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Brief article

# Does visual word identification involve a sub-phonemic level?

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**Abstract**

The phonological codes activated in visual word recognition can be thought of minimally as strings of discrete and unstructured phoneme-like units. We asked whether these codes might additionally express a letter string's phonological form at a featural or gestural level. Specifically, we asked whether the priming of a word (e.g. *sea*, *film*, *basic*) by a rhyming non-word would depend on the non-word's phonemic-feature similarity to the word. The question was asked within a mask–prime–target–mask sequence with both brief (57 ms in Experiments 1 and 2) and long (486 ms in Experiment 1) prime durations. Non-word primes that differed from their targets by a single phonemic feature (initial voicing as in ZEA, VILM, PASIC) led to faster target lexical decisions than non-word primes that differed by more than a single phonemic feature (e.g. VEA, JILM, SASIC). Visual word recognition seems to involve a sub-phonemic level of processing. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords*: Visual word identification; Sub-phonemic level; Phonological code

## 1. Introduction

There is general agreement that a phonological code is assembled and/or activated in visual word recognition. The specific role (e.g. Coltheart, Curtis, Atkins, & Haller, 1993; Lukatela & Turvey, 1998; Van Orden & Goldinger, 1994) and nature

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(e.g. Abramson & Goldinger, 1997; Berent & Perfetti, 1995; Lukatela & Turvey, 2000) of this code, however, are matters of considerable debate. The content of the code is the focus of the present research. We consider the hypothesis that it includes the features that compose the individual phonemes.

A common hypothesis is that the orthography–phonology mapping occurs either at a level of analysis at which individual letters and letter clusters refer to phonemes (e.g. Coltheart et al., 1993) (that is, the units given by organizations of feature bundles) or at a coarser level (e.g. *onsets* and *rimes*, Treiman & Chafetz, 1987). It would seem, however, that the proposal for a necessary and strong relation between reading and the mechanism of spoken language (e.g. Liberman, 1992, 1998; Rozin & Gleitman, 1977) demands a sub-phonemic level of coding in visual word identification. Phonological segments are not the ultimate constituents of spoken language, and features (Halle, 1990) or gestures (Browman & Goldstein, 1995) are essential to accounts of speech production and a speaker's linguistic knowledge. Whereas features are adjectival properties or attributes of phonemes, gestures are constituent actions of phonemes. It is a current matter of debate as to whether phonemes are more usefully and more properly addressed through the notion of features or through the notion of gestures. We refrain from adopting a position on this issue in the present article. Throughout the text the greater use of the term 'features' is for reasons of simplicity and convention.

In respect to the specific issue of lexical access in spoken language, one major contemporary hypothesis is that features are extracted from the speech input and that features compose the accessed lexical representations (e.g. Lahiri & Marslen-Wilson, 1991; Marslen-Wilson & Warren, 1994). This latter feature-based hypothesis rejects the conventional notion of an intervening segmental level, typically interpreted as a string of discrete and unstructured phoneme-like units. It promotes a single processing step in which feature information is mapped directly onto lexical representations, themselves organized in terms of features.

If the feature-based hypothesis applies similarly to visual lexical access, then a minimal expectation is that feature similarity between letter strings (that is, the number of phonemic features in common) should have psychological consequences over and above those due to segmental similarity (that is, the number of phonemes in common). Evidence for phonemic features in visual word recognition is not, however, evidence against a segmental level. The alphabetic principle and the significance of phonological awareness in learning to read (Brady & Shankweiler, 1991; Rozin & Gleitman, 1977) point to the psychological reality of phonological segments.

