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You can't read two words at once: Evidence of serial processing in visual word recognition

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Abstract

To test the limits of parallel processing in vision, we investigated whether observers can recognize two words at once. Observers viewed brief, masked pairs of words and were instructed in advance to judge both of the words (dual-task condition), or just one of the words (single-task condition). For judgments of semantic category, the dual-task deficit was so large that it supported serial processing: observers could only recognize one word and had to guess about the other. Moreover, observers were more likely to be correct about one word if they were *incorrect* than correct about the other, which supports a serial switching model. In contrast, judgments of text color with identical stimuli were consistent with unlimited-capacity parallel processing. Thus, serial processing is necessary to judge the meaning of words but not their physical features. Our findings inform a long-standing debate about the extent of parallel processing during reading.

Introduction

Vision begins with parallel processing: the retina and early visual cortex encode many stimulus elements at once, across the visual field. If independent and parallel processing continued all the way through the processing stream, observers would be able to perceive multiple objects simultaneously with no cost. At the other extreme, a serial bottleneck would allow only one object to be recognized at a time, causing delays or errors when the observer must attend to multiple stimuli. Divided attention does often impair task performance (Braun, 1998; Carrasco, 2011; Kahneman, 1973), but the impairments are usually too small to be explained by serial processing.

Written words provide an important test of the limits of parallel processing in vision, with clear applications to life in the modern world. Although crowding and poor acuity in the periphery require a sequence of eye movements to scan a page, multiple words can be visible near the center of gaze within one glance. Indeed, words in a line of text are at least partially processed before they are fixated, and many are skipped over by the eyes completely (Rayner, 2009). Within each glance, early visual mechanisms first encode the basic features of many letter shapes in parallel (Grainger, Dufau, & Ziegler, 2016). Eventually, representations of letter combinations lead to full semantic recognition. The present study was motivated by the question: does the visual system's parallel architecture allow for two words to be processed simultaneously, or is recognition constrained by a serial bottleneck?

The extent of parallel processing in natural reading has been fiercely debated (Murray, Fischer, & Tatler, 2013; Starr & Rayner, 2001). Some researchers argue for strictly serial processing along the line of text (Reichle, Liversedge, Pollatsek, & Rayner, 2009), and others argue for a graded allocation of attention and parallel processing of multiple words (Kennedy, 2000; Kliegl, Nuthmann, & Engbert, 2006). The parallel/serial debate has proved difficult to resolve with eye movement studies in natural reading.

To determine whether observers can recognize two words simultaneously when they are forced to try, we abandoned natural reading conditions and focused on isolated word recognition during gaze fixation. Our goal was to measure “capacity limits”: constraints on how much information the perceptual system can process per unit time. Previous studies have shown that word recognition is subject to capacity limits by using varieties of search paradigms (Harris, Pashler, & Coburn, 2004; Mullin & Egeth, 1989; Reichle, Vanyukov, Laurent, & Warren, 2008; Scharff, Palmer, & Moore, 2011a). None of these visual search studies conclusively determined whether the capacity limit is due to a serial bottleneck (see **Discussion**).

Rather than visual search, we adopted another classic paradigm: comparing accuracy in a “dual-task” condition with a “single-task” condition. In two experiments, we presented observers with time-limited and masked pairs of parafoveal nouns. Observers fixated their gaze in the center and either focused attention to detect targets on just one side (single-task condition), or attempted to divide their attention to detect targets on both sides (dual-task condition). We then compared the relative deficit in the dual-task condition to the quantitative predictions of several models of parallel or serial processing.

In separate blocks of trials with identical stimuli and matched difficulty, observers detected either *semantic* targets or *color* targets. Semantic targets were nouns that belonged to a particular semantic category, such as ‘professions.’ Color targets were nouns colored slightly reddish, with word meaning being irrelevant. To assess the capacity limits of each type of judgment, we compared accuracy in dual- and single-task conditions, and we measured how the accuracy of one dual-task response depended on the accuracy of the other. Note that in our “dual-task” conditions, observers made the same type of judgment for both of two words presented simultaneously. They never had to make a semantic judgment and a color judgment in the same trial.

