Reinventing the redundant target paradigm to distinguish serial vs. parallel processing of written words

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ABSTRACT

The visual system can encode many stimuli across the visual field simultaneously, but the number of objects that can be fully identified in parallel is limited. At the extreme, some objects might have to be identified serially. One useful tool for distinguishing parallel from serial processing is the redundant target paradigm, which compares responses to displays containing one target to displays containing two targets. Many parallel models predict a redundant target effect: faster responses to two targets. Here we revisit the redundant target paradigm by developing and testing predictions for a standard serial model that includes errors. Specifically, it predicts slower responses to two-target displays than one-target displays. To test that prediction, we conducted three experiments that each measured performance for three different judgments of written words: color detection (detecting colored letters), lexical decision (detecting real words among pseudowords), and semantic categorization (detecting nouns that refer to living things). In all three experiments, only the color detection task yielded a positive redundant target effect, while the lexical and semantic tasks yielded zero or negative effects. These results are consistent with low-level features (color) for two stimuli being processed in parallel, while the meanings of two words are processed serially. Altogether, this study informs models of reading and suggests opportunities for the redundant target paradigm to investigate other aspects of vision.
The study of perception has long been animated by the question of whether multiple stimuli can be processed in parallel, or whether strict processing capacity limits require serial processing. Here we re-examine that question in the context of visual word recognition: can two words be recognized simultaneously? This is an important question because competing models of natural reading disagree as to whether multiple words are processed in parallel during each gaze fixation (Engbert et al., 2005; Reichle et al., 2006; Reilly & Radach, 2006; Snell & Grainger, 2019b). To investigate whether it is possible to recognize two words simultaneously, here we use the redundant target paradigm. This experimental paradigm differs from natural reading, assessing instead how well participants can process just two words at once when they are encouraged to try. We compare task performance to the predictions of serial and parallel processing. This complements other approaches that use dual-tasks or measure spatial attention effects (Johnson et al., 2022; White et al., 2018, 2020; White, Palmer, et al., 2019).

**Fundamentals of redundant target effects**

The redundant target paradigm grew out of a larger visual search literature to investigate whether observers can process multiple stimuli presented simultaneously at different visual field positions (van der Heijden, 1975). The observer’s task is to view a display and report the presence or absence of stimuli that belong to a target category. On some trials, one target is presented. On other trials, multiple targets are presented simultaneously — that is, the display contains redundant targets. The redundant target effect is a speeding of correct response times on trials with multiple targets compared to trials with a single target. Such an effect, also termed a “redundancy gain,” can be taken as evidence that the targets were processed in parallel. See...

Studies that have used the redundant target paradigm can be divided into two broad categories: first, those that seek to distinguish between a parallel model and a serial model (van der Heijden, 1975). These studies compare response times between displays
that consist of two (or more) targets, vs. trials that contain one target and no other stimuli. Studies in the second category seek to distinguish between two flavors of parallel models: those with separate activations caused by each stimulus, versus those with interactive "coactivations" (C. W. Eriksen et al., 1989; Miller, 1982; Mordkoff & Yantis, 1991). To do so, response times are compared between displays with that contain two targets, vs. displays that contain one target and one distractor. These "mixed" trials are not useful for testing the serial model, which is the focus of the present study.

Therefore, we focus on the classic redundant target paradigm that compares displays with a single target presented alone to displays with two targets. As shown in Figure 1, contrasting predictions for correct response time arise from a standard unlimited-capacity parallel model and a standard serial model. Both models assume that search is self-terminating: the observer responds as soon as they detect a target. The parallel model assumes that when two targets are present, they are independently processed in separate channels that race to produce the response. The completion time of each process is variable across trials. On two-target trials, the response time is determined by the faster of the two processes, so the observer is faster on average than when only one target is present (Raab, 1962). Thus, the parallel model predicts a positive redundant target effect: a speeding of responses.

The standard serial model, in contrast, assumes that one stimulus is processed at a time (Townsend & Nozawa, 1995). If the first target of two simultaneously presented targets is correctly identified, then the response time is on average the same as when only one target is present—the redundant target has no effect on performance. Previous descriptions of this serial model stop there; but as we explain in our new modeling section below, the serial model that incorporates errors predicts a slowing of correct response times if the first target to be processed is misidentified, and search continues to process the second target correctly.
Figure 1: Diagram of a standard parallel and a standard serial model processing displays containing one target (set size 1) or two targets (set size 2). The parallel model predicts faster responses for set size 2 because the response is triggered by whichever process happens to finish sooner. The serial model predicts either zero effect of set size, or a loss (slower responses to set size 2).

Redundant target effects have been used to reject the serial model for processing simple visual features, such as detecting lights, discriminating colors, orientations, and motion directions (Corballis, 2002; Donkin et al., 2014; Egget al., 1989; Ridgway et al., 2008; Schwarz, 2006; Thornton & Gilden, 2001). Redundant target effects have also been found with auditory stimuli (e.g. Schröter et al., 2007) and with bimodal stimuli (e.g. Gondan et al., 2010; Hershenson, 1962). Face recognition has also been studied with redundant target effects (Fitousi, 2021).

Letters are an interesting test case, being the building block of words, which the new experiments reported below investigate. Several studies have used tasks that require the participant to distinguish one target letter from other letters. When the task uses a "go-no/go" design—to press a button when a target is detected and otherwise make no response—there are positive redundant target effects (e.g. (Grice & Reed, 1992; Mordkoff & Yantis, 1991; van der Heijden et al., 1983). That is also true when the observer makes a vocal response ("yes" or "no"; van der Heijden, 1975). However, other studies have found
no redundant target effect when the procedure is slightly different, such as requiring a
two-choice response on each trial (Fournier & Eriksen, 1990; Grice & Reed, 1992; van
der Heijden et al., 1983). One possibility is that letters are processed in parallel, producing
a positive redundant target effect, but that effect can be masked by later decision- or
response-selection processes when the response rule is more complicated.

Redundant target effects for word recognition tasks

We now turn to the central topic of this article: redundant target effects for written
words. Such effects could reveal the extent to which higher-level semantic or linguistic
information about two stimuli can be processed in parallel. A handful of studies have
gone down that road, with mixed results. They have differed in four important respects:
whether the redundant targets in a single trial are identical words; whether the single-
target trials also contain a ‘filler’ stimulus or distractor; what the task is (semantic
categorization vs. lexical decision), and how the subject responds (go/no-go vs. choice).

We first summarize studies that used a lexical decision task, in which the targets
are real English words and the distractors are meaningless pseudowords. In Mullin &
Egeth (1989), words were presented above and below fixation. The task was to make a
go/no-go response to the presence of a word. Trials either contained 1 pseudoword, 1 real
word, 2 pseudowords, or 2 real words (a “pure” design with no mixed pairs). In one
experiment (their Experiment 2), the redundant targets were identical words. In that case,
there was a significant redundant target facilitation of response times. A similar result
was reported by Egeth et al., (1989), and, with words present to the left and right of
fixation, by Hasbrooke & Chiarelli (1998) and Mohr and colleagues (Mohr et al., 1994,
1996). However, a redundant target effect for identical words might be explained by
facilitation at a sub-lexical level (Shepherdson & Miller, 2014). Mullin & Egeth (1989)’s

\[ \text{[right]} \quad \text{[left]} \]

\[ \text{[right]} \quad \text{[left]} \]

\[ \text{[right]} \quad \text{[left]} \]

1 Nonetheless, presenting copies of the same word across the field provides a redundancy gain that might help
patients with macular degeneration to read, with rapid serial visual presentation (Spill et al., 2022).
third experiment included a condition with two real word targets that were different from each other (also in a lexical decision task). In that experiment, the redundant target effect was significantly negative, meaning that response times were slowed by the addition of a second target.