## 2. Experiment 1

Consider a written monosyllabic word with initial letter representing a voiceless fricative, for example, *sea*. The consonantal grapheme *s* can be replaced by a voiced counterpart *z* producing a non-word, for example, *zea*. It can also be replaced by a grapheme such as *v* that represents a phoneme differing from /s/ by more than one feature. We predicted that if the similarity of non-words to words at the level of phonemic features was of significance, then the prime–target pair ZEA–*sea* should result in a faster lexical decision on the target than the prime–target pair VEA–*sea*. Given a phonemic-feature level of processing and representation, the fewer the differences in phonemic features between a non-word prime and its target, the greater should be the prior activation by the prime of the target's lexical representation. In conception and design, Experiment 1 is related to priming experiments directed at how spoken words are matched to their internal representations (e.g. Connine, Blasko, & Wang, 1994; Marslen-Wilson, Moss, & van Halen, 1996). Of particular relevance are experiments showing that auditory non-word primes, which differ by no more than two phonemic features from their base words, can prime visually presented targets that are semantically related to the base words (Connine, Blasko, & Titone, 1993).

The above prediction of greater priming by ZEA-like primes than VEA-like primes was evaluated at a short (57 ms) and long (486 ms) onset asynchrony between prime and target within a presentation sequence of mask–prime–target–mask. Phonological priming has been demonstrated for both time scales (e.g. Lukatela, Frost, & Turvey, 1998; Lukatela & Turvey, 1994).

### *2.1. Method*

#### *2.1.1. Participants*

Seventy-two University of Connecticut undergraduates participated in partial fulfillment of a course requirement. Each participant was randomly assigned to one of four groups (18 participants per group).

#### *2.1.2. Materials*

A base set of 24 words was assembled as the set of targets. Some were three-letter (CVC or CVV) monosyllabic words (e.g. *sea*, *boy*) and some were four-letter (CVCC or CVVC) monosyllabic words (e.g. *bank*, *pool*) (see Appendix A). The three defining characteristics of the targets were: (a) the initial letter/phoneme of each target was a plosive or fricative; (b) each target was a dominant member, in terms of frequency of occurrence, of the neighborhood defined by the target's vowel or vowel plus coda; and (c) the neighborhoods defined by the visual and phonological forms of the vowel or vowel plus coda were identical.

Test primes were generated by replacing each word's initial letter/phoneme by a letter/phoneme that differed only in voicing (e.g. *sea* yields ZEA; *bank* yields PANK). The selection of voicing as the to-be-manipulated feature in the present experiment was motivated by the expectation that sub-phonemic contributions to visual word identification would be especially difficult to detect. It seemed prudent, therefore, to identify and exploit that single-feature difference between the non-word test prime and its word target that rendered the two most similar. A difference in voicing seemed to satisfy the preceding requirement given that the acoustic spectra of two spoken rhyming words are most alike when the feature contrast between their initial phonemes is simply one of voicing.

Control primes were generated by replacing each word's initial letter/phoneme by a letter/phoneme so that the resulting control prime differed from the target by two or more features (e.g. *sea* yields VEA; *bank* yields ZANK). An important criterion for the construction of a control prime was that if it also differed from a word by a single feature in the initial letter/phoneme, the word in question (e.g. *sank*) was lower in frequency than the word (*bank*) corresponding to the test prime. The targets and primes are identified in Appendix A. For the targets, the mean frequency (Kucera & Francis, 1967), mean bigram frequency of the initial two letters, and mean neighborhood (N-metric) size were 148 ± 235, 28.7 ± 22.4, and 13.6 ± 6.0, respectively. For the test and control non-word primes, the average bigram frequencies of the initial two letters were 19.4 ± 19.9 and 19.9 ± 42.1, respectively.

### *2.1.3. Design*

Two counterbalanced lists (A and B) were created consisting of 24 non-word–word pairs. In each list, 12 target words were primed by test non-words and 12 target words were primed by control non-words. For example, if the target word *sea* in List A was preceded by the test prime ZEA (e.g. ZEA–*sea*), then in List B this target word was preceded by the control prime VEA (e.g. VEA–*sea*). One half of the participants saw List A, and the other half saw List B. Additionally there were 174 filler prime–target pairs. Of these, 72 were word–non-word, 72 were non-word–word, 15 were word–word and 15 were non-word–non-word. An additional 57 prime–target pairs were used for practice trials.

