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(e.g., [3,5]). Only by understanding the degree to which findings generalize across paradigms and measures can we infer how they transfer to natural reading scenarios. Using newly developed methods of co-registration of electroencephalography with volitional eye movements during reading can reveal the neural attention mechanisms that are engaged in natural reading (e.g., [3]), but further efforts should be made to explicitly compare the effects of task goals and experimental paradigms (e.g., reading for comprehension versus making explicit judgments). Furthermore, future research should relate online neural and eye movement measures to offline measures of comprehension to determine how these fundamental processes change as a function of engagement in the task and to reveal important trial-to-trial dynamics of word processing.

In summary, although S&G raise interesting questions, we caution against 'dogmatizing' parallelism as a default that becomes masked by a serial behavior based on limited evidence from a set of contrived tasks. In contrast, we suggest that the needed paradigm shift in reading research is one that bridges domains and brings insight into the reading process in concert with decades of evidence we have already accumulated, not in spite of it. These new approaches may answer some yet-unasked questions. However, we anticipate they will reinforce longstanding conclusions that the brain can perform many processes in parallel (e.g., discriminating visual features of letters and objects), but just as attention is needed to bind multiple features of objects during visual search, some aspects of the natural reading process (e.g., word identification) must engage the serial allocation of attention (e.g., [9]).

Acknowledgements

We are grateful to Kara D. Federmeier and John M. Henderson for comments on an earlier draft of this letter.

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https://doi.org/10.1016/j.tics.2019.06.005

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Letter

You Can't Recognize Two Words Simultaneously

Alex L. White ,[1,2,*]
Geoffrey M. Boynton,[3] and
Jason D. Yeatman[1,2]

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

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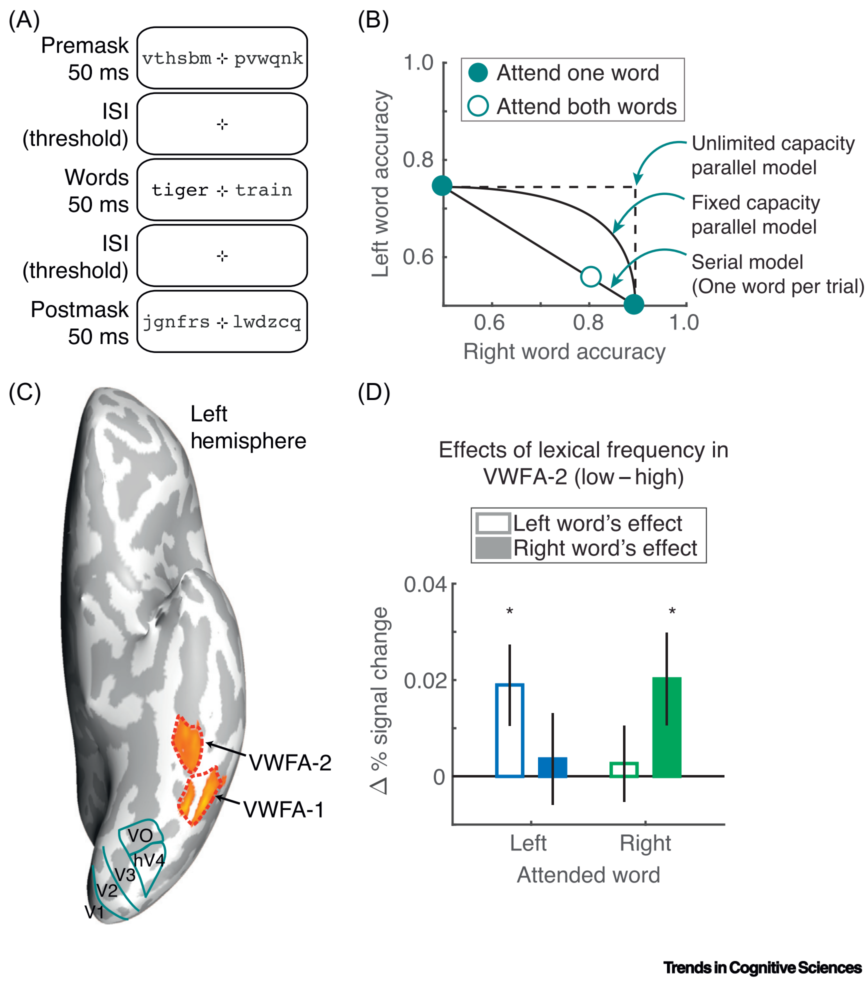

Figure 1. Behavioral and Neuronal Evidence of a Serial Bottleneck in Visual Word Recognition. (A) Example stimuli. At the start of each trial, a precue (not shown) directed attention to one side or both. The task was to categorize a postcued word as 'living' or 'nonliving'. (B) The average 'attention 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.