Comparing the relative dual-task deficits across semantic and color judgments allows us to test whether the capacity limit in divided attention

depends on which stimulus aspect is task-relevant. Previous studies have demonstrated that detecting changes in low-level features of nonlinguistic stimuli has unlimited capacity (Bonnell, Stein, & Bertucci, 1992; Scharff et al., 2011a; White, Runeson, Palmer, Ernst, & Boynton, 2017). However, if words are recognized automatically, as some researchers have suggested (Augustinova & Ferrand, 2014; Stroop, 1935), then we would predict similar dual-task deficits for both judgment types.

In the first experiment, observers detected targets embedded in rapid serial visual presentation (RSVP) streams (**Figure 1a**). RSVP of single words has been studied as an alternate way to present text that doesn't require saccades, with the hope of aiding low vision (Chung, Mansfield, & Legge, 1998; Potter, 1984). On each trial we presented five pairs of unrelated words in RSVP. The presentation rate was adjusted to keep each observer's single-task semantic performance below ceiling. Fast rates limit the time available to process each pair of words, and reduce the likelihood of a serial shift of attention from one word to the other within one frame. To match color and semantic single-task difficulty levels, we adjusted the saturation of the red targets.

The second experiment tested whether the semantic dual-task deficit in Experiment 1 was due to the RSVP streams overloading memory or other cognitive mechanisms, rather than a limit on the immediate processing of each pairs of words. The design of Experiment 2 was similar except each trial contained only one masked pair of words (**Figure 1b**).

METHODS

Observers:

Twelve volunteers (7 female, ages 19-31) with normal or corrected-to-normal visual acuity and normal color vision participated in exchange for fixed monetary payment. Each experiment had ten observers, and eight individuals participated in both experiments. All but two (including author AW) were naive as to the research aims. One additional observer chose to discontinue the study

after one session. The sample size of 10 was chosen prior to Experiment 1 on the basis of a pilot experiment, in order to produce standard deviations of the dual-task deficits near 0.01 (in A_g units, see below). This is small relative to the theoretical predictions of 0.08 and 0.15 made by the two capacity-limited models against which we compare our results.

Each observer gave informed consent in accord with the Declaration of Helsinki and the Institutional Review Board at the University of Washington. All observers learned English as their first language, and all scored above the norm of 100 ($M \pm SEM$: 118.5 ± 2.5) on the composite Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999).

Equipment and stimuli:

We presented stimuli on linearized CRT monitors with 120 Hz refresh rate while the right eye's gaze position was monitored by an Eyelink eye-tracker (SR Research). The stimuli consisted of a white background, a small dark fixation cross 0.3×0.3 degrees of visual angle (dva) in size and dark letter strings in Courier font. The letter strings had 83% Weber contrast. The words were drawn from 12 distinct semantic categories (e.g., "professions") each with 35 nouns (see **Supplementary Materials**). The median lexical frequency was 6.4 per million, according to the Clearpond database (Marian, Bartolotti, Chabal, & Shook, 2012). They ranged from 4 to 6 characters in length, subtending 2.7 to 4.1 dva in width, and 1.1 dva in height. The words were centered at 2.75 dva to the left and right of fixation. In addition, Experiment 1 used two six-character masks (#@#@#@ and @#@#@#).

All the words were dark gray except for the color targets, which were equiluminant but with higher saturation in the red hue. Using the measured luminance values of our linearized monitor, we incremented the red gun and decreased the green and blue guns to keep the total luminance constant. As described below, we set the magnitude of the red increment to each observer's detection threshold.

Experiment 1 trial sequence:

The trial began with the observer fixating centrally for at least 1 s. Then the pre-cue appeared: two 0.35 dva lines just to the left and right of the fixation cross. In the dual-task condition, both were black. In the single-task condition, one line was green and the other blue. Each observer was assigned to either green or blue and always attended to the side indicated by that color. A target-defining word (the name of the semantic category, or the word “color”) also appeared 1 dva below fixation.

