Running head: LETTERS READ SIMULTANEOUSLY

Letters in words are read simultaneously, not in left-to-right sequence.

James S. Adelman and Suzanne J. Marquis

University of Warwick

Maura G. Sabatos-DeVito

University of North Carolina, Chapel Hill

999 words.

Corresponding Author:

James S. Adelman

Department of Psychology,

University of Warwick,

COVENTRY,

CV4 7AL,

UK.

Telephone: +44 (0) 24 7615 0233 Electronic mail: J.S.Adelman@warwick.ac.uk

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The identification of individual letters is necessary for reading words in alphabetic script (Pelli, Farell, & Moore, 2003). Sequential models of letter processing (Whitney, 2001) in reading words posit an initial left-to-right sequence of letter processing (in left-to-right languages, such as English), each letter taking 10–25 ms to process before the next is processed. In contrast, simultaneous models of letter processing (e.g., Tydgat & Grainger, 2009) in reading words posit that information about the identity of each letter starts to be extracted at the same time point, regardless of horizontal position. Here we show that people reading four-letter words do not extract identity information for any letter from an 18 ms display of the word, but some information about all four letters is available from 24 ms of display. Our results indicate that a left-to-right sequence of attention across letters is not used in establishing the cognitive representation of words. Instead, all letters are processed simultaneously.

The sequential nature of alphabetic written language as a representation of speech sounds, and of words, implies that letters could be processed one-by-one in left-to-right sequence at the earliest stages of letter identification. Several phenomena have been treated as consequences of this left-to-right sequence of attention in sequential models of letter processing (Whitney, 2001). One such phenomenon is better identification of letters to the left of a briefly presented string (Stevens & Grainger, 2003). In priming paradigms, where a letter string is read quicker when preceded by a briefly presented similar letter string, similarity to the left is more important (Peressotti & Grainger, 1995; Schoonbaert & Grainger, 2004). (It is conversely sometimes claimed that increases in contextual enchancement caused by previews (Rumelhart & McClelland, 1982) demonstrate within-letter-level simultaneous processing, but the effect could be attributed in sequential models to increased activation at the feature level.) Whitney and Cornelissen

(2007) attribute a wide array of effects, including many involving briefly presented, masked, letter strings, and length effects, to the (obligatory) left-to-right sequential read-out of letters. The precise intervals between the processing of the individual letters are taken to be critical for encoding positional information and word identification, and therefore also critical for explaining effects related to words with transposed letters (*wrods*). If this account is correct, the lag between processing a letter and its neighbour to the right is necessary in processing words.

Simultaneous models of letter processing (Rumelhart & McClelland, 1982; Tydgat & Grainger, 2009) attribute phenomena at the letter level — such as left-to-right decreases in accuracy — to differing levels of signal strength throughout letter processing that arise from attentional properties of letter detectors. Other effects, such as length, are presumed not to be perceptual (notwithstanding eye movements), and are attributed to downstream processes involving the left-to-right application of spelling-sound rules in producing a pronunciation (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), or to articulation itself (Seidenberg & Plaut, 1998). At the initiation of letter-level processing, however, identification of each letter should begin at the same time, although efficiency or attention could decline towards the right of the word.

We investigated whether differences in letter identification were due to lag for later letters (per sequential models) or lower efficiency for later letters (per simultaneous models).

Method

31 staff and 54 students of the University of Warwick, and 13 other respondents to local advertisements were tested as part of a larger study. Pro rated, remuneration was approximately £4 (ca. US$6). The participants attempted to read briefly presented four-letter words, and choose it from two options, presented laterally to match the

response buttons on a button box. 864 trials were presented, of which 384 critically differed in one letter (e.g., *sung* vs. *lung* at the left-most position, or *fish* vs. *fist* at the right-most). At each of the 4 positions, 12 word pairs were used, at each of 8 durations from 12–54 ms. A Sony CPD-G200 17" monitor and an NVIDIA GeForce 7025 graphics card delivered a 6 ms frame rate at resolution 640x480. Given the posited 10–25 ms effect, this precision suffices. The word was preceded by a hash mask (##########) and followed by a 6 ms blank and the mask again to terminate visual processing (Figure 1a)[1]. Every 108 trials, accuracy feedback and a break were given.

Results and Discussion

Accuracy increased with display duration, and the critical duration of display was found to be 18–24 ms. After displays of only 18 ms, people performed at chance, regardless of the position of the required information (from left to right, single-sample tests against chance, $t_{\text{subjects}}(97) = -0.60, 0.75, -0.12, 1.31$, $p = .547, .454, .907, .194$; $t_{\text{items}}(23) = -0.29, 0.64, 0.28, 1.28$, $p = .773, .528, .786, .213$). With just 6 ms more display, that is, displays of 24 ms, people performed better than chance, regardless of whether information was required from the left or the right of the word ($t_{\text{subjects}}(97) = 6.47, 6.93, 6.45, 3.42$; $t_{\text{items}}(23) = 7.09, 7.13, 5.02, 2.95$, all $p < .001$)[2]. The data and a linear mixed effects (LME) analysis are presented in Figure 1b.

