

# Bayesian multi-level modelling for predicting single and double feature visual search

Anna E. Hughes<sup>a</sup>, Anna Nowakowska<sup>b</sup>, Alasdair D. F. Clarke<sup>1</sup>

<sup>a</sup>*Department of Psychology, University of Essex, Colchester, CO4 3SQ, UK*

<sup>b</sup>*School of Psychology, University of Aberdeen, Aberdeen, AB24 3FX, UK*

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## Abstract

Performance in visual search tasks is frequently summarised by “search slopes” - the additional cost in reaction time for each additional distractor. While search tasks with a shallow search slopes are termed efficient (pop-out, parallel, feature), there is no clear dichotomy between efficient and inefficient (serial, conjunction) search. Indeed, a range of search slopes are observed in empirical data. The Target Contrast Signal (TCS) Theory is a rare example of quantitative model that attempts to predict search slopes for efficient visual search. One study using the TCS framework has shown that the search slope in a double-feature search (where the target differs in both colour and shape from the distractors) can be estimated from the slopes of the associated single-feature searches. This estimation is done using a contrast combination model, and a collinear contrast integration model was shown to outperform other options. In our work, we extend TCS to a Bayesian multi-level framework. We propose running a new fully within-subjects experiment ... investigate using normal and shifted-lognormal distributions, and show that the latter allows for a better fit to previously published data. We also show that in the case of contrast combination, previous datasets are not sufficient to distinguish between the hypotheses that had been considered. We will conduct experiments that attempt to replicate the key original findings, with some changes to help distinguish between theories.

*Keywords:* Visual search, Efficient search, Parallel processing

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## 1. Introduction

Visual search, where participants are asked to find a target within a cluttered scene, has been extensively studied within psychology. Several models have been

developed that can generate testable predictions about how different types of distractors and targets affect search efficiency. One of the key distinctions in the field has been between efficient (also referred to as parallel or pop-out) and inefficient (serial) search. These are often studied in the context of the regression slope between the number of distractors and mean reaction time, which has been termed the *search slope*. When the search slope is shallow (usually positive, but occasionally negative), the search is called efficient or parallel, and the addition of more non-target distractors has little impact on an observers difficulty in finding a target. When the slope is steeper, each additional distractor has a noticeable impact on increasing difficulty, and the search is described as inefficient or serial. However, the distinction between these types of search is often less clear in real experimental data, with a range of different search slopes being seen for different types of targets and distractors (Cave and Wolfe, 1990).

In the current study, we are interested in what has traditionally been termed efficient or parallel search, and the factors that affect search slope in these conditions. Recent work has suggested that for efficient search, there is a logarithmic relationship between distractor set size and reaction time, and that this relationship can be modified by target-distractor similarity (Buetti et al., 2016), providing evidence that search behaviour in parallel search is more complex than has previously been assumed. This observation has formed the basis of the ‘Target Contrast Signal (TCS) Theory’ (Lleras et al., 2020), which aims to provide a means of predicting observer search slopes for new search arrays by quantifying target-distractor differences. For example, by measuring search slopes for conditions in which the distractors differ from the target along a *single feature* (e.g. colour *or* shape), it has been shown that you can predict search times for arrays in which the target differs from the distractors along two features (e.g., colour *and* shape) which we refer to here as *double feature* search. (Buetti et al., 2019). Here, we aim to replicate and extend this work both theoretically and empirically, to test the generalisability of the TCS model, and to suggest ways in which the TCS model could be improved to generate better predictions.

