Trends in Cognitive Sciences

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Letter

You Can't Recognize Two Words Simultaneously

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In their compelling opinion piece, Snell and Grainger [1] breathe new life into the debate about parallel versus serial processing of text during reading. They marshal several pieces of evidence against the established view that words are recognized one at a time. We agree that this debate 'cannot be resolved without treading beyond the methodological scope of tracking eye movements'. However, in treading the same new landscape we have come to different conclusions.

In our view, the core question is: can people recognize multiple words at exactly the same time? Thus, timing is critical. We must measure word recognition performance while carefully controlling the time available to process each word, and compare the results to quantitative predictions made by models of parallel versus serial processing. We took such an approach in a series of experiments using a semantic categorization task: observers were presented with briefly flashed and masked pairs of words, one on either side of fixation (Figure 1A). On some trials, observers were precued to attend to one side and categorize one of the words, and in other trials they had to divide attention to categorize both words independently. Critically, the time between the words and the postmasks was adjusted for each observer, such that they could achieve ~80% correct when attention was focused on one word. The question is: In that same amount of time, can they recognize both words? The answer is: No. Observers could recognize one word but performed at chance for the other [2].

When plotted on a graph called the 'attention operating characteristic' [3], the data fall in line with the prediction of a serial model that assumes only one word can be fully processed on each trial, and far below the predictions of two different parallel processing models (Figure 1B). This pattern holds for a semantic categorization task as well as a lexical decision task, regardless of whether the words are positioned to the left and right of fixation or above and below fixation, and even when both words are short or high in lexical frequency.

Among their 'Outstanding Questions', Snell and Grainger ask: 'Might there be effective neuropsychological markers of parallel word processing, as measured with electroencephalography and fMRI?' We recorded fMRI responses while participants performed the semantic categorization task described previously [4]. We observed parallel processing of the two words in bilateral retinotopic visual areas, and in a posterior portion of the left hemisphere 'visual word form area,' VWFA-1 (Figure 1C). However, a different pattern

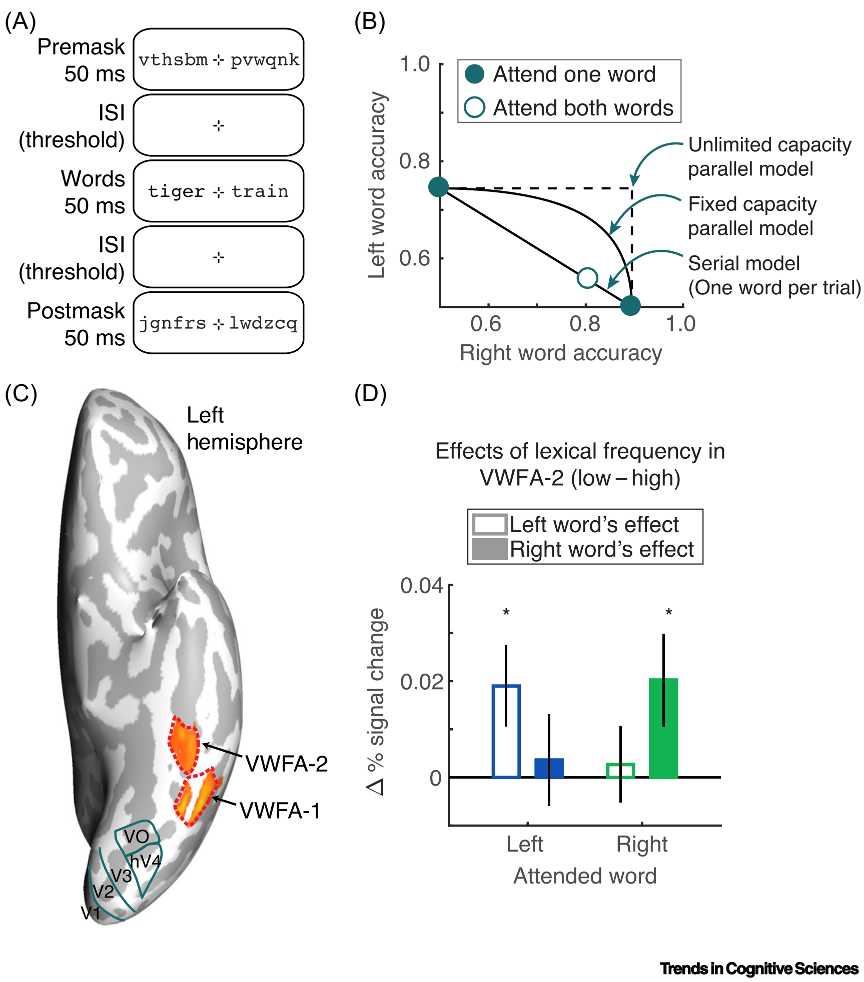

Figure 1. Behavioral and Neuronal Evidence of a Serial Bottleneck in Visual Word Recognition. (A) Example stimuli. At the start of each trial, a precue (not shown) directed attention to one side or both. The task was to categorize a postcued word as 'living' or 'nonliving'. (B) The average 'attention operating characteristic' (*N* = 15). Accuracy is consistent with the serial model. (C) Ventral view of one participant's left hemisphere, showing the two subregions of the visual word form area (VWFA). V1, V2, V3, hV4, and VO are retinotopic visual areas. (D) The effects of lexical frequency on mean fMRI responses in VWFA-2 (*N* = 15). Only one attended word per trial has an effect [4]. Abbreviation: ISI, inter-stimulus interval.

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emerged in the anterior VWFA-2, which lies at the intersection of the visual and language systems [5]. Activity in VWFA-2 was consistent with a single channel that was modulated by the lexical properties of only one word on each trial (Figure 1D).

Those results, as well as Snell and Grainger's results with the flanker paradigm [6] and the sentence superiority effect [7], can be explained by the following model: word recognition begins with massively parallel visual processing, up to the level of orthographic analysis. Multiple words can be attended, and their sublexical features can be maintained in a short-term memory buffer even after the visual input is removed. However, lexical access is serial. The serial bottleneck is revealed by masking the stimuli rapidly enough to disrupt the memory trace and prevent switching of attention from one word to the other. The final serial stage may be very fast – faster than the 170 ms that Snell and Grainger consider to be required for recognizing individual words.

However, it is conceivable that the backwards masks in our experiments push the system into a serial processing mode that does not occur in natural reading. There is some evidence against that hypothesis: when participants judge the color of the letters, rather than the meaning of the words, their behavior is consistent with parallel processing [2]. That is true even when the masks constrain accuracy in the same way as they do for lexical judgments.

We also acknowledge that in sentence reading, unlike in our experiments, neighboring words are related and somewhat predictable. Contextual factors could, in theory, reduce the amount of information that readers must extract from the visual input and allow parallel processing of multiple words. That is an empirical question. But we contend that future investigations must adequately control stimulus timing in order to test for truly parallel recognition.

We are excited that new ideas and new methods are flourishing in the study of reading, as represented by Snell and Grainger [1]. More work, both theoretical and empirical, is required to determine the conditions under which word recognition appears serial or parallel, and how each processing stage is instantiated in neural circuitry. We are confident that investigating these questions will continue to advance the study of perception and cognition more broadly.

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https://doi.org/10.1016/j.tics.2019.07.001

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