The initiation of letter identification therefore occurred for all letters at the same time point, namely when lower level information arrived from the 18th–24th ms of the stimulus display. The slight horizontal decrease in accuracy observed here (LME linear trend, $z = 2.29$, $p = .022$) at 24 ms, and in previous studies (Stevens & Grainger, 2003; Tydgat & Grainger, 2009), must therefore be due to differences in the efficiency of information extraction at the different positions.

Overall, these data rule out a sweep of attention sequentially from left-to-right in the reading of letters. Rather, the identity of letters is processed simultaneously across several horizontal positions with differing efficiency.

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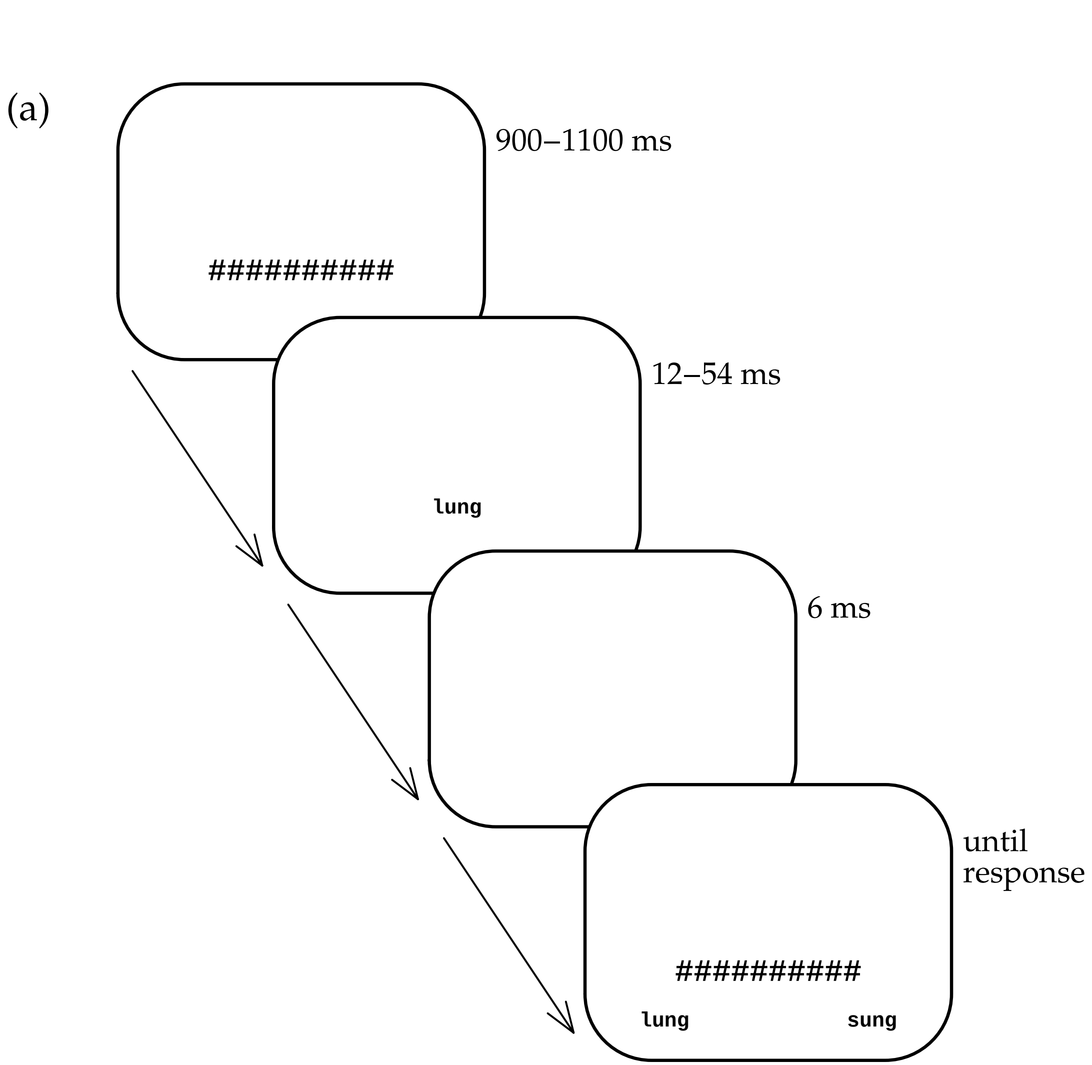
Footnotes

[1]This procedure is identical to the Adelman and Brown study cited by Whitney and Cornelissen (2007), although the design differs.

[2]The by-items analyses are based on target-foil pairings, treating reversals as different.

Figure Captions

Figure 1. (a) Sequence of events in an experimental trial. Participants indicated their response with the left- or right-hand button on a button box. (b) Accuracy of identification for choice between two alternatives differing in 1st (e.g., *sung* vs. *lung*), 2nd (e.g., *salt* vs. *silt*), 3rd (e.g., *buns* vs. *buys*), or 4th (e.g., *fish* vs. *fist*) position, for displays lasting 18 or 24 ms. Error bars are 95% central confidence intervals on the basis of a logistic mixed effects model on the relevant conditions with random slopes per subject up to the position by duration interaction, and random slopes per item up to the duration effect (this model matches the design of the experiment under the assumption of random subjects and items).



(a)
900–1100 ms
##########
12–54 ms
lung
6 ms
until response
##########
lung
sung
(b)
Accuracy
.65
.60
.55
.50
1st
2nd
3rd
4th
Critical Letter Position