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 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.

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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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Letter

Consciousness Is Not Key in the Serial-versus-Parallel Debate

Joshua Snell[1,*] and Jonathan Grainger[1]

In response to our recent claim that 'Readers are parallel processors' [1], our peers have voiced several ideas that will undoubtedly help illuminate the road to scientific consensus about the reading brain. Schotter and Payne [2] echo our plea for bridging traditionally isolated literatures [3]. In terms of theory, our model OB1-reader is one attempt to do just that: specifically, it bridges the domains of single word recognition and eye movements in text reading. Equally important is the integration of methodologies, of which Schotter and Payne highlight an excellent instance – the combination of eye-tracking and electroencephalography, which arguably provides a more direct window onto the cognitive processes driving reading while ecologically approximating a natural setting. We trust that such set ups will help verify whether the cognitive architecture as inferred with artificial paradigms indeed pertains to natural reading (Box 1).

Regarding the serial-versus-parallel processing debate, Schotter and Payne, as well as White *et al.* [4], are more or less univocal in their definition of the central issue at stake: can readers (allocate attention such so as to) identify multiple words simultaneously? As voiced in our opinion article, the ultimate answer to this question warrants complete certainty about what word identification is. Before addressing this issue, we should note that the eye movement literature – which for decades has been the only driving force behind the serial processing claim – has abstracted away from the recognition process. For the theoretical frameworks that thrived in those years, the question of which words would be recognized at which moment largely depended on the distribution of spatial attention [5,6]. The strict serial allocation of spatial attention was a theoretically strong assumption, due to its falsifiability. Although some of our peers have long supported it (e.g., [7]), we are relieved that most have now come to agree that spatial attention is distributed across multiple words [2,4].

In painting a revised serial scenario, Schotter and Payne and White *et al.* apply similar strokes: in the words of White *et al.*, 'word recognition begins with massively parallel

Box 1. Ideas for Future Research

We reckon that the following experiments may yield useful information about the reading brain:

- Parafoveal-on-foveal fixation-related potential effects of syntactic compatibility: Combining eye-tracking and electroencephalography, fixation-related potentials (i.e., event-related brain potential time locked to the fixation on a target word) elicited by a given target word may be influenced by syntactic properties of the following word in sentence reading. During the fixation on target word n, word n+1 is replaced by either a syntactically compatible or incompatible word. More negative N400 deflections are expected in the case of incompatibility (e.g., [10]), which would indicate that syntactic processing of the upcoming word occurred concurrently with the fixated word. Early effect onsets are key here.

- Syntactic cues in same-different matching of sentences: Schotter and Payne believe that syntactic constraints in word position coding (e.g., [13]) will not play a role in clauses such as 'a big beautiful fluffy white dog' [2]. Let us put it to the test. We hypothesize that it will be more difficult for readers to distinguish 'a big beautiful white fluffy dog' from 'a big beautiful fluffy white dog' precisely because the same syntactic representation is activated by both sequences. Same–different responses in such a condition could be compared with a condition where a transposition would change the syntactic structure (e.g., 'baby dog eats meat' – 'baby eats dog meat'). Accommodating Schotter and Payne's plea for ecological validity, participants can be allowed to move their eyes.

- Are BOLD responses to central target words modulated by semantic properties of flanking words? White *et al.* [4] make a good case for carefully timing stimulus durations. The flanker studies discussed in our opinion article should therefore be tested again with briefer (e.g., 50 ms) stimulus durations. Syntactic or semantic parafoveal-on-foveal influences would in such a setting provide stronger evidence that the system can in principle process multiple words in parallel. When employing fMRI in the same constrained setting, we hypothesize that a classifier trained on dissociating semantic categories will output stronger evidence for a given category when the flanking words are semantically congruent.