### 1.1. Previous Work

Many different forms of visual search models have been proposed. One well developed class of models are the saliency models, which aim to predict eye movements during scene viewing, including visual search. They rest on the assumption that fixations are directed to objects or locations that are most dissimilar to the background or other objects in the visual display (Itti and Koch, 2000; Itti et al., 1998; Koch and Ullman, 1987). While the original saliency model was

able to predict fixation allocation in a visual search task above chance (Parkhurst et al., 2002), further research demonstrated that a comparable level of performance could be achieved using a simple central fixation bias heuristic (Tatler, 2007). The saliency models have since been extended and improved (see for example Zhang et al. (2008)): however, the main issue with this family of models remains their limited usability in complex real-life search arrays (Tatler et al., 2011; Koehler et al., 2014). In addition, in most instances of visual search, the target is clearly defined (i.e. the goal is to find a specific object) and inspecting the most salient areas of the display may in these cases be inefficient. Finally, by focusing on eye movements, these models do not necessarily provide a theoretical framework for the cognitive processes underlying visual search.

Perhaps the most established class of models of visual search are based around Feature Integration Theory (Treisman and Gelade, 1980), which has been modified and extended by Wolfe and colleagues in the Guided Search Model (Wolfe et al., 1989; Wolfe, 2014). These theories have been developed using data from visual search tasks with discrete sets of abstract items. These models combine top-down influences (how closely an item resembles the observer’s goal) with bottom-up image properties. For example, if one’s goal (top-down processing) is to find a red horizontal bar, all the red and horizontal items in a visual search display will be given greater weight than distractors (e.g. vertical and blue items) in the model. The salience of a given object in the display (how distinctive it is from the surrounding objects) also activates bottom-up processing. For instance, a blue item among red items is ranked higher than red among orange items. In such cases, a salient item can capture attention even without resembling the target. Combining bottom-up and top-down sources of activation generates an activation map which generates a prediction of the order in which stimuli are processed in visual search. Thus, these models aim to produce a representation of the visual properties of the distractors at each location in the visual field. However, these are predominantly qualitative models, and thus it is difficult to use them to make specific quantitative predictions.

TCS falls under a class of models that take a different approach, in that they focus solely on representing the difference between targets and distractors. For example, in work on eye movement patterns, it has been proposed that performance in inefficient (serial) visual search is mostly determined by the size of the ‘functional viewing field’, whose size varies as a function of target-distractor similarity (Hulleman and Olivers, 2017). Similarly, work on attention has proposed the notion of ‘relative features’, where attention is tuned to feature relationships i.e. the appearance of the target relative to distractors in the environment (Becker

et al., 2014; Becker, 2010). TCS also has features in common with other models that propose parallel identification of all items in a scene, with diffusion based mechanisms for identifying targets from distractors (Moran et al., 2013, 2016). However, TCS (Lleras et al., 2020) aims to provide a unifying framework that can make quantitative behavioural predictions for visual search based on this general assumption. As such, it is an attractive candidate model for a formal registered replication.

A key assumption of the TCS model is that behaviour is determined by comparing the target template (held in memory) with every element present in the scene in parallel. This allows the visual system to reject peripheral non-targets quickly; the speed at which items are evaluated is determined by how different the item is from the template through an evidence accumulation process (formally, the slope of the logarithmic function is assumed to be inversely proportional to the overall magnitude of the contrast signal between the target and distractor). The model thus focuses on an initial, efficient processing stage of search; if sufficient evidence is not accumulated during this process, the model posits that a second stage is entered, requiring a sequence of eye movements to search for the target in a serial manner. TCS has been successful in predicting a number of empirical results, including search performance in heterogeneous scenes based on parameters estimated in homogeneous scenes, both with artificial stimuli (Buetti et al., 2016; Lleras et al., 2019) and with real-world objects visualised on a computer display (Wang et al., 2017). Table 1 provides an overview of studies investigating the TCS framework to date.

The original version of the TCS model is essentially a (natural) log-linear model in the number of distractors. The full model contains a variable  $L$ , which represents the number of different types of distractors present in the display. However, in our paper, we will follow Buetti et al. (2019) and only consider the specific case of  $L = 1$ , of a target among a homogeneous set of distractors. In this case, the TCS model can be represented in the following way:

$$\hat{RT} = a + D \log(N_T + 1) \quad (1)$$

The intercept,  $a$ , corresponds to search arrays in which only the target is present and there are no distractors.  $N_T$  is the total number of distractors.