A second set studies of word recognition have used semantic categorization tasks. In Mullin and Egert (1989)'s first and fourth experiments, one or two words were presented above and below fixation. The task was a go/no-go response to the presence of a word belonging to a given semantic category (e.g., ‘animals’). Notably, each of the four categories contained only 5 words. In one experiment, when two targets were presented they were identical words, and in the other experiment the two targets were different words. There was no significant redundant target effect in either experiment, consistent with the serial model.

The second relevant study using semantic categorization was by Shepherdson & Miller (2014). We focus on their Experiment 3. Stimuli were presented to the left and right of fixation. On each trial, the subject had to make a yes/no response to report the presence of a word belonging to a target semantic category. Most importantly, the “single-target” trials also contained a "filler" stimulus that was a pseudo-word. They found an advantage for the redundant target condition compared to this modified baseline. Interpreting this experiment is difficult. The critical question is whether a serial, self-terminating model predicts no effect between these conditions. Such a prediction follows only if the target is always processed first by the serial process and the filler pseudoword is never processed first, which seems unlikely. Thus, we conclude this experiment should be considered along with experiments that used a mixed-trial baseline to test co-activation models and not as a test of the serial, self-terminating model.

In summary, the effects of redundant targets in word recognition tasks require further investigation. The presence of a redundant target effect might depend on the subject’s task (lexical decision or semantic categorization), the mode of response (go/no-
go or forced-choice), and on whether the experiment includes trials in which a target is paired with a distractor. In the new experiments reported below, we investigate all those factors, and compare lexical and semantic tasks to a font color task. In doing so we also test new models of parallel and serial processing that consider both response time and accuracy.

Response speed and accuracy in redundant target effects

Most of the redundant target studies reviewed above focused only on correct response times and use tasks in which accuracy is near ceiling. Other studies have focused on accuracy, for instance in the context of spatial summation (e.g., Robson & Graham, 1981; Verghease & Stone, 1995). One important study compared redundant target effects on accuracy and speed (Mordkoff & Esch, 1993). We believe that, when testing the serial model, it is important that task encourages the subject is to respond quickly. This is because the serial and parallel models assume that search is self-terminating. Indeed, there is some evidence that redundant target effects are stronger when the subject's instructions emphasize response speed than accuracy (Donkin et al., 2014).

Nevertheless, a full model should explain speed and accuracy. This is because response times to a display containing multiple targets might depend on whether some targets are not identified correctly, even if the final response is correct. Thus, our models below explicitly consider the accuracy of each stimulus recognition process.

New Theory

The new theory builds on previous models of pure response time by adding the possibility of errors (misclassifying targets as distractors or vice versa). Appendix I contains full mathematical descriptions of three classes of models. Here we describe them in more intuitive terms and summarize the qualitative redundant target effects they each predicts.
Consider the standard self-terminating serial model developed for response time (Townsend & Nozawa, 1995). It has been called standard because it includes a number of independence properties. To this model, we add the possibility of an error and additional independence assumptions concerning the error and the relationship between error and response time. The four primary results from this new work are described in the following paragraphs.

Predictions of Our Serial Model

The most important result concerns the predictions made by our new standard self-terminating serial model with errors. Specifically, it predicts a negative redundant target effect. This is unlike the pure response time model that predicts no effect of redundant targets. The source of this different result has to do with what happens when there is an error in processing the first stimulus; if the first target to be processed is misidentified as a distractor, processing continues for the second stimulus. If this second target is correctly identified, then this correct response time is included in the analysis with the other trials in which the first target was processed correctly. Thus, the correct response times for the redundant target condition are a mixture of two cases: those trials in which the first target was correctly identified and the response was made quickly, and those trials in which the first target was not correctly identified and processing continued to the second target. This new result makes the serial model with errors more distinctive from the parallel models, in terms of response times. The predictions for errors are discussed below.

Predictions of Our Unlimited-Capacity, Parallel Model

Our second result concerns the standard unlimited-capacity, parallel model with errors. The corresponding model without errors predicts a positive redundant target effect. We show that this generalizes to models with errors. Errors reduce the size of the
Insert 9 x

the response time is made of

like other models of its type, it queries database process for each student. In addition, it needs time to allow for residual processes that do not depend on the student.
Insect QA

This model is quantitatively the predicted value.

Target effect is given by Equation 5 in the appendix and is repeated here:

\[- \left( \frac{1 - p_+}{\bar{2} - p_+} \right) E[D_{t, \text{target}}].\]

It depends on only two factors:

the probability count in a single test trials \( p_+ \) and the \( E[D_{t, \text{target}}] \) mean count process time at a target when there is an error (miss).

\( E[D_{t, \text{target}}]. \)
An illustration of the prediction is in Panel A of Figure 2. It plots the real target angle as a function of the point error for a single target. For this illustration we assume a 500 ms mean response time. The solid curve is for the case where the current process is equal to the mean (redaltation) current process. The solid curve is for the case with the constant process time function twice the true in ambient, and for ambient time (see the end of the Appendix for more detail).
Together, these predictions give a rough idea of the expected result for each effect. It is always negative and becomes more negative with increasing error. Given the 500 ms stimulation time and 5% error, it is typically between 165 to -30 ms.
effect, but it always remains positive. Thus, there remains a sharp contrast in the predictions for this parallel model and the standard self-terminating serial model.

Predictions of Our Fixed-Capacity, Parallel Models

The parallel model that can most mimic a serial model is one that has limited capacity. The limited capacity slows processing when there are two stimuli and thus reduces and possibly eliminates the redundant target effect. Unfortunately, this model is so general that it does not make any specific predictions. Here, we consider a special case of the limited-capacity parallel model: the fixed-capacity parallel model. The idea of fixed capacity is that a set of parallel processors extract the same amount of information from multiple stimuli as they do from a single stimulus. Thus, splitting a fixed set of 'resources' between multiple stimuli introduces costs of a specific magnitude. Most of the prior work with this model has been in the domain of accuracy (Scharff et al., 2011; Shaw, 1980; White et al., 2018).

We investigated special cases of fixed-capacity parallel models in which we assume a particular stochastic process for each stimulus being processed. First, with a diffusion model (Palmer et al., 2005) of sensory evidence accumulation, we show that the model yields positive redundant target effects on response times, for all relevant parameter values (as well as a positive effect on accuracy). However, with a linear ballistic accumulator model (Brown and Heathcote, 2008), the fixed-capacity parallel model can predict a negative redundant target effect on response time (a slowing), despite a positive effect for accuracy. The rationale is that because of fixed processing capacity, the addition of a second target slows processing of both. Thus, among many parallel models that generate positive response time effects of redundant targets, there is one particular model with a certain processing capacity limit and evidence accumulation structure that yield the opposite result.
The predictions of this model are given by Equation 11 in the appendix and is:

\[
\left(\frac{1}{2-p_t}\right)E[D_{t,\text{count}}] = \left(\frac{p_t}{2-p_t}\right)E\left[\min(D_{t,\text{count}}, D_{t,\text{pre}})\right]
\]

Here, \( p_t \) is the project count for a single test, \( E[D_{t,\text{count}}] \) is the count project mean count response time for a single test, and \( \min(D_{t,\text{count}}, D_{t,\text{pre}}) \) is the pre-processing minus of the mean complete time after the two tests are correctly processed.
An illustration of this prediction is in Panel B of Figure X. The axes are the same as Panel A. For this illustration, we used predictions of specific two models described in the appendix.