### *2.1.4. Procedure*

Participants, run one at a time, sat in front of the monitor of a DIGITAL 466 computer. The viewing distance was about 60 cm. The refresh rate of the VENTURIX monitor was 70 Hz making a refresh cycle (i.e. a 'tick') equal to 14.3 ms. The stimuli appeared on the screen as white characters on a dark background. Each trial consisted of a sequence of four visual events in the same location on the center of the screen: (1) a row of five hash marks for 20 ticks (286 ms); (2) an uppercase non-word prime for four ticks (57 ms) or 34 ticks (486 ms); (3) a lowercase word target for six ticks (86 ms) or 36 ticks (515 ms); and (4) a row of five letter xs in lower case for three ticks (43 ms). All interstimulus intervals were 0 ms. Spatially, the pre-prime and the post-target masks overlapped the prime and target, respectively. The two conditions consisted, therefore, of a short prime (57 ms)–short target (86 ms) and a long prime (486 ms)–long target (515 ms) sandwiched between two masks. The role of the post-target mask was to make the lexical decision on the target less robust and, therefore, more sensitive toward subtle influences, such as, perhaps, the phonemic-feature description of the prime. This hypothesized function of the post-target mask was expected to be most effective at the short prime–short target condition.

Dark adaptation (low levels of screen and room illumination) facilitates the demonstration of phonological priming by masked primes in the lexical decision task with mask–prime–target sequences (e.g. Berent, 1997; Lukatela et al., 1998;

Lukatela & Turvey, 2000).[1] Accordingly, participants in the short condition were run under dark adaptation (ambient room illumination ≈ 0.07 fc, screen illumination ≈ 0.5 fc). In contrast, participants in the long condition were run under light adaptation typical of vision in a well-lit office. The preceding light parameters prevailed during instructions, practice and experiment.

Controlled presentation of the sequence of stimuli at the identified temporal parameters was by means of DMASTR software (developed at Monash University and University of Arizona by K.I. Forster and J.C. Forster). Participants were instructed to press the appropriate key as quickly as possible in making their lexical decision on the lower case letter string, ignoring the upper case letter string. If the latency (measured from target onset) was longer than 1400 ms a warning message ('TRY FASTER!') appeared on the screen.

### 2.2. Results

Reaction times (RTs) were trimmed minimally by applying a cutoff of 100 ms for fast responses and a cutoff of 1800 ms for slow responses. The outliers constituted less than 0.5% of all responses (see Ulrich & Miller, 1994, p. 69).

In the short prime–short target condition, mean RT and mean error rates were 608 ms and 18.3% for ZEA–*sea* and 624 ms and 18.8% for VEA–*sea*. In the long prime–long target condition these values were 527 ms and 6.7%, and 536 ms and 7.6%, respectively.

A 2 × 2 × 2 (Group × Duration × Prime type) analysis of variance (ANOVA) was conducted on correct latencies.[2] Duration × Prime type was not significant ($F < 1$), but both component main effects were significant (prime type (Test = 568 ms versus Control = 580 ms): $F1(1,68) = 7.76$, $P < 0.01$, MSE = 689; $F2(1,22) = 6.46$, $P < 0.02$, MSE = 677; prime duration (Short = 616 ms versus Long = 532 ms): $F1(1,68) = 16.83$, $P < 0.001$, MSE = 15115; $F2(1,22) = 163.57$, $P < 0.0001$, MSE = 1131). Group × Prime type ANOVAs revealed that prime type was significant in the short condition ($F1(1,34) = 5.53$, $P < 0.03$, MSE = 826;