### *1.2. Rationale for proposed work*

While many aspects of the TCS framework have been tested, with extremely promising results, there remains a great deal of scope for verification of some of

Reference	Overview
Buetti et al. (2016)	For efficient search with a specific target, there is a logarithmic relationship between distractor set size and reaction time. The steepness of this relationship is modulated by distractor-target similarity, with steeper slopes for more similar distractors.
Wang et al. (2017)	Data from homogeneous search arrays can be used to predict search reaction times in heterogeneous displays containing images of real-world objects, using an equation assuming parallel, unlimited capacity, exhaustive processing, and independence of inter-item processing.
Madison et al. (2018)	Logarithmic efficiency in efficient search cannot be explained by crowding in peripheral vision.
Ng et al. (2018)	Logarithmic efficiency in efficient search cannot be explained by eye movements.
Lleras et al. (2019)	Validation of previous results showing data from homogeneous search arrays can be used to predict reaction times in heterogeneous displays. Distractor-distractor interactions can also facilitate processing when nearby items are similar to each other.
<b>Buetti et al. (2019)</b>	Data from search arrays where the distractors are distinguished from the target by one feature can be used to predict search reaction times in displays with compound stimuli, defined by two features. Reaction times can be predicted using a collinear contrast integration model, which assumes that the overall target-distractor contrast is the sum of the contrasts from the two feature vectors separately.
Lleras et al. (2020)	Full proposal of the Target Contrast Signal Theory, proposing that the initial stage of processing computes a difference signal between each item in the scene and the target template, using this to determine which items in the scene are unlikely to be the target.
Ng et al. (2020)	Attention works in a two stage process, first discarding target-dissimilar distractors in a distributed, parallel way. Focused spatial attention then visits target-similar items at random.
Xu et al. (2021)	Extension of Buetti et al. (2019) to new features (shape and texture), which combine according to a Euclidean metric (orthogonal contrast integration model).

Table 1: An overview of work on the Target Contrast Signal Theory. The key paper for our replication is highlighted.

the key findings to date, and extensions of aspects of the model. In all implementations of TCS so far, predictions of search efficiency (e.g. in heterogeneous scenes) have been made on the average of a group of participants, using data from a different group performing a different task (e.g. searching in homogeneous scenes). Thus, we know that TCS can replicate group-level averages between subjects in search well, but we do not know to what extent it is also able to make predictions at the individual level. This is particularly important given that conclusions based on aggregate data can be different from those that take individual differences into account; in one study where participants searched for a target in an array of randomly oriented line segments, aggregating the data suggested that participants were using a stochastic search model (Nowakowska et al., 2017). However, when considering each participant individually, it became clear that there was a high level of heterogeneity in responses, with some participants performing close to optimally, and others actually performing worse than chance (Nowakowska et al., 2017). Similarly striking variability has also been reported in other search studies (Irons and Leber, 2016, 2018; Clarke et al., 2020).

Taking search time distributions into account is also important for constraining theories of visual search (Wolfe et al., 2010; Liesefeld and Müller, 2020): for example, they have been used to help distinguish between models that make similar predictions at the level of average reaction times (Moran et al., 2016, 2017). Including subject and trial level data into our implementation of the TCS will therefore further aid model development and assumption testing.

In the current manuscript, we focus on replicating and extending findings from Buetti et al. (2019). In their study, participants searched for a target in a scene of homogeneous distractors (see Figure 1). First, parallel search efficiency (measured by the logarithmic search slope) was estimated for cases where the distractors varied from the target in one dimension: either colour (e.g. a cyan target being searched for in either yellow, blue or orange distractors) or shape (e.g. a semicircle target in either circle, diamond or triangle distractors). New participants then searched for the same targets in displays where the distractors were compounds, differing from the target in both colour and shape (e.g. searching for a cyan semicircle in either blue circles, orange diamonds or yellow triangles). The logarithmic search slopes in the initial experiments were then used to predict the logarithmic slopes and reaction times using a number of models. The authors found that the best model was a ‘collinear contrast integration model’ where the distinctiveness scores were summed along each attribute in the unidimensional experiments, creating an overall contrast score that was used for compound stimuli predictions. In our registered replication, we will attempt to verify the conclusions of Buetti

et al. (2019), that the collinear contrast integration model does indeed offer the best characterisation of contrast signal combinations in visual search within the TCS framework.