Figure 1. Example dual-task semantic trials of Experiments 1 (a) and 2 (b). In Experiment 1, the RSVP presentation rate was adjusted for each observer (see text). Not shown in this diagram are the inter-stimulus intervals (ISIs) between each frame, during which only the fixation cross was presented. In Experiment 2, the duration of the two ISIs between masks and words was adjusted for each observer. Note that the category word (“anatomy”) that is presented along with the pre- and post-cues was actually below fixation. In these examples, the post-cue is the blue line that points to the side to be judged, but for half the observers the post-cue was the green line.

The 1-s pre-cue was followed by a 600-ms inter-stimulus interval (ISI). Then the RSVP sequence began with pre-masks that covered the upcoming word locations, followed by a blank ISI containing only the fixation cross. Then 5 pairs of words were presented sequentially, separated by blank ISIs. The pre-mask, words, and ISIs all had the same duration, D_{RSVP} , which was adjusted to control semantic judgment difficulty (see below). After the last ISI, the *post-cue* frame appeared. This consisted of post-masks and a green and a blue line as in the pre-cue. After 700 ms, a beep prompted the subject to respond. Responses before the beep were not recorded.

The post-cue remained visible until the observer pressed one of four keys with the hand on the same side as the post-cue, reporting with a 1-4 rating the level of confidence that a target was present: “sure absent”; “guess absent”; “guess present”; or “sure present”. Each key-press was immediately followed a high- or low-pitched feedback tone for correct or incorrect responses, respectively.

If the observer’s gaze position moved too far from the fixation mark during the presentation of the stimuli, the trial was immediately terminated (see **Supplemental Materials**).

Experiment 2 trial sequence:

The trial sequence in Experiment 2 (**Figure 1b**) was similar to Experiment 1’s except as follows. After the pre-cue, a pre-mask display appeared for 42 ms. It consisted of two strings of 6 randomly chosen consonants, centered at the same positions as the upcoming words. Then only the fixation mark was presented for an ISI, the duration of which (D_{ISI}) was set for each subject (see below). Then a pair of words appeared for 42 ms, followed by a second ISI of the same duration of the first. The following post-mask display was similar to the pre-mask, 42 ms in duration, but with different random consonants. After the post-mask, the trial sequence finished in the same way as in Experiment 1.

Tasks:

For *semantic judgments*, the targets were nouns of a particular semantic category. For *color judgments*, the targets were words colored slightly red, as defined above. On each trial, on each side, there was an independent 50% chance of semantic target presence, and an independent 50% chance of color target presence. For both target types, therefore, in any given trial there could be no targets, one target, or two targets (one on each side).

In Experiment 1, the time of each target type within the sequence was uniformly and independently distributed. When there were two targets of the same type, they appeared simultaneously. Only 10% of semantic targets happened to also be color targets. The particular words on each trial were chosen randomly from the entire set with the following constraints:

1. All words on each side were unique.
2. The same word was never presented at both sides simultaneously.
3. No more than one word from the target category could be present on one side.
4. Target words were not allowed to repeat across sequential trials.

In Experiment 2, there was an independent 50% chance that the one word on each side was drawn from the target category. Otherwise, it was drawn randomly from one of the other 11 categories. No word was allowed to appear on two consecutive trials, or to appear on both sides in the same trial. There was also an independent 50% chance that each word was a color target.

In single-task trials, the pre-cue instructed observers to attend to one side and ignore the other. The post-cue always indicated the same side as the pre-cue, requiring just one response. In dual-task trials, observers had to make independent judgments of target presence for both sides. Note again that both judgments were of the same type (semantic or color). The post-cue first prompted the observer to respond to one side, and then after the key-press and feedback tone, the post-cue switched and the observer responded to the other side. The post-cue order (left or right side first) was randomized across trials.