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[1] Phonological effects of masked primes in lexical decision with light adapted participants occur in mask–prime–mask–target sequences (Lukatela, Carello, Savic, Urosevic, & Turvey, 1998; Lukatela, Frost, & Turvey, 1999; Lukatela, Savic, Urosevic, & Turvey, 1997). Without an intervening mask, that is, in mask–prime–target sequences, such effects have proven elusive under conditions of light adaptation (Lukatela, Carello et al., 1998). The successful demonstrations with dark adapted participants (Berent, 1997; Lukatela, Carello et al., 1998; Lukatela & Turvey, 2000) implicate additional significant factors, all well-known in the masking literature (such as relative energy levels, spatial characteristics of the mask, complexity of three-field interactions). Clearly, parametric examination of presentation conditions is needed for a fuller understanding of visual word processing at brief time scales (see also Xu & Perfetti, 1999).

[2] Interactions involving the group factor are ignored. Group A experiences the control stimuli that correspond to Group B's test stimuli and, conversely, Group B experiences the control stimuli that correspond to Group A's test stimuli. The contrast between performance on test and control stimuli within a group is, therefore, meaningless, as is any difference between the groups in the magnitude of the test–control contrast.

$F2(1,22) = 4.14$, $P < 0.05$, MSE = 830), but not in the long condition ($F1(1,34) = 2.48$, $P = 0.12$, MSE = 552; $F2(1,22) = 2.50$, $P = 0.13$, MSE = 488). Although Duration × Prime type was non-significant, the preceding within-duration analyses suggest that the phonemic feature effect was more pronounced in the short (and presumably more sensitive) condition.

In the three factors ANOVA on errors, only prime duration (Short = 18.52% versus Long = 7.17%) was significant ($F1(1,68) = 27.96$, $P < 0.0001$, MSE = 166; $F2(1,22) = 29.41$, $P < 0.0001$, MSE = 105).

## 3. Experiment 2

Experiment 1 found that *sea* was responded to more quickly following ZEA than following VEA. This result is in agreement with the hypothesis that the assembled phonological structure for a presented letter string may include the feature description of the individual phonemes. An alternative account of Experiment 1 follows, however, from considering the possibility that errors in processing at brief exposures sometimes lead to visual codes and, subsequently, phoneme-level codes that differ from those expected. If the probability of processing the test prime ZEA as SEA is greater than the probability of processing the corresponding control prime VEA as SEA, then the prime type effect of Experiment 1 could be attributed, more simply, to greater similarity between activated letter and phoneme units in ZEA–*sea* than VEA–*sea*. We applied a letter feature analysis to the stimuli of Experiment 1 (see Evett & Humphreys, 1981). On average, 3 and 9 visual features distinguished test primes and control primes, respectively, from the upper case versions of their targets ($t = -9.00, P < 0.0001$). The likelihood was greater, therefore, for test primes to be mistakenly processed as identity primes than for control primes to be mistakenly processed as identity primes.

An additional version of the visual feature hypothesis is framed by the following question: did the number of common visual features in ZEA–*sea* exceed that in VEA–*sea*? That is, were test primes more visually similar to the lower case targets than control primes? The aforementioned letter feature analysis was adapted to lower case letters. On average, 3.5 and 6 visual features distinguished test primes and control primes, respectively, from their targets ($t = -4.08$, $P < 0.001$).

In Experiment 2, the mean numbers of visual features distinguishing test primes from the targets written in upper case and control primes from the targets written in upper case were equated. Further, the difference between prime and lower case target was greater for the test than the control primes.

### *3.1. Method*

#### *3.1.1. Participants*

Forty-six University of Connecticut undergraduates participated in partial fulfillment of a course requirement. Each participant was randomly assigned to one of two groups (23 participants per group). None had participated in Experiment 1.