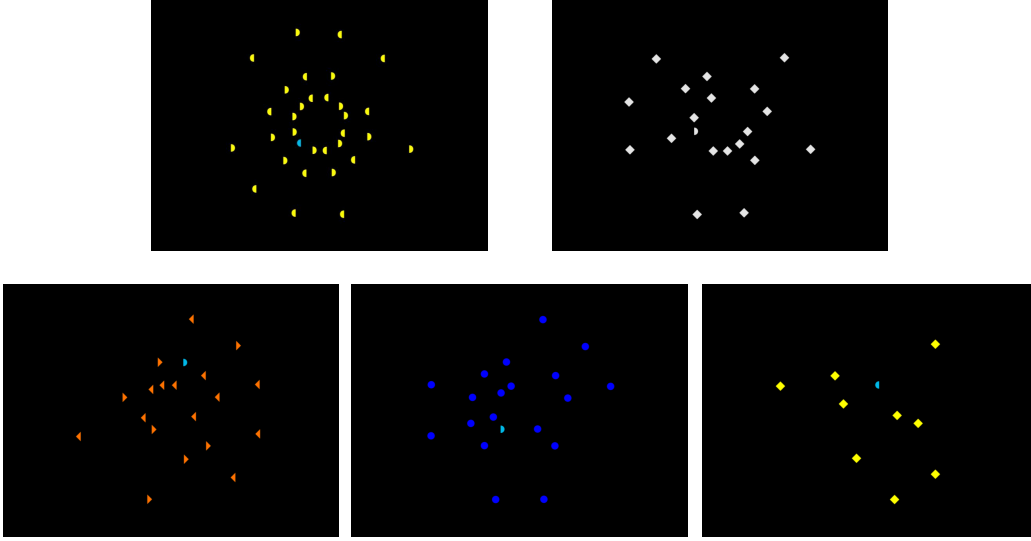


Figure 1: Example stimuli from Buetti et al. (2019) Top left: Expt 1A. Here, the target is a blue semicircle within a set of homogeneous (yellow semicircle) distractors. Top right: Expt 1B. The target is a grey semicircle in circular grey distractors. Bottom left: Expt 2A. The target is a blue semicircle in orange diamond distractors. Bottom middle: Expt 2B. The target is a blue semicircle in dark blue triangle distractors. Bottom right: Expt 2C. The target is a blue semicircle in yellow circular distractors.

We begin by verifying the analysis of Buetti et al. (2019), and then we use their data to show how we are able to extend their model of how multi-dimensional contrasts are calculated, both by incorporating a multi-level design to predict within-subjects effects and by utilising a Bayesian generalised linear model framework to better represent the distribution of responses (e.g. avoiding predicting negative reaction times, accounting for uncertainty in model predictions). We then describe our proposed replication study and our registered hypotheses.

## 2. The Target Contrast Model

We first describe the original Target Contrast Model, as presented in Buetti et al. (2019) and verify that we can successfully replicate the original analysis

(both using frequentist modelling and Bayesian modelling; see Supplementary Materials).

