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The role of letter features in visual-word recognition: Evidence from a delayed segment technique☆

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ABSTRACT

Do all visual features in a word's constituent letters have the same importance during lexical access? Here we examined whether some components of a word's letters (midsegments, junctions, terminals) are more important than others. To that end, we conducted two lexical decision experiments using a delayed segment technique with lowercase stimuli. In this technique a partial preview appears for 50 ms and is immediately followed by the target item. In Experiment 1, the partial preview was composed of terminals + junctions, midsegments + junctions, or midsegments + terminals — a whole preview condition was used as a control. Results only revealed an advantage of the whole preview condition over the other three conditions. In Experiment 2, the partial preview was composed of the whole word except for the deletion of midsegments, junctions, or terminals — we again employed a whole preview condition as a control. Results showed the following pattern in the latency data: whole preview = delay of terminals < delay of junctions < delay of midsegments. Thus, some components of a word's constituent letters are more critical for word identification than others. We examine how the present findings help adjust current models of visual word identification or develop new ones.

1. Introduction

In cognitive psychology today, a formidable consensus now exists that 1) a parallel letter recognition process involving explicit labelling at the letter level and 2) a mapping of these labelled entities onto abstract letter units mediates visual-word recognition. In line with this, a fundamental goal of computational models of visual-word recognition has been to specify in detail how, and in what sense — implicitly as feature conjunctions[1], or explicitly as labelled entities — the words' constituent letters are extracted from the visual features.

In the past years, there has been significant progress in our understanding of the response properties of the various layers in the visual and inferior temporal cortex. Sophisticated computational attempts to model orthographic processing and lexical access have been put forward and fitted to data. But *whether* or *to what extent* — in neuro-physical and cognitive-processing terms — explicit labelling occurs, or *where* and *how* the mapping unto abstract letter identities is attained, or *what* — in perceptual processing terms — the key components of the letter are during visual word recognition and reading, remains unclear. Theoretical framing options for staking-out the *what* and tracking-down the *how*, are many-fold and discrepant. Here we focus on the *what*, and try to establish the relative importance for *visual word recognition* of several components that have been presumed in previous experiments to be key components.

Many current computational models of visual-word recognition employ three processing levels: letter features, letters, and words (e.g., see Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001; Davis, 2010; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Perry, Ziegler, & Zorzi, 2007; see also Carreiras, Armstrong, Perea, & Frost, 2014, for a recent review). But despite the intrinsic relevance of the widely acknowledged "feature detection" (feature-analytic) and "feature integration" processes at the perceptual processing front end, models of visual-word recognition have focused most assiduously on the intricacies of the hypothesized letter-level and word-level processing further downstream, and been satisfied to leave the structural particularities of the "letter feature level" (e.g., see Finkbeiner & Coltheart, 2009, for discussion), and the microprocesses occurring at the perceptual processing

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[1] As discussed by McClelland (1996), in an intrinsic integration model, a letter is a pattern over feature units, and a word is a pattern over sets of feature units. Letters, words, and phrases appear as "simply the coherent and relatively independent sub-patterns of larger, more coherent whole patterns" (p. 647).

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front end comparatively under-specified. In computational modelling per se the prevailing strategy has been to "take a leap of faith and assume we have made it to the letter" where the computational prospect might be "a bit more tractable" (Balota, Yap, & Cortese, 2006, p. 289).

As a concomitant of this, all the above-cited models employ the — highly artificial from a typographical point of view — 14-feature uppercase-letter font created by Rumelhart and Siple (1974). In this font, the critical features of the letters correspond to straight-line segments or "quanta" that are location-specific and determinate with respect to orientation. Each of these oriented segments is numbered according to its position, so that the letter A would be represented by the binary feature pattern: 11111010100000 (see Fig. 1).

Davis (2010) noted, "McClelland and Rumelhart's (1981), (p. 383) assumption that 'the basic results do not depend on the font used' seems like a reasonable starting point" (p. 725), but as Mewhort and Johns (1988, p. 139) point out, the Rumelhart/Siple scheme leaves the computational representation of the alphabetic system vastly overdetermined. So, while this assumption might be heuristically valuable as an exploratory principle, the artificiality of the scheme might not be inconsequential: it might not provide an operationally viable proxy for how the visual system actually breaks down the stimuli used in reading. Essentially, over-determination at the feature level might, for example, skew a calculation of the "capacity benefits" resulting from orthographic neighbourhood effects (see Houpt, Townsend, & Donkin, 2014, for a discussion of capacity benefits in visual word-recognition).

Thus, an unresolved issue for constructing realistic computational models of visual word-recognition is: what, if any, domain-specific perceptual processing primitives are critical in visual-word recognition.