Procedure:

In the first session, observers read the entire word list and practiced both judgment types. In the second session, they ran *staircase* blocks to estimate thresholds. A staircase for single-task semantic judgments established the threshold word duration D_{RSVP} in Experiment 1 and ISI duration D_{ISI} in Experiment 2. Then, with the stimulus timing fixed, a staircase for single-task color judgments established the threshold color increment magnitude I . In Experiment 1, the average D_{RSVP} was 83 ± 8.5 ms, corresponding to a presentation rate of 6.7 ± 0.7 Hz. The average I (expressed as a proportion of the maximum possible equiluminant red saturation) was 0.09 ± 0.01 . In Experiment 2, the average D_{ISI} was 71 ± 6.2 ms, and the average I was 0.14 ± 0.01 .

Main experimental trials were run in blocks of 16 in Experiment 1 and blocks of 20 in Experiment 2. The target type (semantic or color) was constant within each block, as was the semantic target's category and the pre-cue condition (dual-task; single-task right; single-task left).

Analysis

As a bias-free measure of accuracy, we computed the area under the Receiver Operating Characteristic (ROC) curve, known as Green's Area or A_g (Pollack & Hsieh, 1969). Like proportion correct, A_g is a proportion that ranges from 0.5 (guessing) to 1.0 (perfect). See **Supplementary Materials** for details.

RESULTS

Dual-task deficits:

Semantic accuracy was significantly impaired in the dual-task conditions of both experiments (Table 1). The mean dual-task deficit (single-task A_g minus dual-task A_g) was 0.12 ± 0.01 in Experiment 1 (comparison to 0: $t(9)=17.17$, $p<0.001$; 95% bootstrapped CI = [0.11 0.13]), and 0.14 ± 0.01 in Experiment 2 ($t(9)=10.14$, $p<0.001$; CI = [0.12 0.17]). Color judgments, in contrast, suffered

minimal deficits: 0.02 ± 0.01 in Experiment 1 ($t(9)=1.55$, $p=0.15$; $CI = [0.0 \ 0.04]$) and 0.04 ± 0.01 in Experiment 2 ($t(9)=4.63$, $p=0.001$; $CI = [0.02 \ 0.06]$). Dual-task deficits were significantly greater for semantic than color judgments, according to ANOVA interactions between judgment type and pre-cue condition (Experiment 1: $F(1,9) = 54.48$, $p<0.001$; Experiment 2: $F(1,9) = 30.73$, $p<0.001$). The same analysis of d' (which, unlike A_g , is unbounded) supported the same conclusion (interactions: $F(1,9) = 28.06$, $p<0.001$; $F(1,9)=40.21$, $p<0.001$).

Accuracy was consistently higher for targets on the right than left side of fixation, especially for semantic judgments consistent with previous reports (Ducrot & Grainger, 2007; Mishkin & Forgy, 1952). Details are in the **Supplementary Materials**.

Table 1: mean accuracy levels (A_g) in single- and dual-task conditions. In all cells, $SEM = 0.01$.

	Experiment 1		Experiment 2	
	<i>semantic</i>	<i>color</i>	<i>semantic</i>	<i>color</i>
single-task A_g	0.83	0.82	0.84	0.82
dual-task A_g	0.71	0.80	0.70	0.78

Attention Operating Characteristics:

The “Attention Operating Characteristic” (AOC) allows us to compare dual-task deficits to specific models of processing capacity limits (Sperling & Melchner, 1978). **Figure 2** plots accuracy for words on the left side of fixation against accuracy for words on the right. The single-task conditions are pinned to their respective axes. The accuracy levels in the dual-task condition form a single point (open symbol) in that 2D space. We then compare that point to the predictions of three specific models of capacity limits (Bonnell & Prinzmetal, 1998; Ernst, Palmer, & Boynton, 2012; Scharff et al., 2011a; Shaw, 1980; Sperling & Melchner, 1978). Below they are described in brief, with more details in the **Supplementary Materials**.

Figure 2. Attention Operating Characteristics (AOCs) for semantic judgments (left column) and color judgments (right column) in Experiments 1 (top row) and 2 (bottom row). Solid points pinned to the axes are single-task accuracy levels (A_g); open points are dual-task. Error bars show ± 1 SEM.

