Ql, Qy, Rn, Rq, Vg, Vn, Vx, and Yq. For Experiment 3, they were Bg, Ce, Cs, Dh, Dp, Gb, Gd, Gp, Ob, Od, Op, Pd, Tl, Uc, Vw, and Vy. Each was presented in two orders (e.g., "Qa" and "aQ"), resulting in 54, 48, and 32 total stimuli.

In addition to *different* pairs, each experiment employed mixed-case *same* pairs consisting of all of the letters used in the *different* pairs. Letter pairs were 1.1° wide by 0.6° high.

Procedure. In all three experiments, a trial began with the presentation, for 900 msec, of a small rectangle outlining the area in which the letter pair would appear. It was removed, and then after 100 msec the pair was presented for 150 msec. The subjects responded by pressing one of two RT keys, depending on a "same" or "different" judgment. Brief feedback giving the correctness of the response and the RT ensued, followed by a 500-msec blank interval. The subjects were allowed to use either hand or both hands for the responses, with the restrictions that a different finger was to be placed on each key and that the assignment was to remain the same throughout the session.

Blocks consisted of 54 trials (Experiment 1), 48 trials (Experiment 2), or 64 trials (Experiment 3). An experiment consisted of

a 1-h session in which a practice block of randomly selected trials was followed by 12 blocks (Experiment 1), 8 blocks (Experiment 2), or 10 blocks (Experiment 3) of experimental trials. Half of the trials presented *same* and half *different* pairs.

Results and Discussion

To provide an initial description of the results, median RTs were calculated for correct responses, separately for each *different* pair stimulus and for each subject, followed by a calculation of the mean of the medians for each stimulus across subjects. The mean RTs constituted one variable, ordered by stimulus, in a partial correlational analysis. The other variables were the similarity values stated to be predictive of RT by each of the five variants of the generation model and by the abstract-letter-identity model. The result was six correlation coefficients (r), each reflecting the fit of a particular model to the mean RTs. In calculating the correlations, the effect of veridical similarity (the rated similarity of the original stimulus letters) was partialled out to provide model fits that were free of any visual confusion between the stimulus letters themselves. These partial correlations appear in Table 1. Because similarity increases with rated similarity value, a successful letter-matching model should produce a positive correlation to RT.

Across experiments, the best fit was produced by the variant of the generation model in which generation proceeds from the uppercase letter ($r = +.25$).² To determine the significance of this outcome, partial correlations that removed any variability due to veridical similarity were next calculated for each subject using that subject's median RTs for each stimulus pair. The z -transformed correlation coefficients were entered into an analysis of variance (ANOVA) with two factors: model (6 levels) and experiment (3 levels). The only significant effect was that of models [$F(5,190) = 10.08, p < .001$], with no interaction existing between models and experiments [$F(10,190) = 1.62$]. Comparisons between the best-fitting model (generation from the uppercase) and each of the other models showed all comparisons to be significant ($ps < .001$). Thus, although the differences between correlations in Table 1 appear small, they were sufficiently consistent across subjects to result in a significantly best fitting model.

Similar analyses of percent errors produced only slightly more complex results. The fits based on the results accumulated across subjects are shown in Table 1. The ANOVA conducted on individual subjects' correlations to percent errors showed a significant interaction between models and experiment [$F(10,190) = 2.40, p = .01$] and significant main effects of experiment [$F(2,38) = 4.85, p = .01$] and of model [$F(5,190) = 3.05, p = .01$]. Decomposition of the interaction showed what is obvious from Table 1: there was a significant effect of models in Experiment 1 [$F(5,45) = 12.43, p < .001$] but not in Experiment 2 [$F(5,70) = .73$] or Experiment 3 [$F(5,75) = 1.50$]. In Experiment 1, generation from the uppercase letter produced a fit that was significantly better than that provided by any other model ($ps < .02$).