#### 3.1.2. Materials

A base set of 48 monosyllabic and bisyllabic words was assembled. One half of the stimuli were words of four letters in length, and the other half were words of five letters in length. Similar to Experiment 1, a set of the 48 test prime–target pairs (e.g. FOICE–*voice*) and a set of 48 control prime–target pairs (e.g. KOICE–*voice*) were constructed. All stimuli are shown in Appendix B. In addition, 203 different filler prime–target pairs consisting of stimuli three-, four-, or five-letters in length were prepared. Their use was to discourage strategic effects. For the targets, the mean frequency (Kucera & Francis, 1967), mean bigram frequency of the initial two letters, and mean neighborhood (N-metric) size were $163 \pm 269$, $38.4 \pm 30.0$, and $3.3 \pm 3.4$, respectively. For the test and control non-word primes, the average bigram frequencies of the initial two letters were $19.5 \pm 21.5$ and $22.4 \pm 30.8$, respectively. The mean number of visual features distinguishing test and control primes from the targets if written in upper case was 6.4 and 5.7, respectively ($t = 1.11$, $P = 0.66$). The mean number of visual features distinguishing test and control primes from their lower case targets was 6.6 and 5.0, respectively ($t = 2.69$, $P < 0.01$).

#### 3.1.3. Design and procedure

The stimuli were partitioned into subsets in the manner described for Experiment 1, with the groups of participants distinguished, as in Experiment 1, by the subsets they received. The illumination values and stimulus exposures of the short prime–short target condition of Experiment 1 were used in Experiment 2.

### 3.2. Results

Mean RT and mean error rates were 571 ms and 14.67% for the test prime condition (e.g. VILM–*film*) and 581 ms and 15.04% for the control condition (JILM–*film*). A $2 \times 2$ (Group $\times$ Prime type) ANOVA conducted on latencies revealed a main effect of prime type ($F1(1,44) = 4.86$, $P < 0.03$, MSE = 451; $F2(1,22) = 4.08$, $P < 0.05$, MSE = 853). In the corresponding error analysis, prime type was not significant ($F < 1$).

### 3.3. Discussion

The stimuli of Experiment 1 were composed of three or four letters. Words of three letters in length that satisfy the criteria of the present experimental design are relatively rare. One consequence of this latter fact was that the initial phoneme manipulation in Experiment 1 was constrained primarily to the letter contrasts of P versus B and D versus T, thereby reducing the generality of the results. The use of words composed of four and five letters in Experiment 2 extended the range of initial-phoneme contrasts. In particular it resulted in (a) an equalizing of the visual similarity between the upper case test and control primes and the upper case versions of their targets and (b) a smaller visual difference between test primes and their lower case targets than between control primes and their lower case targets. The finding of a continued advantage of test primes over control primes under the conditions of Experiment 2 is, therefore, important. It strengthens the conclusion from Experiment 1 that visual word identification involves sub-phonemic processing. We emphasize, however, that the evidence has emerged under the conditions described in Sections 2.1 and 3.1. It remains to be seen whether sub-phonemic processing can be observed under different presentation parameters.

## 4. General discussion

To accommodate the present results, models of visual word recognition (e.g. Coltheart et al., 1993; Plaut, McClelland, Seidenberg, & Patterson, 1996) would have to include processing and representation in terms of phonemic features.[3] They could do so, we think, without compromising major architectural assumptions. For example, in the dual-route cascade model (Coltheart et al., 1993), activation of phonemic features could occur on either the lexical or non-lexical route or it could occur on both routes. On the lexical route, visually activated whole-word units in the orthographic lexicon activate, in turn, whole-word units in the phonological lexicon. In light of the present results, the phonological lexicon could be characterized by sub-phonemic representations of words along with phonemic representations. Similarly, on the non-lexical route, sub-phonemic processing could occur prior to or subsequent to phonemic processing. A more radical revision would dispense altogether with phonemes, in keeping with the radical and controversial proposition for dispensing with an intervening segmental level in the modeling of auditory word recognition (e.g. Lahiri & Marslen-Wilson, 1991; Marslen-Wilson & Warren, 1994).