### 2.1. TCS modelling overview

In Experiment 1a of Buetti et al. (2019), participants searched for a cyan semicircle target among blue, yellow or orange semicircular distractors i.e. they searched for a target that differed from the distractors by a *single feature* (colour). The experiment was then repeated (1b) using a different single feature (shape, with participants searching for the semicircular target within triangle, circle or diamond distractors). In Experiments 2a, 2b and 2c, participants again searched for a cyan semicircle, but this time, the distractors differed in both shape and colour. We will refer to these conditions as *double features*. Note, unlike in standard conjunction searches, in this paradigm, the distractors are all identical with respect to these features (i.e. orange triangles). Examples of all these stimuli are shown in Figure 1. Buetti et al. (2019) also carried out a replication of their basic results using slightly different target and distractor stimuli (Experiments 3 and 4).

The *Target Signal Contrast* theory is built around a linear model for predicting mean reaction times from the logarithm of the number of distractors (see Equation 1). In particular, the TCS theory allows us to predict the value of the logarithmic slope,  $D_{c,s}$ , in this condition based on the corresponding  $D_i$  in the single feature search experiments.

#### 2.1.1. Calculating the intercept, $a$ , and the logarithmic slope parameter, $D_i$

Experiments 1a and 1b and 3a and 3b were used to calculate the logarithmic slope parameter  $D_i$ . In all experiments, the number of distractors varied, allowing the data to be used to fit a log-linear model for reaction times, where reaction times increase logarithmically with  $N_T$ , the number of distractors see Equation 1). In the original model the error distribution was assumed to be normal. Thus the results of Experiments 1 and 3 were used to calculate  $D_i$ , for each type of distractor. When colour varied, we will refer to  $D_c$ , for  $c = 1, 2, 3$ . Similarly for shape we will denote this ( $D_s$ ), and the compound features are denoted as ( $D_{c,s}$ ).

Fitting the model specified in Equation 1 to the data, we obtain the values for  $D_c$  and  $D_s$  given in Table 2. As can be seen, the more similar the distractors are to the target, the steeper the slope parameter is.

#### 2.1.2. Estimating $D_{c,s}$ , the logarithmic slope parameter for compound features

In the context of the current experiments, the core idea of TCS theory is that we can estimate the logarithmic slope parameter for a double feature visual search



feature	$D_c$	feature	$D_s$
blue	76.8	triangle	141.1
yellow	16.0	diamond	77.2
orange	9.8	circle	62.1

Table 2: A table of  $D_i$  values for Experiment 1a and 1b. See Supplementary Material for full values for all experiments.

from the slopes parameters in the two independent single feature searches i.e.,  $D_{c,s} = f(D_c, D_s)$ . Buetti et al. (2019) tested three different models for predicting  $D$  for compound colour-shape stimuli. The best feature guidance model (Equation 2) suggests that when the target and lures differ in two dimensions, participants will choose to attend to whichever feature dimension is the most discriminable (i.e. has the smallest  $D$  value):

$$D_{c,s} = \min(D_c, D_s) \quad (2)$$

The orthogonal contrast combination model instead suggests that independent feature dimensions comprise a multidimensional space, where an object can be described by the overall vector in this space, and thus  $D_{c,s}$  can be represented as:

$$D_{c,s} = \frac{1}{\sqrt{(\frac{1}{D_c})^2 + (\frac{1}{D_s})^2}} \quad (3)$$

Finally, the collinear contrast integration model also assumes independence of feature dimensions, but assumes that while the visual features create a multidimensional space, the contrast between them is unidimensional. As  $D$  is assumed to be inversely proportional to contrast, the equation can be written as follows:

$$\frac{1}{D_{c,s}} = \frac{1}{D_c} + \frac{1}{D_s} \quad (4)$$

Buetti et al. (2019) found that with their dataset, the collinear contrast integration model was best able to predict  $D_{c,s}$  from  $D_c$  and  $D_s$ , with  $R^2 = 0.915$ . We verified we were able to replicate this result using the dataset available on OSF (<https://osf.io/f3m24/>)<sup>1</sup> and using the exclusion criteria originally applied; see Figure 2 (left panel) and *Supplementary Materials* for details. We show that

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<sup>1</sup>downloaded on 28th August 2020