The solid curve is for a diffusion model with parameters that generate relevant target large effects, and the dashed curve is for a linear additive common model with parameters that generate relatively small effects, while not strictly linear. These predictions show the vague typical self-terminating predictions from unlabeled capacity parallel models.
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They are always positive and may only slightly be errors.
This last result introduces an asymmetry in using the redundant target paradigm to test serial and fixed-capacity parallel models. A positive redundant target effect rejects the standard serial model, but a negative redundant target effect does not reject all possible fixed-capacity parallel models. Thus, the redundant target paradigm is a good test for rejecting both the serial model and the unlimited-capacity parallel model but not the fixed-capacity parallel model. Nevertheless, it is relevant to distinguishing serial and parallel models. Indeed, many experiments with simple feature tasks have used this test to rule out the standard serial model (e.g., van der Heijden, 1975).

Predictions About Errors

Our last result concerns the usefulness of models that incorporate errors. All of the models described above predict a positive redundant target effect for errors (that is, fewer errors on trials with 2 targets than on trials with 1 target). This is not a surprise for typical parallel models that have been investigated in summation experiments of accuracy alone (Graham et al., 1978). What is new is that this result also occurs for our serial model, even though that model predicts slower response times for two targets. The reason is that when two targets are present and processed sequentially, there are two chances to correctly detect target presence, so accuracy increases compared to when only 1 target is present – even though doing so takes more time on average. While this result for errors does not distinguish between the serial and parallel models, it introduces a result that is specific to errors and that is not accounted for by pure response time models.

Summary of our experiments

We conducted three experiments that differed in two factors. The first factor was how participants responded to the stimuli. "Go/No-Go" is the task procedure that requires the participant to press a button if they see a target and to make no response if they see no targets. This is a common, simple procedure for redundant target effects.
Insert 11A

An illustration of the predictions of this model as in Panel C of Figure X. The solid and dashed curves represent the predictions of the same two models used in Panel B but with final capacity rules of unlimited capacity. Now the prediction can be both positive or negative and the effect of errors is more evident.
“Choice” (short for two-alternative choice) is the procedure that requires the participant to press one of two buttons to categorize each stimulus display. This is the most common procedure in the larger visual search literature. As discussed above, some prior research suggests that a go/no-go procedure is more sensitive for detecting redundant target effects (Grice & Reed, 1992). Previous studies about word recognition have used a mix of go-no/go and choice procedures, so we used both in different experiments. The second factor we manipulated was whether the words presented on two-word trials were "correlated." In the "correlated" design, the two words were either both targets or both distractors. In the "uncorrelated" design, there also were trials in which one target was paired with one distractor. The correlated design includes all the conditions needed to test the serial model (one target alone vs two targets), but the uncorrelated design is more typical in visual search more generally. The inclusion of mixed trials might affect the participant’s strategy and encourage them to process both stimuli, thus we use it in Experiment 3 to compared to the pure correlated-stimuli design. Altogether, these variations in procedure span the range of tasks used in prior redundant target studies.

Notably, in all three experiments, when two words were present, they were two different words. This differs from some previous redundant target experiments that used identical words on two-target trials (Mullin & Egith, 1989) and could produce effects due to sub-lexical facilitation.

In each experiment, we also measured performance in three different tasks (color detection, lexical decision, and semantic categorization). The color task required participants to judge a low-level visual feature of the words, and served as a baseline measure for which we expected positive effects. The lexical decision task requires the subject to distinguish real English word targets from pseudoword distractors. The semantic categorization task requires categorizing words either as targets that belong to a category of “living things” and distractors that belong to a category of “non-living things. The semantic and lexical tasks might tap into different levels of linguistic processing, and
have both been used in prior redundant target studies (Egeth et al., 1989; Mullin & Egeth, 1989). In sum, within each of our three experiments, we carry out a side-by-side comparison of redundant target effects that arise in three tasks using the same stimuli. The tasks differ in which they require low-level color feature detection, lexical access, or semantic categorization.

**Experiment 1: Go/No-Go procedure with correlated stimuli**

**Methods**

Participants: Participants were recruited using Prolific (www.prolific.co, accessed August 2021-May 2023). Participants gave informed consent in accordance with the Declaration of Helsinki and Barnard College’s Institutional Review Board. All participants indicated being fluent speakers who learned English as their first language, with no literacy difficulties, and normal or corrected-to-normal vision. For each task, we aimed to recruit an independent sample of 28 participants, half male and half female. That sample size was chosen on the basis of a power analysis of an independent pilot data set, seeking at least 95% power to detect a response time effect of 15 ms.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Task</th>
<th>N included</th>
<th>N Female</th>
<th>N excluded</th>
<th>Mean age [min max]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Go/No-Go, correlated</td>
<td>Color</td>
<td>28</td>
<td>12</td>
<td>2</td>
<td>32 [19 50]</td>
</tr>
<tr>
<td></td>
<td>Lexical</td>
<td>28</td>
<td>12</td>
<td>0</td>
<td>32 [20 47]</td>
</tr>
<tr>
<td></td>
<td>Semantic</td>
<td>28</td>
<td>14</td>
<td>0</td>
<td>30 [20 47]</td>
</tr>
<tr>
<td>2: Choice, correlated</td>
<td>Color</td>
<td>29</td>
<td>16</td>
<td>0</td>
<td>27 [18 50]</td>
</tr>
<tr>
<td></td>
<td>Lexical</td>
<td>28</td>
<td>14</td>
<td>0</td>
<td>29 [19 48]</td>
</tr>
<tr>
<td></td>
<td>Semantic</td>
<td>28</td>
<td>18</td>
<td>0</td>
<td>27 [19 50]</td>
</tr>
<tr>
<td>3: Choice, uncorrelated</td>
<td>Color</td>
<td>28</td>
<td>22</td>
<td>0</td>
<td>20 [18 24]</td>
</tr>
<tr>
<td></td>
<td>Lexical</td>
<td>28</td>
<td>15</td>
<td>1</td>
<td>31 [20 48]</td>
</tr>
<tr>
<td></td>
<td>Semantic</td>
<td>28</td>
<td>14</td>
<td>1</td>
<td>31 [20 48]</td>
</tr>
</tbody>
</table>

**Table 1:** number of subjects in each experiment and task, as well as the ages in years of the included subjects.
Table 1 indicates the number of subjects and exclusions for all experiments in the study. Across all experiments in this study, our criteria for exclusion were: overall proportion correct <0.6, or proportion correct <0.5 in more than 1 block of 60 trials. In Experiment 1, two subjects in the color task were excluded for the latter reason: one of them had 3 blocks with accuracy <0.5, and the other had 4 such blocks (out of 10 blocks). This was a risk of the go/no-go task conducted over the web browser; if the participant gets distracted mid-block, the experiment carries on without them.