Table 1
Correlations of the Models' Predictions to the Aggregated Results of Experiments 1-3*

	Model					Abstract Letter Identities
	Generation From:					
	1st	2nd	Both	Upper	Lower	
Reaction Time						
Experiment 1	.21 (.49)	.14 (.44)	.21 (.52)	.37 (.63)	-.05 (.29)	.25 (.53)
Experiment 2	.27 (.32)	-.04 (.05)	.16 (.24)	.29 (.34)	-.13 (.01)	-.01 (.20)
Experiment 3	-.11 (.01)	.05 (.14)	-.04 (.11)	.15 (.23)	-.11 (.04)	-.21 (-.15)
Weighted mean	.11 (.25)	.04 (.19)	.09 (.26)	.25 (.38)	-.10 (.09)	-.02 (.16)
Percent Errors						
Experiment 1	.35 (.54)	.35 (.54)	.41 (.61)	.52 (.69)	.19 (.38)	.07 (.23)
Experiment 2	.19 (.17)	-.16 (-.13)	.02 (.03)	.03 (.04)	-.01 (.00)	.00 (.00)
Experiment 3	.10 (.15)	.00 (.06)	.08 (.16)	.24 (.29)	-.01 (.07)	-.18 (-.15)
Weighted mean	.20 (.27)	.03 (.12)	.15 (.24)	.25 (.33)	.04 (.12)	-.05 (.00)

*Partial correlations outside parentheses; raw correlations inside parentheses.

Thus, when a difference between fits was found in the error data (Experiment 1), the results supported those from the RT analyses: uppercase generation produced the best fit. Together, the results of the analyses provide support for uppercase generation.

The obtained fits, $r = +.25$ in the overall RT data and $r = +.52$ in the error data from Experiment 1, should be considered underestimates for two reasons. First, the partial-correlation technique removed any variability due to veridical similarity (between the stimulus letters themselves) before the correlations were calculated. This is a conservative procedure in that variability may have been removed that in fact is better explained by the generation model than it is by confusion between the original letters. If raw correlations are calculated without partialing out veridical similarity, the fits increase to $r = +.38$ and $r = +.69$, respectively.

The second reason why the fits should be considered underestimates is more fundamental and is correctable with less certainty. It relates to the restriction of range of the similarity values stated to be predictive of RT, which resulted from the haphazard selection of stimulus pairs in the two experiments. The similarity values had standard deviations of only .67, .40, and .14 in the three experiments, on a 5-point rating scale. Note that the fits for generation from the uppercase follow this ordering rather closely (Table 1). A more systematic selection procedure in which pairs are chosen to broadly sample the spectrum of similarity values would result in a greater range and would carry the potential for a better fit. Such selection is difficult to carry out without a specific model in mind and so was not done in Experiments 1-3. However, now that generation from the uppercase letter has been supported, broadband selection of stimulus pairs is possible in Experiment 4.

In summary, one specific variant of the fast-generation model has been supported. For simultaneous matches, generation appears to proceed from the uppercase mem-

ber of mixed-case pairs. For example, in the pair "Aa," the "A" would generate an "a," and this generated letter would be compared with the original stimulus "a," which supports a *same* match. The fit of the model was as high as $r = +.69$ in the present results, and the fit may well be greater if systematic sampling of *different* pairs is achieved.³

It is noteworthy that the abstract-letter-identity model fared poorly in predicting RTs and errors (Table 1). The convergence of both stimulus letters on a third node (e.g., "Vg" on "Y") had no disruptive effect. Yet such disruption is predicted by the abstract-identity model since it is convergence on common nodes that must be invoked by the model to explain "Qg"-type confusion. The abstract-letter-identity model cannot have it both ways: either there should be confusion both for "Qg"-type pairs (involving convergence on the abstract letters Q and G) and for "Vg"-type pairs (involving convergence on the abstract letter Y) or confusion for neither. It appears that if abstract-letter identities exist at all, they do not participate in mixed-case letter matches.

Having supported a specific variant of the fast-generation model, my attention next turned to its chronometrics. Experiment 4 varied the onset times of an initial uppercase letter and a succeeding lowercase letter and examined the effect of stimulus onset asynchrony (SOA) on RT. The logic of the experiment is as follows. After the initial uppercase letter is presented, generation of the lowercase letter should proceed over some measurable amount of time. Once a representation of the generated letter is sufficiently developed, that representation then serves as a prime for the succeeding lowercase stimulus letter. In other words, the generation of a letter representation should activate pathways involved in processing identical (but not nonidentical) letters. If the letters are the same, the priming should therefore produce an RT benefit relative to the instance where the letters are different. Consequently, the different-same RT disparity should increase

over SOA as the generated representation develops. The logic of this priming benefit is analogous to that used in other studies of priming (Posner, 1978).