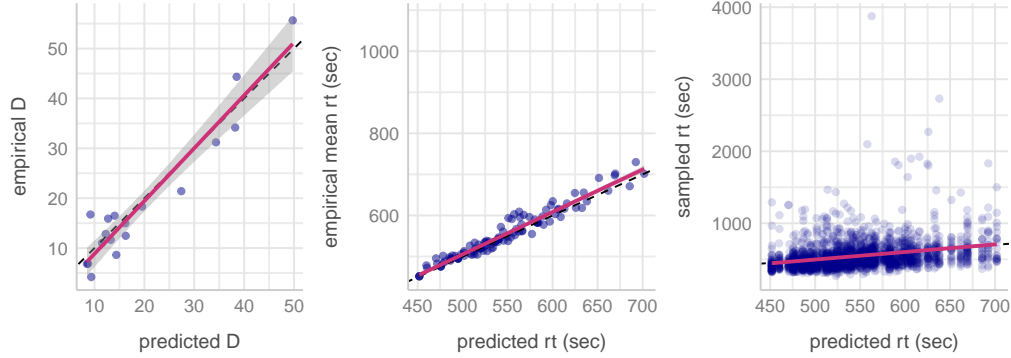


Figure 2: (left) The collinear method for calculating  $D$  offers a good prediction. (centre) Using the TCS to predict reaction times. (right) Each dot now represents a randomly sampled reaction time from an observer. Note that there is greater spread in the data points here, due to the fact that there will be trial-to-trial variability due to target position, inter-item distances, observer differences and so on.

we are able to do this using both the frequentist modelling approaches used in the original paper, and using Bayesian modelling.

### 2.1.3. Estimating $a$ , the intercept parameter for compound features

As  $a$  is the intercept of the model, it represents how long observers take to find a target when  $N_T = 0$ , i.e., there are no distractors. As such, it should be independent of both shape and colour, and can be thought of as the role of non-search processes (such as motivation, motor preparation etc.) that influence reaction time. In Buetti et al. (2019),  $a$  was calculated for each sub-experiment. Here, we follow that method in order to replicate their results exactly.

### 2.1.4. Estimating mean reaction times

Finally, we can use Equation 1 to predict mean reaction times. As can be seen in Figure 2 (centre panel), these predictions are essentially identical to the empirical RT results:  $R^2 = 0.93\%$ .

### 2.1.5. Discussion

While TCS theory offers a good prediction of search slopes and corresponding mean reaction times for double feature search, there are two related limitations. Firstly, it is unable to account for individual differences between observers, only the changes to the sample average. Secondly, it cannot account for the distribution of reaction times over multiple trials. Figure 2 (right panel) shows clearly that

these factors generate high levels of variability within the individual trial-level data. To address these issues, we propose adapting TCS to make use of multi-level modelling techniques.

### 3. Hypotheses

We plan an experiment to test the extent to which the original results in Buetti et al. (2019) replicate and generalise.

#### 3.1. Proposed Modifications to Experimental Design

In order to better test the above, and increase sensitivity, we propose to make the following changes to the experiment described in Buetti et al. (2019):

1. **Within-subjects design.** This modification should give us greater power to detect differences between different models, as well as allowing us to investigate how individual differences in the single-feature task might explain differences in the double-feature task.
2. **Increase target-distractor similarity.** Our reanalysis of Buetti et al. (2019) indicates that if the distractors are a very different colour from the target, they not distinguish well between different contrast models. We will therefore run a version of the experiment where the target is a red semicircle, with distractors being either orange, yellow or pink.

#### 3.2. Registered Hypothesis

1. **Shifted lognormal model.** We hypothesise that a shifted lognormal model will give the best fit to our single-feature data, when compared to a lognormal and a normal model.
2. **Log-linear effect of  $N_T$ .** We will test the TCS model assumption that  $N_T$  has a log-linear effect by testing models with and without the log of this term. We expect that this will confirm the results previously seen in papers testing TCS i.e. that the log-linear approach will be best.
3. **Contrast model comparisons.** We will test the hypothesis proposed by (Buetti et al., 2019): specifically, that the *collinear contrast ingratiation*

*model* outperforms the *best feature guidance*, and *orthogonal contrast combination models*.