1. *Unlimited-capacity parallel processing:* two stimuli can be fully processed simultaneously just as well as one (i.e., no dual-task deficit). In the AOC, this model predicts that the dual-task data point falls at the intersection of the dashed lines.
2. *Fixed-capacity parallel processing:* The perceptual system extracts a fixed amount of information from the whole display per unit time. Therefore, processing resources must be shared between both stimuli in the dual-task condition, which lowers sensitivity. As the proportion of resources given to the

right stimulus increases from 0 to 1, this model traces out the black curve in the AOC plot.

3. *All-or-none serial processing*: only one stimulus can be processed at any given time, with equal sensitivity as in the single-task condition. The observer does not have time to even start processing the other stimulus and therefore must guess when asked about it. As the proportion v of trials in which the right side is processed increases from 0 to 1, this model traces out the diagonal black line in the AOC plot.

The serial model can be generalized to account for less severe deficits by assuming that on some fraction b of dual-task trials, both sides are fully processed. The resulting accuracy is a mixture of trials in which only one stimulus is processed and trials in which both stimuli are. In conditions with dual-task deficits larger than predicted by either parallel model, we solved for the serial model parameters b and v that best fit each observer's data.

Semantic judgments, Experiment 1: As can be seen in **Figure 2a**, dual-task accuracy (open symbol) fell below the fixed-capacity parallel model's curve, and near but above the all-or-none serial model's line. The mean distance to the nearest point on the fixed-capacity parallel curve was 0.05 ± 0.01 (significantly greater than 0: $t(9) = 4.53$, $p=0.001$; $CI = [0.03 \ 0.07]$). The mean distance to the all-or-none serial line was 0.04 ± 0.01 ($t(9) = 4.87$, $p<0.001$; $CI = [0.03 \ 0.06]$). Fitting the more general serial model, the mean b parameter was 0.20 ± 0.04 ($CI = [0.14 \ 0.28]$), meaning that on an average of 80% of the trials only one stimulus could be processed. The mean v was 0.71 ± 0.05 ($CI = [0.62 \ 0.82]$), meaning that there was a significant bias to process the right stimulus when only one could be processed. This bias could reflect an attentional strategy to process the easier side, given that only one could be processed successfully. Another explanation is that words in the right hemifield reach language areas of the brain more quickly (Rauschecker, Bowen, Parvizi, & Wandell, 2012).

Semantic judgments, Experiment 2: Mean dual-task accuracy fell on top of the all-or-none serial model's prediction (**Figure 2c**). The average distance from

that line was 0.005 ± 0.012 , not significantly above 0 ($t(9) = 0.41$, $p=0.69$; CI = [-0.02 0.03]). The average distance to the closest point on the fixed-capacity parallel curve was 0.08 ± 0.02 ($t(9) = 4.52$, $p=0.001$; CI = [0.05 0.12]). The mean value of b was 0.06 ± 0.03 (CI = [0.01 0.14]), meaning that on 94% of trials only one stimulus could be processed. There was again a strong bias to process the right stimulus: mean $v = 0.79 \pm 0.04$ (CI = [0.71 0.86]).

Color judgments, Experiment 1: The mean dual-task accuracy point fell well above the fixed-capacity parallel curve, near the intersection that marks the prediction of the unlimited capacity parallel model (**Figure 2b**). The mean distance to the nearest point on the fixed-capacity curve was 0.09 ± 0.01 , significantly above 0 ($t(9) = 7.07$, $p<0.001$; CI = [0.06 0.11]).

Color judgments, Experiment 2: As in Experiment 1, dual-task accuracy fell near the unlimited-capacity parallel model's prediction (**Figure 2d**). The mean distance from the fixed-capacity parallel curve was 0.06 ± 0.01 ($t(9) = 6.25$, $p<0.001$; CI = [0.04 0.07]).