It is also possible that a generated representation decays over some time interval. If so, the priming benefit should be lost and the different-same RT disparity should decrease.

Selection of the proper SOAs to show the temporal development and possible decay of generated representations is guided by the consideration that fast generation probably occurs in less than 100 msec. Recall that mixed-case matches are typically made less than 100 msec slower than pure-case matches and that this interval places an approximate limit on the chronometrics of fast generation. In Experiment 4, SOAs of 0 to 200 msec were used in an effort to capture the appropriate interval.

EXPERIMENT 4

Method

Subjects. Twenty-four subjects participated, all undergraduate volunteers from the University of Colorado at Boulder.

Apparatus and Stimuli. The apparatus was the same as that used in Experiments 1 and 3. Eighteen letter pairs were selected, with the letters drawn from the same character set employed in Experiments 1-3 and in the previous rating study of similarity (Boles & Clifford, 1989). Care was taken to sample pairs across a wide range of similarity values under the hypothesis that generation proceeds from the uppercase: the range was from 1.38 to 4.42, with a standard deviation of .78. The pairs used were Ag, Bo, Ck, Fs, Gq, Hv, Kh, Lb, Np, Ol, Pr, Qz, Rf, Sy, Un, Vc, Yu, and Za. Only upper-lower pairings were used (e.g., "Sy," but not "yS"). Same pairs were created from the initial letters used in *different* pairs. Other characteristics of the stimuli were as in Experiments 1-3.

Procedure. A trial began with a fixation rectangle presented for 900 msec, followed by a blank delay of 100 msec and then an initial stimulus display. If the SOA was 0 msec, the initial display showed both letters. Otherwise it showed only the first, uppercase letter. The nonzero SOAs employed were 33, 67, 100, 133, 167, and 200 msec, and at the end of the SOA the second letter was shown. The first letter remained on the screen while the second was shown, and then both were removed 300 msec from the onset of the first letter. After the subject's "same" or "different" response, brief feedback was displayed, and a 500 msec interval ensued between trials.

Trials were organized into blocks of 63, with one block of practice trials followed by 8 blocks of experimental trials. The 7 SOAs, *same* and *different* trials, and 18 stimulus pairs were equally represented within the 1-h session.

Results and Discussion

Median correct RTs were calculated for "same" and "different" responses at each SOA and for each subject. Difference scores were then calculated (different - same) for each SOA. The means of the difference scores are shown in Table 2.

Planned comparisons were conducted to evaluate the linear and quadratic trends in the difference scores over SOA. A linear trend is predicted if a generated representation develops over time, producing priming for "same" responses, and does not decay; a quadratic trend is predicted if representational development is followed by decay.

Table 2
Results From Experiment 4

	SOA (in Milliseconds)						
	0	33	67	100	133	167	200
Reaction Time							
Different	605	577	554	539	518	510	491
Same	546	522	477	466	446	435	430
Difference	+59	+55	+77	+73	+72	+75	+61
Percent Errors							
Different	10.7	13.8	11.6	12.0	13.7	9.9	7.5
Same	12.6	12.0	9.8	8.4	8.3	6.8	10.4
Difference	-1.9	+1.8	+1.8	+3.6	+5.4	+3.1	-2.9

The linear trend was found to be nonsignificant [$F(1,23) = 1.27$]. However, as Table 2 suggests, there was a significant quadratic trend [$F(1,23) = 9.56, p < .01$].

Similar analyses were conducted on the percent errors with similar results. Table 2 shows the mean difference scores. The linear trend was again nonsignificant [$F(1,23) = .12$], whereas the quadratic trend was highly significant [$F(1,23) = 24.94, p < .001$].

These results indicate that both the product of fast generation and its decay occur within the 200-msec interval of SOAs. Examination of Table 2 allows more precise estimation of these events. As reflected in the error data, fast generation appears to produce a usable representation within 33 msec of its initiation. The representation is essentially complete within 67 msec, as shown in the RT data, and begins a very rapid decay 167 msec after generation begins. Virtually all of the representation seems to be gone within 200 msec.⁴

Since Experiments 1-3 supported a specific generation model, there was no plan to contrast the variants of the model using the results of Experiment 4. Indeed, the similarity values stated to be predictors of performance were very highly correlated between all pairings of models. Thus, between all pairings of first/uppercase letter generation, second/lowercase letter generation, both-letter generation, and abstract-letter identities, mean $r = +.89$. With such high intercorrelations among the predictors, the models would most likely not be separable using the results of Experiment 4, and so the results were not used in that manner.