We will test each of these hypotheses by calculating the marginal likelihood of the relevant models, and then calculating the poster probabilities. This will give us a probability for each model that represents the likelihood that the model gives the best prediction. We will consider there to be evidence for one model over the others if a given model has a probability above 90%. We will consider there to be strong evidence for one model over the others if that model has a posterior probability above 99%.

### 3.3. *Planned Explorations*

We plan to investigate the effect of individual differences in this paradigm: to what extent performance in the single-feature task can predict performance in the double-feature task for a given individual (Buetti et al. (2019) were not able to investigate this due to the between-subjects design of their study). We plan to do this by specifying a more complex random effects structure for the model, that allows for individual differences across different slopes for different features. This allows us to then study the random effect correlation structure. However, given these models can be challenging to fit, we will do this in an exploratory manner after carrying out our formally registered analysis.

We will also run exploratory analyses including a factor for which ring the target is in to assess whether this improves model fit or affects any of the conclusions that can be drawn from the model.

### 3.4. *Pilot Experiment*

Full details of a pilot experiment with  $n = 4$  participants (xxx trials) can be found in supplementary materials. This suggests that even with a small sample, we can convincingly demonstrate H1 and H2, however more data will be required to discriminate between the models in H3.

## 4. **General Methods**

### 4.1. *Sample Size: Participants and Trials*

To determine our sample size, we carried out a simulation study to estimate the effect of reducing the number of trials and increasing the number of participants on our ability to accurately measure the  $D_i$ . While our reanalysis of Buetti

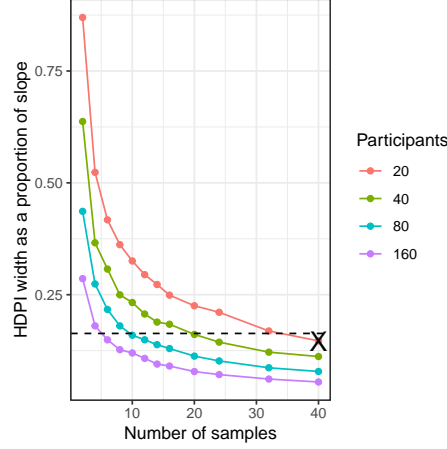


Figure 3: Simulation sensitivity analysis, showing the 97% HPDI width for the blue distractor condition in a shifted lognormal model, across different numbers of trials and participants. The X shows the real HPDI width as a proportion of slope for the blue distractor condition in Buetti et al. (2019).

et al. (2019)’s data is unable to distinguish between the three models of contrast combination, we believe that this is due to the feature values used in their study, rather than low statistical power from sampling (see above and Figure ??). Therefore, we will base our sensitivity analysis around the width of the 97% HPDI when estimating  $D_{\text{blue}}$ . We have chosen to look at this single feature level as the blue distractor trials offer the greatest discrimination between the three contrast models.

We carried out our simulation sensitivity analysis by generating synthetic data from the shifted lognormal model outlined in Section ??, Figure ??, for the blue distractor conditions. This was done for several different sample sizes, both in terms of number of trials and number of participants. For each synthetic dataset, we then refit the model and calculated the width of the 97% HPDI (see Figure 3).

As we are moving from the between-subjects design used by Buetti et al. (2019) to a within-subjects design in which each participant sees all combinations of features, we prefer to decrease the number of trials per person  $\times$  condition from 40 to six. Increasing the number of participants from 20 to 150 will allow us to maintain sufficient accuracy in the estimating of logarithmic search slopes.

Ethical approval for the study was granted by the University of Aberdeen (application number PEC/4677/2021/2).