Recently, in a connectionist computational model with a back-propagation routine by which the components a hidden layer between actual bitmapped stimuli and real words are constructed and revealed, presumably during letter level processing, Chang, Furber, and Welbourne (2012) used principal component analysis to define a set of eight crucial features spanning upper and lower case letters. The features identified in the Chang et al. (2012) model have some simple circular and angular shapes as well as combinations of line segments and direct line segments, arguably encompassing structural letter parts and relational features. The list distinguishes a category of round curve-shaped features (as in G, O, and U); an n-shaped feature (A, K, R, X; a, h, k, n); a vertical center line feature; an inverted L-shaped feature; a v-shaped feature; a c-like feature; a hook-shaped feature; and

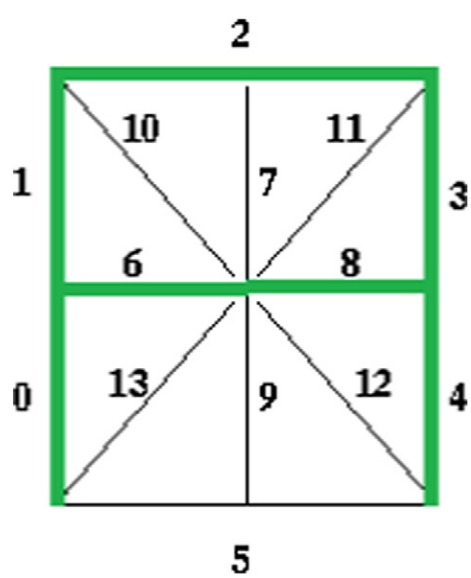

Fig. 1. Representation of the letter "A" in the 14-feature uppercase-letter system created by Rumelhart and Siple (partially adapted from Fig. 2 in Rumelhart & Siple, 1974).

a repeated vertical strokes feature. An unresolved issue in this account surrounds the fact that running the routines suggest that 50 units in the hidden layer seems to give the best fit to behavioural results, yet, only 8 features are identified and freely interpreted in the principal component analysis.

Over the last five or six decades, in psychophysical, behavioural and neurophysical, studies outside of the strictly computational modelling environment, various other — often incommensurate (though perhaps complimentary) — classes of "feature-level" operators have been proposed as candidates for what the perceptual processing primitives in letter identification and word recognition are. For example, edges or boundaries between light and dark, oriented bars and annular forms (see Hubel & Wiesel, 1959); aggregated segments of varying orientations and curvatures (Gibson, Gibson, Pick, & Osser, 1962; Gibson, 1965; Smith, 1969) — or discriminant parts and distinctive features of these segments, and their junctions (Fiset et al., 2008; Petit & Grainger, 2002; Lanthier, Risko, Stolz, & Besner, 2009) —global features of letter wholes (Bouma, 1971; Chang et al., 2012).

It appears then that there is too little consensus on the "identity" of the "key components" issue — the proper resolution of which the "relative importance," or "role" question appears to require.

1.1. The "role" issue

The identity and relative importance of different visual constituents in perceptual processing has been investigated previously in the area of object recognition (e.g., see Biederman, 1987). In the object recognition domain, Biederman proposed that, though the underlying visual processing is feature-based, object recognition is mediated by a segmentation into parts of an "intermediate complexity" between simple features and independent wholes. The segmentation and recognitional process occurs on the basis of structural and relational features of the input image. In the Biederman (1987) experiments, participants had to identify line-drawn three-dimensional pictorial representations of objects with midsegments or vertices deleted. Results revealed that the removal of vertices was more detrimental to object recognition than the removal of midsegments. However, one needs to be cautious at generalizing these findings to letter/word recognition. As Petit and Grainger (2002) indicated, "two-dimensional letter shapes are not segmented in a manner analogous to three-dimensional objects." (p. 352).

The literature on the role of vertices vs. midsegments vs. junctions in letter/word recognition is sparse. In a pioneering work, Petit and Grainger (2002) employed a masked prime paradigm using briefly presented, partial-letter primes that were followed by the target stimuli to determine which parts of letters play a critical role in the process of letter perception. Their experiments used letter naming and alphabetic decision tasks. The partial primes were created by deleting parts at different regions of the target letters and were composed of the same number of pixels in each condition: i) local segmental junction primes were composed of the pixels around the intersection between two lines plus pixels at the ends of the lines; ii) local segmental midsegment (or junctionless) primes were composed of pixels at regions between junctions; iii) global primes were constructed with pixels randomly distributed across the entire target; and iv) neutral primes were constructed with pixels randomly distributed across the rectangular space that a complete version of the prime would occupy (see Fig. 1 in Petit & Grainger, 2002). Eighteen letters of the Roman alphabet in upper-case format (font: Courier, 24 pt) were used. Petit and Grainger found a significant advantage for the target letters when preceded by a global prime than when preceded by a junction or neutral prime (Experiment 1), but note that this experiment did not include the "midsegment" condition. In addition, the letter-naming task showed faster response times to targets when preceded by complete and junction primes compared with the targets preceded by a neutral prime. Importantly, in Experiments 2 and 3 Petit and Grainger found an advantage for the targets