However, Experiments 1-3 provided support for the variant in which generation proceeds from the uppercase letter. The stimulus pairs in Experiment 4 were selected from a wide range of the similarity values stated to be predictive by this variant. Such broad-spectrum selection should have provided an excellent medium for assessment of the model's predictive power. This appears to have been the case; when RTs were aggregated across SOAs and subjects and were correlated to the similarity values, r equaled $+.84$. Even with veridical similarity partialled out, the correlation was $+.81$. Similarly, the aggregated percent errors showed a raw correlation of $+.85$ and a partial correlation of $+.82$. Clearly, generation from the

uppercase can account for a substantial proportion (about 70%) of the variance in letter-matching performance.

In conclusion, the results of Experiment 4 are at least consistent with those of Experiments 1–3, which indicated that generation from the uppercase appears to underlie simultaneous mixed-case letter matches. In addition, the experiment also indicates that a generated representation has a limited lifespan and is virtually gone 200 msec after commencement of the generation process.

What happens at SOAs greater than 200 msec? Boles and Eveland (1983) reported a continuance of “Qg”-type confusion at 2-sec SOAs, so generation continues to be involved. Assuming that generation is a mandatory operation to support a match, two possibilities are that (1) the previously generated representation, once decayed, is regenerated to allow the match or (2) generation proceeds from the second letter at long SOAs. Both are testable hypotheses that are pursued in Experiment 5. However, it is important first to consider the implications of these hypotheses. Both imply that generation can proceed from the lowercase, since the lowercase member of mixed-case pairs could be presented as either the first or second letter. By this view, for simultaneous matches generation normally proceeds from the uppercase letter only because it is more efficient than generation from the lowercase, not because generation from the lowercase is impossible.

Two reasons can be proposed for the greater efficiency of generation from the uppercase. First, in written language, lowercase letters far exceed uppercase letters in frequency, with the latter largely found at the beginning of sentences. If a case-normalization process is used as an aid in reading, it makes sense to normalize the less frequent uppercase to the more frequent lowercase rather than vice versa. In other words, overlearned reading habits may result in facilitated generation from the uppercase.⁵ Second, there is evidence that uppercase letters resemble one another more than do lowercase letters (Boles & Clifford, 1989). Having generation normally proceed from the uppercase would therefore tend to result in less confusion among the representations of the generated and original letters than would be the situation if generation proceeded from the lowercase. Together or separately, the existence of established reading habits and of differences in confusability among letters may work to make sense of what otherwise appears to be an arbitrary aspect of fast generation.

Experiment 5 tested the competing hypotheses that successive mixed-case matches depend on regeneration from the first letter as opposed to a generated representation from the second letter. Both successive and simultaneous pairs were used, and attention focused on just three variants of the fast-generation model. These were that (1) generation proceeds from the first letter (as implied by the present regeneration hypothesis), (2) generation proceeds from the second letter (as suggested by the alternative for successive pairs), and (3) generation proceeds from the uppercase letter (as supported by Experiments 1–3 for simultaneous pairs).

EXPERIMENT 5

Method

Subjects. Thirteen subjects participated, all undergraduate volunteers from Rensselaer Polytechnic Institute.

Apparatus and Stimuli. The apparatus was the same as that used in Experiments 1, 3, and 4. Twenty-six mixed-case *different* pairs were selected that showed a fairly high degree of dissociation in similarity values (derived from Boles & Clifford, 1989) stated to be predictive of performance by the targeted variants of the fast-generation model (i.e., with generation proceeding from the first, second, or uppercase letter). Across the three pairings of models, the mean intercorrelation was $r = +.29$ (ranging from $-.05$ to $+.44$). The pairs used were Bg, Bo, Ce, Cs, Cu, Dg, Dh, Do, Dp, Ec, Gb, Gd, Gp, Hd, Ob, Od, Op, Pd, Pg, Po, Sc, Uc, Vw, Wv, Vy, and Yv. Members of a pair could be presented in either order, resulting in a total of 52 *different* pairs. In addition, *same* pairs were used that consisted of all of the letters used in the *different* pairs. Other characteristics of the stimuli were as in Experiments 1–4.