Effect of accuracy on the other side

The all-or-none serial model assumes that only one side can be processed per trial and no information is acquired about the other. If we also assume that the focus of attention switches across trials between the left and right sides, the model predicts a negative correlation between the accuracies of dual-task responses (Bonnell & Prinzmetal, 1998; Ernst et al., 2012; Lee, Koch, & Braun, 1999; Sperling & Melchner, 1978). In other words, the observer is more likely to be correct about one side when s/he is *incorrect* than correct about the other side.

There are several ways to test this prediction, including computing correlation coefficients between the accuracies of the left- and right-side responses. For semantic judgments, the correlation coefficients were negative except when neither side contained a target (see **Supplementary Materials**). This complex pattern seemed related to changes in decision criterion or bias as a

function of the other side's task. We therefore need a bias-free measure of accuracy, such as area under the ROC curve (A_g). So, as another direct test of the serial switching model's prediction (Braun & Julesz, 1998; Lee et al., 1999), we coded all dual-task responses by whether the response to the other side on the same trial was correct or incorrect, and then computed A_g for both sets of trials (**Figure 3**).

Figure 3. Dual-task accuracy (A_g) when the other side's response was incorrect plotted against accuracy when the other side's response was correct. **(a)** Experiment 1; **(b)** Experiment 2. Each point is one observer's data for one judgment type (semantic judgments = blue circles; color judgments = red diamonds). Points below the unity line indicate that accuracy was better when the other side's response was incorrect.

For semantic judgments in Experiment 1, accuracy was on average 0.06 ± 0.02 A_g units lower when the other side's response was *correct* than incorrect ($t(9)=3.31$, $p=0.009$; CI = [0.03 0.11]). In Experiment 2, this difference was 0.11 ± 0.02 ($t(9)=5.87$, $p<0.001$; CI = [0.07 0.14]). This pattern supports the serial switching model.

For color judgments, the effect was exactly opposite: In Experiment 1, accuracy was on average 0.07 ± 0.02 A_g units *higher* when the other side's response was correct than incorrect ($t(9)=3.60$, $p=0.006$; CI = [0.03 0.10]). The

same pattern occurred in Experiment 2: the mean difference was 0.04 ± 0.02 ($t(9)=2.99$, $p=0.015$; $CI = [0.02 \ 0.08]$). This positive effect of the other side's accuracy is consistent with fluctuations in overall effort or arousal that could cause positive correlations in sensitivity between the two sides (Bonnell & Prinzmetal, 1998).

In both experiments, the effect of other side's accuracy significantly differed between semantic and color judgments (ANOVA interactions in Experiment 1: $F(1,9)=30.63$, $p<0.001$; Experiment 2: $F(1,9)=57.02$, $p<0.001$).

DISCUSSION

With the same word stimuli, we measured dual-task deficits for color judgments and semantic judgments. For color judgments, there was minimal deficit, which is consistent with unlimited-capacity parallel processing. For semantic judgments, there was a large dual-task deficit, which is inconsistent with unlimited-capacity or even fixed-capacity parallel processing. Instead, it is consistent with an all-or-none serial model: a bottleneck in the recognition process that allows only one word to be categorized at a time. Given limited processing time, the serial model predicts that observers would process only the left stimulus on some trials and only the right stimulus on others. Fulfilling that prediction, semantic accuracy for each side was relatively impaired when the other side was judged correctly. The opposite was true for color judgments. Based on these contrasting results, we argue that serial processing is necessary to judge the meaning of words but not their physical features.

The consistently large semantic dual-task deficit is unlikely to be explained by a memory limit, for several reasons. First, observers in Experiment 2 only had to remember two words for the brief interval between the stimuli and the post-cue. Two words is within the limits of working memory (Chen & Cowan, 2009). Second, dual-task color trials required two reports with the same timing and suffered hardly any deficit. Finally, accuracy of the second responses on dual-task trials was not worse than the first responses. We therefore favor the

hypothesis that the serial bottleneck lies in perceptual and/or linguistic analysis. Note however that the semantic dual-task deficits were not due to poor resolution or crowding outside the fovea, because we enforced central gaze fixation in all conditions.