Stimuli: We created and presented stimuli with PsychoPy 3 (Peirce et al., 2019), run through the web browser using Pavlovia (https://pavlovia.org/). Each stimulus size and position were defined as a fraction of the height of the participant’s screen; thus, the dimensions degrees of visual angle likely varied across participants. Participants were asked to sit with their head roughly 1 arm’s length from their screen. A central black fixation cross, 4.5% of screen height in width, was present throughout each trial except during feedback. The stimuli consisted of letter strings, of length between 4 and 6 letters. The word lists are described below and provided fully in Appendix II. They were drawn in Courier font, with the height of an “o” or “x” occupying 3.8% of the screen height. That is roughly 0.7 degrees visual angle on a typical laptop. The specific words (or pseudowords) and font color varied across tasks, as described below.

Trial sequence: An example trial is illustrated in Figure 2A. Each trial began with just the fixation mark present for 750 ms. Then either 1 or 2 words were presented for 183 ms. There were two possible word positions, centered horizontally and either just above or just below the fixation mark with a distance of 10% of the screen height (roughly 1.8 degrees visual angle on a typical laptop). About two letter o’s would fit stacked vertically in the space between the screen center and the words.
Figure 2: Stimuli and Design. (A) Example trial sequence with two color targets. (B) Examples of the trial types in Experiments 1 and 2. The text above each panel indicates the percentage of trials that were of that condition. "D" = distractor, "T" = target. In this illustration, the colored words all refer to living things, thus could be color or semantic targets. But in the actual color task, the semantic category and letter colors were uncorrelated. In the semantic and lexical tasks, the letters were all dark gray.

The trials were evenly distributed between these 4 conditions: 1 target, 1 distractor, 2 targets, and 2 distractors. Figure 2B illustrates examples of each trial type, and Table 2 lists the proportion of trials assigned to each combination of stimuli at the top and bottom locations. Each location could have no word ("None"), a distractor word, or a target word. When just 1 word was present, it was equally likely to be in the top or bottom location. Unlike in Experiment 3, here were never any mixed pairs of 1 target and 1 distractor. Thus, in this experiment, the words in each display were "correlated," meaning that when there were 2 words present, they were either both distractors or both targets.

After the words disappeared, the participant was free to respond. In these go/no-go tasks, the participant was instructed to press the space bar as soon as they detected a target, and to do nothing except wait for the trial to end if they saw no targets. Up to 1
second was allowed for a response. After the response interval elapsed or was ended by a keypress, feedback was given: the fixation cross was replaced with a smiley face for 500 ms if the response was correct, or a neutral face for 750 ms if the response was incorrect. Then, the fixation cross reappeared and another trial began (except when it came time for a break between blocks, see below).

Table 2: The probability of stimulus pairings at the top and bottom locations in Experiments 1 and 2. The word at each location was either absent, a distractor, or a target. The green shading highlights conditions when 2 words were present. In this design, the two words were perfectly correlated, meaning that they were either both targets or both distractors.

Procedure: Once they accessed the experiment in Pavlovia, participants read a consent form and indicated their acceptance by pressing a key to continue. The program advanced through four pages of instructions with example stimuli. Then the participant conducted practice trials, which continued for at least 50 trials until the participant had responded correctly to 36 of the most recent 40 trials. Having completed that, they began the main experimental trials which came in 10 blocks of 60 trials each. Before starting the first block, participants were reminded to keep their head 1 arm’s length from the screen, maintain central fixation, and to respond as quickly as possible without making unnecessary errors. Between each block they were given written feedback about their percent accuracy (P) and the opportunity to rest. If P for the most recent block was at least
96%, the feedback said, “Very nice! You got \([P]\)% correct. In the next block, try to go a bit faster, while still getting at least 90% correct.” If \(P \leq 72\)% correct, the feedback said, “Good job. You got \(P\)% correct. In the next block, try to get above 90% correct.” Otherwise, the feedback simply said, “You’re doing great!” Participants completed the whole experiment in roughly 30 minutes, on average.

**Color detection task:** Each word was either drawn in all dark gray letters (RGB 79, 79, 79) or its letters alternated between dark red (RGB 115,18,18 out of 255) and dark green (RGB 17,102,15). Targets were defined as words written in colored letters; distractors were words written in gray letters. The words were drawn from the same set as in the semantic categorization task (see below).

**Lexical decision task:** All the letters were dark gray (RGB 79, 79, 79). There were a total of 246 items in the stimulus set, half real English words and half pronounceable pseudowords. Within both categories, 33 had 4 letters, 46 had 5 letters, and 44 had 6 letters. The real words were all nouns that were also used in the color & semantic tasks, with mean lexical frequency 16.4 occurrences per million (ranging 0.3-391). The pseudowords were generated using MCWord (Medler & Binder, 2005) to have trigram statistics (the probability of any sequence of three letters) matched to real words. Across the 600 trials in the experiment, each word was repeated on average 3.7 times. We took care to match the mean lexical frequency and word lengths across trials with 1 real word and trials with 2 real words.

**Semantic categorization task:** All the letters were dark gray as in the lexical task. There were a total of 246 English nouns in the stimulus set, half of which referred to living things and half to non-living things. Within the living category there were 39 4-letter words, 42 five-letter words, and 42-six-letter words. The non-living category had 37 4-letter words, 42 five-letter words, and 44-six-letter. The distributions of lexical frequencies in the living and non-living categories were highly overlapping, with means
19.7 and 14.5, respectively. Each word was repeated on average 3.7 times within the experiment.

**Analysis:** We computed two measures of performance in each condition: the mean response time on correct trials, and the percent of trials with incorrect responses (errors). In most cases we focus on trials with targets, because only those test our models that assume self-terminating search for targets. For both measures, we compared the means on trials with two targets to trials with one target with paired t-tests. All t-test p-values were corrected for false discovery rate across the 9 tests done for each measure in the entire study (Benjamini & Hochberg, 1995). We also used bootstrapping to get a 95% confidence intervals (CI) of each mean difference. Lastly, we supplement our pairwise tests with Bayes factors (BFs), which quantify the strength of evidence (Rouder et al., 2009). The BF is the ratio of the probability of the data under the alternate hypothesis (that two means differ) relative to the probability of the data under the null hypothesis (that there is no difference). A BF of 10 would indicate that the data are 10 times more likely under the alternate hypothesis than the null. BFs between 3 and 10 are regarded as substantial evidence for the alternate hypothesis, and BFs greater than 10 as strong evidence. Conversely, BFs between 1/3 and 1/10 are considered substantial evidence for the null hypothesis, etc. We computed BFs using the bayesFactor toolbox by Bart Krekelberg (https://doi.org/ 10.5281/zenodo.4394422).

To compare across tasks across experiments, we also fit linear mixed effect (LME) models to single-trial data, with fixed effects of the task, the set size (number of words), random intercepts and slopes by participant, and random effects for individual stimulus items. All p-values for a certain test were corrected for false discovery rate across the 9 tests done in the study.
Results

Response times: Figure 3A shows that in the color task, there was a positive redundant target effect: a speeding of correct responses to two targets compared to one. However, in the semantic task, there was a significantly negative effect (a slowing of responses). In the lexical decision task, there was no effect of redundant targets. Table 3 list the statistics on each effect. The mean response times in each individual condition (rather than the differences between one and two targets) are shown in the top row of Figure 4.