Procedure. A trial began with the presentation, for 900 msec, of a small rectangle outlining the area in which the pair would appear. It was removed, and after 100 msec either both letters or the first letter was presented for 150 msec. If a pair was presented, the subject responded as in Experiments 1–3. Otherwise, the second letter was presented, after an 850-msec delay, for 150 msec, and the subject responded. The successive-pair SOA was therefore 1 sec.

Blocks consisted of 60 trials.⁶ The experiment involved a 1-h session in which a single practice block was given, followed by 12 experimental blocks. Within the experimental blocks, the type of match, pair, and pair order were randomly intermixed.

Results and Discussion

The results were handled similarly to those of Experiments 1–3, except that attention focused on the three specific variants of the generation model that were of theoretical interest. The correlations of RT to the models are shown in Table 3, with veridical similarity again partialled out.

For simultaneous matches, the best fit was produced by the variant of the generation model in which generation proceeds from the uppercase letter ($r = +.35$). For successive matches, the best fit was for generation proceeding from the first letter ($r = +.56$). When an ANOVA was run using z -transformed correlation coefficients, with factors of model (3 levels) and delay (2 levels), there was

Table 3
Correlations of the Models' Predictions to the
Aggregated Results of Experiment 5*

	Model		
	Generation From:		
	1st	2nd	Upper
Reaction Time			
Simultaneous	.16 (.18)	.15 (.17)	.35 (.36)
Successive	.56 (.55)	.07 (.11)	.34 (.36)
Percent Errors			
Simultaneous	.15 (.22)	.03 (.11)	.08 (.16)
Successive	.41 (.45)	.19 (.25)	.27 (.32)

*Partial correlations outside parentheses; raw correlations inside parentheses.

in fact a significant model $\times$ delay interaction [$F(2,24) = 5.00, p < .02$]. There was also a significant main effect of model [$F(2,24) = 6.87, p < .005$].

Decomposition of the interaction proceeded by testing the model factor at each level of delay. For simultaneous matches, the factor was marginally significant [$F(2,24) = 3.25, p = .06$]. Table 3 shows results congruent with those from Experiments 1–3 (see Table 1). For successive matches, the model factor was highly significant [$F(2,24) = 8.69, p = .001$]. The best-fitting model, generation from the first letter, fit significantly better than did generation from the second letter [$F(1,12) = 11.00, p < .01$] and marginally better than generation from the uppercase letter [$F(1,12) = 3.71, p = .08$].

The partial correlations of percent errors to the models are shown in Table 3. The two-factor ANOVA did not show any significant effects.

It is worth noting that the selection of letter pairs with the aim of dissociating the three contrasted models once again reduced the variability of the similarity values: across models, the standard deviations were only .32, .32, and .15. In all likelihood, the reduced variability accounts for the fact that the obtained correlations were lower than in Experiment 4 but on a par with those in Experiments 1–3.

The results of Experiment 5 essentially replicate those of Experiments 1–3 in suggesting that for simultaneous mixed-case matches, the model in which generation proceeds from the uppercase letter fits better than models in which generation proceeds from the first or second letter. Thus the RT results from Table 3 mirror those from Table 1. Even though the error results for simultaneous matches were less congruent, the fits were poor in this study (Table 3).

Of primary importance is the outcome for successive matches. Evidence was found that successive matches are supported by generation from the first letter. This was seen in the RT results, where the model fit significantly or marginally better than either of the alternatives. The percent error results were also reasonably consistent with this view.

In conjunction with the findings from Experiment 4, the results support the interpretation that once the first 200 msec have elapsed following the presentation of a letter and any generated representation has decayed, that representation can be regenerated to support a match to the second letter. There is no support found for the logical alternative, that generation proceeds from the second letter. The interaction with delay is striking (Table 3), and it lends confidence to the idea that quite different generation products are used for simultaneous and successive mixed-case matches.

GENERAL DISCUSSION

Experiments 1–3 investigated simultaneous mixed-case letter matches and supported a specific variant of the fast-generation model in which generation proceeds from the uppercase letter of mixed-case pairs. This variant fit sig-

nificantly better than four others and better than a model based on abstract-letter identities on the basis of the RT results of both experiments and the error results of Experiment 1. The lack of specificity in the generation model as described by Boles and Eveland (1983) has therefore been remedied.