The color judgment data fell at the opposite extreme despite the fact that the stimuli and single-task difficulty levels were the same. Therefore, the extent of parallel processing is not fixed by the stimulus but depends on the demands of the task and which stimulus attributes are relevant. This finding also casts doubt on hypotheses that word recognition is automatic (Augustinova & Ferrand, 2014; Stroop, 1935), which may have predicted that automatic semantic processing would cause dual-task deficits when judging the words' color.

Although the color data were *consistent* with parallel processing, our design was not optimized to rule out a rapid switching of attention that sequentially processed both colors, because the stimulus timing was set to control semantic difficulty only. The more predictable color target features could also account for the difference in results. Nonetheless, we show that different tasks of equal difficulty performed on the same stimuli can have very different capacity limits.

It is likely that the large semantic dual-task deficits depended on our use of displays that limited the amount of time available to process each word pair. By the time one word was recognized, information about the other was lost or replaced by subsequent stimuli. In contrast, another study from our group using a semantic search task without post-masks found results consistent with the fixed-capacity parallel model (Scharff et al., 2011a). The lack of masking may have allowed multiple words to be processed sequentially. We propose that recognition is always serial, but multiple words can be processed in a single presentation if the stimuli or their iconic memory traces last long enough.

Prior studies have demonstrated semantic capacity limits with evidence that response times increase with set size during search for particular words (Harris et al., 2004; Reichle et al., 2008). However, search slopes alone are

insufficient to distinguish between serial and parallel models (Carrasco & Yeshurun, 1998; Townsend, 1990).

The “redundant target” paradigm has also been used to investigate capacity limits in word recognition. Assuming that search is self-terminating, capacity-free parallel models predict faster responses when the display consists of two targets than a single target. The earliest such study of semantic categorization found no redundancy gains and concluded that capacity is limited, potentially (but not necessarily) due to a serial process (Mullin & Egeth, 1989). However, later studies reported contradictory results (Shepherdson & Miller, 2014, 2016).

More generally, serial processing has rarely been observed in dual visual tasks. The studies that have found the same signatures of serial processing involved task conditions more complex than ours (Bonnell & Prinzmetal, 1998; Braun & Julesz, 1998; Lee et al., 1999; Sperling & Melchner, 1978). In all of these cases, the ‘attentional set’ (i.e., which stimulus features the subject looks for and discriminates) was different for the two concurrent tasks. When the conditions were relaxed (for instance, by defining both targets in the same way), observers could process the two stimuli in parallel with less of a cost.

Our study is therefore unique: the left- and right-side tasks were defined in the same way, with the same ‘attentional set’. This may be because words are a unique class of especially complex stimuli, but it remains debatable whether high-level visual recognition more generally has such severely limited capacity (e.g., Rousselet, Fabre-Thorpe, & Thorpe, 2002; Scharff, Palmer, & Moore, 2011b).

Reading researchers have long debated whether words in a line of text are necessarily processed one at a time (Murray et al., 2013; Reichle et al., 2009). Much of the debate has focused on eye movement studies that demonstrate that readers begin processing word $n+1$ before the eyes leave word n (Murray et al., 2013; Rayner, 2009). According to a recent review (Murray et al., 2013), the

literature is at an impasse, because both serial and parallel models can modify their assumptions to account for a range of experimental results.

Our study avoids that impasse and casts doubt on the notion that full semantic meaning can be extracted from two words in parallel. But our color judgment data show that surface visual features *can* be extracted in parallel, so further research with our paradigm should test whether that also applies to intermediate processing of sublexical orthographic or phonological information.

Of course, the conditions of our study differed from natural reading, so we cannot say with certainty how our findings apply to the cognitive operations that process a whole page of text. For instance, parallel processing may be more likely when pairs of words are related to each other and form phrases. Reading is a remarkable skill, and future research must explore a wider range of tasks and stimulus configurations to map out the cognitive functions that support it.

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Author contributions

ALW, JP and GMB designed the study; ALW collected and analyzed the data; ALW wrote the manuscript, and ALW, JP and GMP edited it. All authors approved the final version of the manuscript.

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