*Redundant target effects in Expt. 1 (Go/No-Go, correlated stimuli)*

![Graph showing redundant target effects in Expt. 1](image)

**Figure 3:** Redundant target effects in Experiment 1. These bar plots show the mean improvement in (A) mean correct response time (RT) and in (B) accuracy for 2 targets compared to 1 target. The mean performance levels from which these difference scores were derived are in Figure 4. Error bars are ± 1 SEM. Asterisks indicate that the mean effect is significantly different from 0 (***p<0.001, **p<0.01, FDR-corrected).

To compare the redundant target effects across tasks, we also fit three linear mixed-effect models to single-trial correct response times (target-present trials only). Compared to the color task, both the lexical and semantic tasks had significantly different
redundant target effects (both $F>36$, $p<10^{-8}$). The lexical and semantic tasks yielded effects that were marginally different ($F(1, 15475) = 3.86$, $p=0.056$).

**Performance in each task of Expt. 1 (Go/No-Go, correlated stimuli)**

![Graph](image)

**Figure 4:** Mean performance in each task of Experiment 1, plotted separately for targets and distractors, for set size 1 vs. 2. (A) Mean correct response times. Note that there is no correct response time data for distractors, because in these go/no-go tasks, the correct response to distractors was to not press any key. (B) Percent of trials with errors. There are data for distractors are plotted with open symbols and dashed lines (showing how often the participants made false alarms). Error bars are ±1 SEM.

**Accuracy:** Figure 3B shows the mean improvements in accuracy caused by a redundant target. There was a significant improvement in all three tasks (see statistics in Table 3). The mean error rates in each condition (including for trials with distractors) are plotted in the bottom row of Figure 4. Compared to the color task, both the lexical and semantic tasks had smaller redundant target effects on accuracy for detecting targets (both $F>39$, $p<10^{-8}$). The effects did not differ significantly between the lexical and semantic tasks ($F(1, 18573) = 0.75$, $p=0.38$).
<table>
<thead>
<tr>
<th>Task</th>
<th>Effect mean</th>
<th>Effect SEM</th>
<th>95% CI</th>
<th>$t$</th>
<th>$p$</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correct response time (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>31.98</td>
<td>2.49</td>
<td>[27.36]</td>
<td>12.67</td>
<td>6.35x10^{-12}</td>
<td>1.09x10^{10}</td>
</tr>
<tr>
<td>Lexical</td>
<td>-0.11</td>
<td>3.53</td>
<td>[-6.8]</td>
<td>0.03</td>
<td>0.98</td>
<td>0.20</td>
</tr>
<tr>
<td>Semantic</td>
<td>-10.67</td>
<td>3.53</td>
<td>[-17.6]</td>
<td>3.60</td>
<td>0.002</td>
<td>27.69</td>
</tr>
<tr>
<td></td>
<td>Errors (percent)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>7.95</td>
<td>2.10</td>
<td>[4.54 13.23]</td>
<td>3.72</td>
<td>0.001</td>
<td>35.778</td>
</tr>
<tr>
<td>Lexical</td>
<td>2.12</td>
<td>0.80</td>
<td>[0.62 4.02]</td>
<td>2.59</td>
<td>0.017</td>
<td>3.22</td>
</tr>
<tr>
<td>Semantic</td>
<td>1.90</td>
<td>0.86</td>
<td>[0.49 4.12]</td>
<td>2.19</td>
<td>0.038</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Table 3: Statistics on redundant target effects in Experiment 1, describing the mean improvement in response time or error rate, contrasting 1-target displays vs. 2-target displays. The degrees of freedom for the t-tests was 27. For each measure (response time or accuracy), p-values are corrected for false discovery rate across all 9 comparisons including all 3 experiments in the study. BF = Bayes Factor.

Discussion

The redundant target effects in this first experiment suggest that the colors of the letters within two words can be processed in parallel, leading to speeding of response times. However, the meanings of the two words are not necessarily processed in parallel. This is because the presence of a second word target in the lexical decision task yielded 0 improvement in response time, and the semantic categorization task yielded a significant slowing of response time.

Our new theory demonstrates for the first time that such a negative response time effect is in fact consistent with the standard serial model, even when accompanied by an increase in accuracy (see Appendix). It can be explained by participant occasionally mis-categorizing the first target they process as a distractor, then going on to correctly process the other target, with a slower response time compared to correct trials with single targets. It is potentially interesting that this negative redundant target effect was
significant in the semantic task but not the lexical task, but we lack strong statistical
evidence that those two results were significantly different from each other.

It is also noteworthy that redundant targets improved accuracy in all three tasks
(although that effect was significantly larger in the color task than in the other
two). Is that evidence of parallel processing of two words in all three tasks? Not
necessarily: the serial model also predicts improvements in accuracy that go along with
slowing of response speeds. This is merely a statistical facilitation: there are two chances
to reach the correct decision when two targets are present. Also note that, as shown in the
bottom row of Figure 4, error rates on trials with distractors increase when the set size is
2 compared to 1 (a decrease of accuracy, opposite to the pattern for trials with targets).
This might also be consistent with a shift in decision criterion, as participants are
somewhat more likely to report “target present” when they see two words than when
they see one word.

Thus, the entire data set is consistent with parallel processing only in the color task
that yields a positive redundant target effect in both response time and accuracy —and
we consider the effects on response time to be most diagnostic.

This experiment assessed redundant target effects with the simplest possible
design (“correlated stimuli”, meaning no trials with mixed targets and distractors) and
the procedure known to be most sensitive (go/no-go). In the next two experiments, we
used variations of the paradigm that have previously been used to study word
recognition and might alter the participant’s strategy. In Experiment 2, we used the same
“correlated” stimulus conditions as Experiment 1, but we required participants to report
a judgment (target present vs absent) on every trial.

**Experiment 2: Choice procedure with correlated stimuli**

**Methods**
Participants: Participants were recruited in the same way as in Experiment 1. See Table 1 for counts. Applying the same accuracy criteria as in Experiment 1, no participants had to be excluded.

Stimuli and procedure: All methodological details were the same as in Experiment 1, except the participant had to make a categorization judgment on every trial: press the left arrow if no target was present on the screen, or the right arrow if any targets were present on the screen. The response interval was unlimited, but participants were requested to "respond as quickly as you can without making unnecessary errors."

Analysis: Trials were excluded with response times more than 4 standard deviations above each participant's grand mean. The mean percentages of trials thus excluded in the color, lexical and semantic tasks were 0.61%, 0.72%, and 0.84%, respectively.

Figure 5: Mean redundant target effects in Experiment 2. Format as in Figure 3.

Results

Response times: Figure 5A demonstrates that the redundant target effects on correct response times in Experiment 2 were similar to those in Experiment 1. There was a significant speeding of response times in the color task, no significant effect in the lexical
task, and a significant slowing in the semantic task. Statistics on the effect for each task are reported in Table 4. Compared to the color task, both the lexical and semantic tasks had significantly different redundant target effects (both F>18, p<10⁻⁴). The lexical and semantic tasks yielded effects that were not significantly different (F(1, 15141)=2.61, p=0.11). See the top row of Figure 6 for mean correct response times in each condition separately.