Experiment 4 extended these results by showing that generation from the uppercase can account for a substantial proportion of the variance in both RT and error results if care is taken to broadly sample *different* letter pairs for the amount of confusion stated to be present by the model. The correlations between the predictive similarity index and the dependent measures ranged from +.81 to +.85.

The chronometrics of the fast-generation process were also revealed by Experiment 4. A manipulation of SOA between pair members provided evidence that fast generation creates a usable product within 33 msec of its initiation and a complete product within 67 msec. These estimates are consistent with the estimate of less than 100 msec for the time course of generation, derived independently from the disparity in mixed-case and pure-case RTs. Indeed, in Boles and Eveland (1983) and Boles and Hellige (1984), the disparity between stimulus types averaged 61 msec, a figure that shows remarkable agreement with the currently estimated 67-msec completion time for fast generation.

Experiment 4 also indicated that generated representations decay within 200 msec of commencement of the generation process. Experiment 5 addressed the question of how successive mixed-case matches can be made given such rapid decay. Support was found for the existence of a regeneration process, in that matches made with a 1-sec SOA were apparently supported by a representation generated from the first letter. Models invoking generation from the second letter, or from the uppercase letter regardless of its sequential position, could not account for the results.

Together the experiments provide a reasonably coherent view of mixed-case matches. Normally, simultaneous matches rely on generation from the uppercase letter, a process that presumably is more efficient than the alternatives. That generation *can* occur from lowercase letters, however, is shown by the fact that successive matches rely on a regenerated representation from the first letter, regardless of whether it was upper- or lowercase.

It is instructive to compare the characteristics of fast generation with the slower process of generation employed in imagery. Fast generation is fast in dynamics (less than 67 msec), produces a representation that decays rapidly (less than 200 msec), and judging from the introspections of subjects, involves no subjective imagery. Furthermore, one can speculate that it is an automatic process, since rapid dynamics and inaccessibility to introspections (e.g., no imagery) are often characteristic of automatic processes. In contrast, slow generation shows slow dynamics (500–1,500 msec to develop a letter image), produces a representation that is maintainable, involves subjective imagery, and on the basis of the effort involved, is proba-

bly a controlled process (Posner, 1978). The contrast makes clear that fast and slow generation are two very distinct processes, even though both involve types of visual representation.

In large part, it is the specifically visual nature of fast generation that allows the mechanism to be distinguished from the more general concept of automatic activation. The latter might suggest that a plethora of codes (e.g., visual, phonetic, and semantic) can be generated from a stimulus letter, but it is specifically a visual code, and even more specifically the visual code of the opposite case, that appears to support mixed-case matches. It thus seems appropriate to use the term "fast generation" to distinguish the process both from general automatic activation and from the slow-generation process used in imagery.

Finally, treatment of the present findings would not be complete without once again considering the original model of mixed-case matching: that such letter pairs are matched using a phonetic representation of the letter names (Posner, 1978). Does phonetic similarity between letters predict *different* RTs? The answer is resoundingly no. Using the acoustic confusion matrix of Conrad (1964), the correlations of phonetic similarity to the aggregated RTs and errors in the purely simultaneous match experiments (1-3) are all found to lie between $r = -.02$ and $r = +.07$. In the remaining two experiments, the picture is not much better. Collapsing across the SOAs of Experiment 4, phonetic similarity correlated only at $r = -.07$ for RT and $r = -.02$ for errors. And in Experiment 5, the correlations to RT were $r = +.24$ for the simultaneous matches and $r = +.16$ for the successive matches; the corresponding correlations to errors were $r = -.09$ and $r = +.09$. It is clear that there is little, if any, support in these results for the use of a phonetic representation of letter names. Although the name-code model has had an irrepressible life of its own and continues to appear in cognitive psychology texts (Ashcraft, 1989, pp. 278-279; Glass & Holyoak, 1986, p. 63; Solso, 1988, pp. 152-154), the time may finally have come to lay it to an honored rest.