Aside from issues of how to adjust current models of visual word identification, the present results underline the pervasive involvement of phonological coding in processing printed words (e.g. Frost, 1998; Lukatela et al., 1999; Van Orden, Pennington, & Stone, 1990). Our finding that the phonology in question may be as detailed as that provided by phonemic features or gestures suggests that the visual word recognition system is even more intimately connected to the machinery of speech production and perception than heretofore recognized. Future research, directed at other phonemic features and other presentation parameters, will be needed to determine the generality of our finding and to ascertain the sensitivity of the visual word recognition system to a letter string's sub-phonemic structure.

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[3] We must be circumspect, however, about the assumption that the present data justify adding an additional level of representation to established models. Reaction time data obtained using the subtraction method (such as the design of the present experiment) cannot sufficiently motivate either the insertion or deletion of mental processes (Pachella, 1974).

## Appendix A. Stimulus materials in Experiment 1

Each row identifies, in order, the target word, the test prime, and the control prime.

1. BAG, PAG, VAG
2. BANK, PANK, ZANK
3. BARN, PARN, LARN
4. BED, PED, VED
5. BIRD, PIRD, JIRD
6. BOAT, POAT, NOAT
7. BOB, POB, VOB
8. BOY, POY, MOY
9. BULK, PULK, MULK
10. DARK, TARK, NARK
11. DAY, TAY, VAY
12. DESK, TESK, NESK
13. DID, TID, YID
14. DUST, TUST, HUST
15. PAL, BAL, NAL
16. PINK, BINK, NINK
17. POOL, BOOL, LOOL
18. POST, BOST, VOST
19. SEA, ZEA, VEA
20. SIN, ZIN, NIN
21. TAP, DAP, VAP
22. TEAM, DEAM, NEAM
23. TEST, DEST, MEST
24. TOP, DOP, JOP

## Appendix B. Stimulus materials in Experiment 2

Each row identifies, in order, the target word, the test prime, and the control prime.

1. BABY, PABY, SABY
2. BANK, PANK, ZANK
3. BASIC, PASIC, SASIC
4. BIRDS, PIRDS, JIRDS
5. BOAT, POAT, JOAT
6. BUSES, PUSES, SUSES
7. CITY, ZITY, YITY
8. CLEAR, GLEAR, SLEAR
9. COMIC, GOMIC, LOMIC
10. DARK, TARK, NARK

11. DESK, TESK, NESK
12. DIRT, TIRT, YIRT
13. DOZEN, TOZEN, VOZEN
14. FACT, VACT, YACT
15. FELT, VELT, RELT
16. FILM, VILM, JILM
17. FINAL, VINAL, HINAL
18. FIRST, VIRST, MIRST
19. FOCUS, VOCUS, JOCUS
20. FUND, VUND, YUND
21. GIRL, KIRL, LIRL
22. GIVEN, KIVEN, MIVEN
23. GREET, KREET, PREET
24. KEPT, GEPT, LEPT
25. PAGE, BAGE, NAGE
26. PANIC, BANIC, LANIC
27. PROOF, BROOF, CROOF
28. SAFE, ZAFE, LAFE
29. SALAD, ZALAD, LALAD
30. SELF, ZELF, KELF
31. SEVEN, ZEVEN, JEVEN
32. SIZE, ZIZE, HIZE
33. SOFA, ZOFA, MOFA
34. SOFT, ZOFT, YOFT
35. SOLAR, ZOLAR, YOLAR
36. SOLID, ZOLID, DOLID
37. SOON, ZOON, HOON
38. SORT, ZORT, JORT
39. SUCH, ZUCH, KUCH
40. TASK, DASK, JASK
41. TINY, DINY, YINY
42. TOTAL, DOTAL, JOTAL
43. VALID, FALID, CALID
44. VIRUS, FIRUS, YIRUS
45. VISIT, FISIT, KISIT
46. VITAL, FITAL, JITAL
47. VIVID, FIVID, SIVID
48. VOICE, FOICE, KOICE

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