**Figure 6.** Mean performance in each task of Experiment 2. Format as in Figure 4.

**Accuracy:** Figure 5B plots the mean improvements in accuracy caused by redundant targets, which were significant in all three tasks (as also reported in Table 4). The mean error rates in each condition are plotted in the bottom row of Figure 6. Compared to the color task, both the lexical and semantic tasks had smaller redundant target effects on accuracy (both F>21, p<10⁻⁵). The redundant target effects did not differ significantly between the lexical and semantic tasks (F(1, 16689)=0.05, p=0.82).
<table>
<thead>
<tr>
<th>Task</th>
<th>Effect mean</th>
<th>Effect SEM</th>
<th>95% CI</th>
<th>t</th>
<th>p</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>response</td>
<td>28.29</td>
<td>3.26</td>
<td>[22.35]</td>
<td>8.52</td>
<td>1.3x10^{-8}</td>
<td>4.1x10^{6}</td>
</tr>
<tr>
<td>times (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>-4.51</td>
<td>5.51</td>
<td>[-15.6]</td>
<td>0.80</td>
<td>0.48</td>
<td>0.27</td>
</tr>
<tr>
<td>Lexical</td>
<td>-17.50</td>
<td>4.38</td>
<td>[-26 -10]</td>
<td>-3.92</td>
<td>0.001</td>
<td>57.8</td>
</tr>
<tr>
<td>Semantic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Errors</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>percent</td>
<td>8.14</td>
<td>1.14</td>
<td>[6.04 10.85]</td>
<td>7.02</td>
<td>1.1x10^{-5}</td>
<td>1.2x10^{5}</td>
</tr>
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<td>Color</td>
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<td>[1.71 4.70]</td>
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<td>0.001</td>
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<td>Lexical</td>
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<td>0.60</td>
<td>[1.26 3.55]</td>
<td>4.03</td>
<td>0.001</td>
<td>74.8</td>
</tr>
</tbody>
</table>

Table 4: Statistics on redundant target effects in Experiment 2, formatted as in Table 3. The degrees of freedom was 28 for the color task and 27 for the others.

Discussion

The results of Experiment 2, which used a choice procedure, were consistent with the results of Experiment 1, which used a go/no-go procedure. The redundant target effects on response times were consistent with parallel processing in the color task and serial processing in the lexical and semantic tasks. Again, the redundant target effect in the semantic task was significantly negative.

In both experiments reported so far, the words presented simultaneously on trials with set size 2 were always of the same category (both targets or both distractors, although never the same exact words). That is what we mean by a 'correlated' stimulus design. One potential drawback of this design is that the participant might adopt a strategy of always processing just one word, knowing that the other word will lead to the same correct decision. (Although they cannot simply pick a side of the screen and always ignore stimuli presented on the other side, because half the trials contain just a single word that could be on either side, unpredictably). In the third experiment, we addressed this issue by including some trials in which a target is paired with a distractor. Thus, the
stimuli are uncorrelated. This might motivate the participant to process both stimuli as well as they can. **This is also the more common procedure** in the visual search literature.

**Experiment 3: Forced-choice procedure with uncorrelated stimuli**

**Methods**

**Participants:** Participants in the lexical and semantic tasks were recruited and compensated in the same way as in Experiment 1, via Prolific. Participants in the color task were recruited from the Barnard College Introductory Psychology subject pool, and participated in exchange for course credit. See Table 1 for counts. One participant was excluded for overall accuracy being <0.6, and another because they pressed the same key on every trial (but overall proportion correct was >0.6 because targets were present on 75% of trials).

**Stimuli and procedure:** All details were the same as in Experiment 2, except as noted here. The primary differences is that 30% of trials contained mixed pairs of 1 target and 1 distractor. **Table 2** lists the proportions of trials assigned to each type, which were chosen to ensure that the categories (target vs distractor) of the upper and lower stimuli were independent and uncorrelated. Specifically, on two-word trials, the conditional probability of one stimulus being a target given that the other was a target was 0.5. In contrast, this conditional probability was 1.0 in Experiment 1 and 2. Another difference in Experiment 3 was that across the experiment, the probability of a target being present on any given trial was 0.75, rather than 0.5. That was true both among trials with set size 1 and trials with set size 2. Also, six words were added to the stimulus set for the color and semantic tasks (see Appendix II).

**Analysis:** We analyzed these data in the same way as Experiment 1 and 2, focusing on the comparison between trials with two targets and trials with a single target presented alone, which provide the best test of our self-terminating models of parallel or serial processing. The mean percentages of trials excluded for sluggish response times
(>4 SDs above each participant's mean) in the color, lexical and semantic tasks were 0.48%, 0.56%, and 0.61%, respectively.

Table 5: The probability of stimulus pairings at the top and bottom locations in Experiment 3. The word at each location was either absent, a distractor, or a target. The green shading highlights conditions when 2 words were present. In this design, the two stimuli were uncorrelated and independent: the conditional probability of one stimulus being a target given that the other was a target was 0.5.

Redundant target effects in Expt. 3 (Choice task, uncorrelated stimuli)

Figure 7: Redundant target effects in Experiment 3. Format as in Figures 3 and 5. These bar plots show the mean improvement in correct response time (RT) and accuracy comparing trials with 2 targets to trials with just 1 target and 0 distractors. The mixed-pair trials were not included in this analysis (but are plotted in Figure 8).
Results

Response times: Figure 7A shows that the redundant target effects were consistent with the prior two experiments, although somewhat magnified. As detailed in Table 6, redundant targets improved responses in the color task, but slowed responses in both the lexical and semantic tasks. All three pairwise comparisons between these effects were significant (color vs. lexical and color vs. semantic: both $F>27$, $p<10^{-5}$; lexical vs semantic: $F(24587)=5.70$, $p=0.022$). See the top row of Figure 6 for mean correct response times in each condition separately, including the mixed target-distractor trials, which are represented with single lightly-shaded symbols.

\[
\text{Performance in each task of Expt. 3 (Choice, uncorrelated stimuli)}
\]

![Graph showing performance](image)

Figure 8. Mean performance in each task of Experiment 3. Format as in Figures 4 and 6, except with the addition of ‘mixed’ trials that contained 1 target and 1 distractor.

Accuracy: Figure 7B plots the positive effects of redundant targets on accuracy, which were significant in all three tasks (see Table 6). None of the pairwise comparisons of these effects across tasks were significant after correcting for multiple comparisons.
(color vs. lexical: F(25111)=3.44, p=0.095; color vs. semantic: F(25105)=4.10, p=0.077; lexical vs semantic: F(25114)=0.10, p=0.821). Mean error rates in each condition are shown in the bottom row of Figure 8.

Table 6: Statistics on redundant target effects in Experiment 3, formatted as in Table 3. The degrees of freedom for the t-tests was 27.