REFERENCES

- ASHCRAFT, M. H. (1989). *Human memory and cognition*. Glenview, IL: Scott, Foresman.
- BARNES, S., & BURKE, R. S. (1988). What is Apple-Psych? *Behavior Research Methods, Instruments, & Computers*, **20**, 150-154.
- BESNER, D., COLTHEART, M., & DAVELAAR, E. (1984). Basic processes in reading: Computation of abstract letter identities. *Canadian Journal of Psychology*, **38**, 126-134.
- BOLES, D. B. (1986). Confusion and visual field effects in rhyme and name letter matching. *Perception & Psychophysics*, **39**, 123-128.
- BOLES, D. B., & CLIFFORD, J. E. (1989). An upper- and lowercase alphabetic similarity matrix, with derived generation similarity values. *Behavior Research Methods, Instruments, & Computers*, **21**, 579-586.
- BOLES, D. B., & EVELAND, D. C. (1983). Visual and phonetic codes and the process of generation in letter matching. *Journal of Experimental Psychology: Human Perception & Performance*, **9**, 657-674.
- BOLES, D. B., & HELDIGE, J. B. (1984). Case effects in letter-name matching: A partial replication. *Bulletin of the Psychonomic Society*, **22**, 23-25.
- CARRASCO, M., KINCHLA, R. A., & FIGUEROA, J. G. (1988). Visual letter-matching and time course of visual and acoustic codes. *Acta Psychologica*, **69**, 1-17.
- COLTHEART, M. (1981). Disorders of reading and their implications for models of normal reading. *Visible Language*, **15**, 245-286.
- CONRAD, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology*, **55**, 75-84.
- DAVIS, R., & SCHMIT, V. (1973). Visual and verbal coding in the interhemispheric transfer of information. *Acta Psychologica*, **37**, 229-240.
- GEFFEN, G., BRADSHAW, J. L., & NETTLETON, N. C. (1972). Hemispheric asymmetry: Verbal and spatial encoding of visual stimuli. *Journal of Experimental Psychology*, **95**, 25-31.
- GLASS, A. L., & HOLYOAK, K. J. (1986). *Cognition*. NY: Random House.
- HUNT, E. (1978). Mechanics of verbal ability. *Psychological Review*, **85**, 109-130.
- OSGOOD, G. (1988). Generalizing the Apple-Psych system. *Behavior Research Methods, Instruments, & Computers*, **20**, 155-157.
- POSNER, M. I. (1978). *Chronometric explorations of mind*. Hillsdale, NJ: Erlbaum.
- RUDNICKY, A. I., & KOLERS, P. A. (1984). Size and case of type as stimuli in reading. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 231-249.
- SOLSO, R. L. (1988). *Cognitive psychology*. Boston: Allyn & Bacon.

NOTES

1. The minimum value must be used because if only one stimulus letter resembles the third letter, there is no convergence.
2. Following widely accepted procedures, the *r*-to-*z* transformation and back-transformation were applied in calculating weighted-mean correlations.
3. A reviewer has wondered whether the real words among the letter pairs (e.g., My) might have produced distorted RTs because of their visual familiarity to subjects. If so, this could have depressed the correlation between the best-fitting model and RT. This suggestion is particularly applicable to Experiment 2, which used five such "word" pairs in a familiar visual arrangement (i.e., Ah, Fa, My, On, and Ow). The other experiments used a maximum of one such pair each. To address the question, the data from Experiment 2 were reexamined, and raw correlations were calculated between RT and similarity on the basis of generation from the uppercase letter (the best-fitting model). The correlation changed little when the "word" pairs were deleted, if anything falling slightly from $r = .34$ to $r = .29$. It seems likely that such pairs were too infrequent to much affect the results of this or the other experiments.
4. Lester Krueger has suggested that a waxing and waning response bias, toward and then away from "same" responses, could produce the quadratic trends. Although the point is well taken, a shifting response bias may be an aspect of the mechanism suggested here. That is, as a representation is generated, a bias would likely co-occur for "same" responses to similar patterns, a bias that would be lost as the representation decayed.
5. Rudnicki and Kolers (1984) found that mixing letter cases within words disrupted word recognition and that a single case change was as disruptive as were multiple changes. They interpreted their results as supportive of the use of word shapes in reading. An alternative interpretation is that when mixed cases are present, a case-normalization process is used that operates on all of the letters in a word in parallel. However, this is not a necessary assumption of the fast-generation model.
6. Because of a programming error, four *different* pairs (Bg, Dp, Gb, and Pd) in both orders (e.g., Bg, gB) were presented twice as often as the other *different* pairs, resulting in 60 rather than 52 trials per block. Trial randomization was unaffected.

(Manuscript received March 28, 1991;
revision accepted for publication September 23, 1991.)