<table>
<thead>
<tr>
<th>Task</th>
<th>Effect mean</th>
<th>Effect SEM</th>
<th>95% CI</th>
<th>t</th>
<th>p</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correct response time (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>33.07</td>
<td>9.73</td>
<td>[21.72]</td>
<td>3.34</td>
<td>0.0032</td>
<td>15.2</td>
</tr>
<tr>
<td>Lexical</td>
<td>-41.53</td>
<td>9.67</td>
<td>[-71 -28]</td>
<td>4.22</td>
<td>0.0006</td>
<td>116.5</td>
</tr>
<tr>
<td>Semantic</td>
<td>-73.90</td>
<td>8.74</td>
<td>[-93 -58]</td>
<td>8.30</td>
<td>2x10^-8</td>
<td>1.9x10^6</td>
</tr>
<tr>
<td></td>
<td>Errors (percent)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>2.06</td>
<td>0.38</td>
<td>[1.34 2.76]</td>
<td>5.35</td>
<td>5.3x10^-5</td>
<td>1.8x10^3</td>
</tr>
<tr>
<td>Lexical</td>
<td>1.11</td>
<td>0.27</td>
<td>[0.62 1.58]</td>
<td>4.08</td>
<td>0.001</td>
<td>83.5</td>
</tr>
<tr>
<td>Semantic</td>
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<td>0.26</td>
<td>[0.26 1.34]</td>
<td>2.87</td>
<td>0.010</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Discussion

The results of Experiment 3 were consistent with both prior experiments: there is a positive redundancy target effect on response times in only the color task. One new result in this experiment was that the lexical task, as well as the semantic task, yielded a significantly negative redundant target effect (slowing of responses). These results again are consistent with the hypothesis that colors are processed in parallel, but word meanings are processed serially.

Note that we chose to focus our analysis on trials with targets only. Some prior redundant target studies have compared two-target trials to the mixed target-distractor trials, in some cases to test theories of 'coactivation' (C. W. Eriksen et al., 1989; Miller, 1982; Mordkoff & Yantis, 1991). Other experiments with words have compared trials with two targets to trials with one target and a "filler" pseudoword stimuli that was neither a target nor distractor (Shepherdson & Miller, 2014). However, such contrasts do not clearly distinguish our self-terminating serial model from the parallel models. Even the
serial model predicts faster responses to two targets than to a single target paired with a non-target, because if the non-target is processed first, search must continue. As shown in Figure 8, mean responses to mixed-pair trials were in fact slower (and less accurate) than responses to trials with two targets. Thus, we have focused on comparing two-target trials (set size 2) to single-target trials (set size 1). The result of that contrast was dramatically different across tasks.

GENERAL DISCUSSION

The three experiments reported above consistently demonstrate that there is a positive redundant target effect when the targets are defined by color but not when the targets are defined by lexicality or by semantic category. In all three tasks, the stimuli were written words presented singly or in pairs above and/or below fixation. In the color task, the presence of a redundant target (a word written in colored letters) consistently sped responses compared to trials with a single target. In the semantic task, the presence of a redundant target (a word that refers to a living thing) slowed responses in each experiment. In the lexical decision task, the redundant target had no effect in two experiments (with correlated stimuli), and a significantly negative effect in the third experiment (with uncorrelated stimuli).

These data are all consistent with the hypothesis that low-level features (such as color) of multiple stimuli may be processed in parallel, but written words must be recognized serially. The lexical decision and semantic categorization tasks were two ways to assess word recognition: the lexical decision task requires the participant to judge the familiarity of each letter string, and the semantic categorization task further requires further judgement of the word’s meaning. That said, the results do not rule out all possible parallel models.
Relation to previous redundant target studies of word recognition

In contrast to our key result, some prior studies of word recognition have reported positive redundant target effects. However, several of those experiments presented two copies of the same word on redundant target trials (Egeth et al., 1989; Hasbrooke & Chiarello, 1998; Mohr et al., 1994, 1996; Mullin & Eggeth, 1989, Experiment 1-2). The resulting redundant target effects might be explained by facilitation or co-activation at the stage of letter recognition, for example, rather than actual semantic recognition. The only study to report a positive redundant target effect that did not present identical pairs of words was by Shepherdson & Miller (2014). The found that semantic categorization judgments were faster for two targets than for a single target paired with a pronounceable non-word. This could be interpreted as a positive redundant target effect and evidence for parallel processing. However, the result can be explained by the serial model if we assume that on some one-word trials, the participant processes the non-word before they process the target. Therefore, we consider the best test of our serial model to be the contrast between trials with two targets (which are two different words) and trials with a single target presented alone.

Thus far, all experiments that made the strict test of the serial model (with word recognition tasks) lead to the same conclusion. They were conducted by us in the present study and by Mullin & Eggeth (1989). The experiments in that prior study were like our Experiment 1: they presented words above and/or below fixation and used go/no-go target detection tasks in which targets were never presented with distractors (a correlated stimulus design). In two of their experiments, the words presented together on redundant-target trials were not identical (as in ours). In those experiments, they found that both lexical decision and semantic categorization judgments were slowed by the presence of a redundant target – but significantly so only in the lexical task. Based on these results, the authors rejected the unlimited-capacity parallel processing model for
recognizing two words, as do we. They raised several tentative explanations for how ‘interference’ between two words might cause the negative redundant target effect. But as we discussed, this negative effect is predicted by the standard serial model that accounts for errors in stimulus classification.

We also go beyond previous studies by showing that the conclusions hold for choice tasks (Experiment 2) and well as go-no/go tasks (Experiment 1), and when stimuli are ‘uncorrelated’, meaning that targets can appear with distractors (Experiment 3). Importantly, we also contrasted the word recognition tasks to a color task. The color task served as a positive control that demonstrated that redundant target effects are possible with the same stimuli presented at the same locations.

Thus, we can reject the standard serial model for the color task, but for the word recognition tasks (i.e., lexical decision and semantic categorization). In addition, we can reject the standard unlimited-capacity parallel model for the word recognition tasks, but not for the color tasks. What we cannot do is reject the standard fixed-capacity parallel model the word recognition tasks. That does not mean that the fixed-capacity model is always viable. It can predict the wide range of redundant target effects, depending on the assumptions built into it and the specific parameters. More work is needed to test those assumptions and parameters.

Relation to the wider literature on serial vs parallel word recognition

Two related questions have fueled many studies of visual word recognition and reading: (1) Can multiple words be recognized in parallel? (2) In natural reading, do readers process multiple words in parallel? Both questions are heavily debated. The redundant target effects explored in the present article are one way to investigate the first question. The second question arose earlier, however, so we will review it and then return to the first question.
There is ample evidence that when fixating word \( n \), readers begin processing word \( n+1 \) before the eyes move (e.g., "parafoveal preview"; (Schotter et al., 2012). That might either mean that attention is distributed over multiple words simultaneously, or that before the eyes move from word \( n \), processing shifts to word \( n+1 \), and words are processed serially. Several computational models predict such phenomena assuming either parallel or serial processing of individual words (Engbert et al., 2005; Reichle et al., 2006; Reilly & Radach, 2006; Snell, van Leipsig, et al., 2018). The debate between such models has proven intractable over the years.

One interesting empirical result during a naturalistic reading task is the transposed word effect: readers often fail to notice when the order of two words has been reversed (Mirault et al., 2018). That might be evidence that readers process multiple words in parallel with flexible position coding (Snell & Grainger, 2019b). However, the transposed word effect also occurs when the words in each sentence are presented one at a time, serially, and parallel processing is not possible (Hossain & White, 2023; Huang & Staub, 2022; Liu et al., 2022; Malledge et al., 2023); but see (Mirault et al., 2022).

Given the complexity of natural reading and the wide range of models to explain it, other researchers (including the present authors) have turned to more controlled experimental paradigms. The goal is to investigate the fundamental processing capacity limits of visual word recognition – are readers even capable of recognizing two words in parallel, when they are forced to try?

One such paradigm is the un-speeded dual-task paradigm that measures accuracy. It has provided evidence for a serial “bottleneck” in word recognition (White, Boynton, et al., 2019). In these experiments, participants are presented with two words at once. They either focus on one word or attempt to divide attention to judge both words. A key difference from the redundant target paradigm is that the two words must
be judged independently, rather than integrated to one decision. Also, the primary measure is accuracy rather than response time, and several studies have post-masked the words after an interval calibrated to each individual's performance. Thus, each participant is given just enough time to process one word, and the question is whether they can process two words with divided attention in that same amount of time. Parallel and serial processing models make predictions for the magnitude of the drop in accuracy in the divided attention condition compared to the focused attention condition.

Several dual-task studies have been consistent with the serial model: the observer can recognize only one word per trial and must guess when asked about the other. That has been true for semantic categorization and lexical decision judgments, with words positioned above/below fixation, and to the left/right (White et al., 2018, 2020; White, Palmer, et al., 2019). The cost of dividing attention on accuracy in these experiments rejects the standard unlimited or fixed-capacity parallel models. That measure alone cannot reject a more extreme limited-capacity model. However, another result in these studies is a negative correlation between the two responses made within the same trial. The response to one stimulus is more likely to be correct when the response to the other stimulus is incorrect. This result is consistent with the standard serial model and rejects all standard parallel models. To account for the negative correlation with a parallel model, one must resort to an ad-hoc addition to the model.

The same serial result has arisen in dual-task experiments that probe recognition of letters and phonological features of letter strings (Campbell et al., 2024). However, when the task is to judge the colors of the letters, dual-task accuracy was consistent with an unlimited- or modestly-limited capacity parallel model (White et al., 2018, 2020). These data lead to the same conclusion as the redundant target studies reported in the present manuscript: low-level features are processed in parallel, but words must be recognized
serially. One neuroimaging study identified a potential neural locus of the serial bottleneck in left ventral temporal cortex (White, Palmer, et al., 2019).

A related paradigm is called “partially-valid cuing,” in which one of two stimulus locations is pre-cued as more likely to be task-relevant. One study using post-masked words found that when participants were asked to judge the semantic category of a word that appeared at the uncued (less attended) location, they performed no better than chance (Johnson et al., 2022). This is again consistent with the standard serial model for word recognition. On the face of it, this result is inconsistent with any parallel model. If processing in parallel, why not acquire some information about the low-probability word? To save the parallel model, one must assume a strategy of only processing one word at a time under some conditions; in other words, the parallel model becomes effectively serial.

Not all studies agree, however (Snell & Grainger, 2019a). Varieties of the “flanker paradigm” (Eriksen & Eriksen, 1974) have demonstrated that judgments of one target word are influenced by the characteristics of nearby, task-irrelevant words (Snell et al., 2017; Snell, Mathôt, et al., 2018; Snell & Grainger, 2018). That is true even when the whole display is flashed for 50 ms (Snell, 2024). Moreover, there is a “sentence superiority effect”: when the words that are flashed along with the target form a sentence, the target is reported more accurately than when the word order is scrambled (Snell & Grainger, 2017; Wen et al., 2019). One interpretation of these results is that the words each display were all processed simultaneously (Snell & Grainger, 2019b). It is important to note that these experiments differ from the redundant target experiments reported above in at least two key ways: (1) the target word was fixated directly and flankers were arranged horizontally to the left and right; (2) only one word was task-relevant, so the influence of flankers could be due to automatic, perhaps even subliminal processing.
Thus, prior research on the capacity for processing of multiple words has yielded some inconsistent results. The dual-task studies, in which participants explicitly attempt to recognize two unrelated words at once, have so far been consistent with a serial model. The words in those studies have been positioned in the parafovea and thus may not capture the processing capacity of natural reading. The flanker effect studies have been interpreted as evidence for parallel processing of multiple words (arranged horizontally). These flanker-effect studies have not as strictly controlled the time available to process each display (including from iconic memory), nor tested specific quantitative models of serial processing.

The data reported in the present article add to that prior research in several ways. The redundant target paradigm complements the dual-task paradigm because the words do not have to be post-masked, and the observer needs not make independent judgements about two words simultaneously. Moreover, the effects on response time can be compared to specific quantitative models. Altogether, our results so far are consistent with the dual-task studies in supporting the serial model. It is important to note, though, that we have only tested displays with words placed above and below the fixation point, rather than in more naturalistic arrangements.

Relation to models of visual search more generally

Conclusion

This study makes two primary contributions: first, we developed computational models of the redundant target effect, which yielded some new results. By accounting for errors in target detection as well as response time, the standard serial model predicts that redundant targets slow correct responses, even when they increase accuracy. We also developed specific examples of standard fixed-capacity parallel models, which can predict a wide range of redundant target effects. The standard unlimited-capacity parallel
<table>
<thead>
<tr>
<th>Item</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>This work has been focused.</td>
</tr>
<tr>
<td>2</td>
<td>Townsend &amp; Mize (1995)</td>
</tr>
<tr>
<td>3</td>
<td>The thing that is true, to develop a -- response, is one of the possibilities.</td>
</tr>
<tr>
<td>4</td>
<td>It is seen in this sense, it does not matter.</td>
</tr>
<tr>
<td>5</td>
<td>Relation to the other literature.</td>
</tr>
<tr>
<td>6</td>
<td>In this article, we have explored developments of things of what precedes.</td>
</tr>
<tr>
<td>7</td>
<td>Relevant to the wider literature.</td>
</tr>
</tbody>
</table>

[Diagram: A flowchart or network diagram indicating relationships and processes.]

Insert 36 H
To finish the initial desk check of the first grade, the first grade teacher needs to discuss the checklist with the students. The checklist consists of specific criteria that students need to meet before moving on to the next grade. The second grade is to submit the specific checklist to the teacher for further evaluation.

In June 2014, the second grade teacher needs to send the specific checklist to the teacher for further evaluation.
36C

integrate trust or response time
and accuracy.

Here we try to

combine two approaches
generally.

In seeking distinct

that integrates response time
and accuracy. There are a few

similar effects that work.

In particular, little by little, Biddle

and Townd (2022) have

extended the system factor in technology
to conditions with errors. They have

shown that some of the products

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36D

to coexist with errors math
other condition do not.

In surveying a new
function or theory is the
development of a general
theory of both remain true
and occur, we have developed
such a thing for the what
tent paradox. This coupled
with work developing A for
other paradoxes.
model always predicts positive redundant target effects. Second, we presented experimental tests of these predictions for judgments of words. When the task required judgment of the letter colors, a strong redundant target effect rejected the standard serial model. When the task required recognizing the words, zero or negative redundant target effects rejected the unlimited-capacity parallel model but did not reject the standard serial model. Thus, the redundant target paradigm is a valuable tool for research on word recognition and reading, and shows promise for other domains of visual cognition.

This adds to evidence from other paradigms that word recognition is serial.
37 plus 1/2

Add author notes
and cite in data repository.