#### 4.2. *Stimuli*

The targets and distractors are randomly assigned to the display based on an invisible grid. Within each quadrant of the screen, there are three 'spokes' each with four possible target positions (starting from the centre of the screen and moving outwards), creating 36 different target positions in total, in three concentric circles. A small amount of jitter is added to each possible position to make the target locations less predictable.

**Distractor and target types:** we will replicate the distractor types used in Buetti et al. (2019), apart from that we will change one distractor colour (from blue to pink) to allow us to discriminate better between different models of the data (see above). There are six single-feature conditions (yellow, orange and pink distractors and triangle, circle and diamond distractors) and nine double-feature conditions (all possible pairings of the single-feature conditions). The target is always a red semicircle, except in the trials where the distractors are single-feature shapes (triangles, circles and diamonds) in which case the target is a white semicircle.

**Set sizes:** we will run all the distractor set sizes used in Buetti et al. (2019) (1, 4, 9, 19 and 31). We will also run target-only 'zero distractor' trials (30 in total, with 6 being the white semicircle target and the remainder the red semicircle target).

The experiments were programmed in PsychoPy and Pavlovia (Peirce et al., 2019). Stimuli were pre-made to generate search array images with  $1920 \times 1080$  resolution.

#### 4.3. *Procedure*

Participants will complete the experiment in the laboratory...

Participants will view a fixation cross before viewing a search array: they will press the space bar to continue to the trial. Participants will be told to search for the target among distractors (i.e. will be told to perform a singleton search) and report if the semicircle target points to the left or right, by pressing either the 'f' or 'j' key respectively on their keyboard. They will first complete 16 practice trials where they will receive feedback immediately after completing each trial. In the real experimental trials, participants will receive feedback on their average accuracy and reaction time after each block of 30 trials. Participants will complete 19 blocks of trials (570 trials overall i.e. 114 trials in each of 5 experiments, consisting of 6 set sizes x 3 distractor conditions x 6 repeats + 6 zero distractor trials) with the order of the stimuli being fully randomised i.e. all different conditions

will be completely intermixed (in the terminology of Buetti et al. (2019), participants will complete all of Experiments 1 and 2 in the same testing session, rather than having different participants complete each separate sub-experiment).

In both the practice and experimental trials, the search display will always remain on screen until a response is made, or until 5 seconds had passed.

#### 4.4. Data Pre-processing

Only participants who complete the full experiment will be considered candidates for inclusion in the data analysis. We will apply the same inclusion criteria as the original paper: participants will only be included if their search accuracy over 90% and their average response time is not smaller or larger than two standard deviations from the group average response time.

For participants included in the analysis, we will apply the data cleaning used in Section ?? i.e. removing the top and bottom 1% of their data.

#### 4.5. Analysis Plan

All analysis will be carried out using R (vx.xx)<sup>2</sup>, brms (v.xx.xx) and rStan (vx.xxxx) As discussed above, we will use a mixed-effect models with either normal, lognormal or shifted lognormal distributions.

Please see the analysis of our pilot data for a full implementation of our analysis pipeline, including all code...

We will follow the analysis given in Section ?. Full details of the code used are provided in the *Supplementary Material* and on Github at [https://github.com/scienceanna/TCS\\_Bayesian](https://github.com/scienceanna/TCS_Bayesian).

## 5. Results

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## 6. General Discussion

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### Conflict of interest

The authors declare that they have no conflict of interest.

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<sup>2</sup>Version numbers will be recorded upon completion of final analysis.

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## References

- Stefanie I Becker. The role of target–distractor relationships in guiding attention and the eyes in visual search. *Journal of Experimental Psychology: General*, 139(2):247, 2010.
- Stefanie I Becker, Christian Valuch, and Ulrich Ansorge. Color priming in pop-out search depends on the relative color of the target. *Frontiers in psychology*, 5:289, 2014.
- Simona Buetti, Deborah A Cronin, Anna M Madison, Zhiyuan Wang, and Alejandro Lleras. Towards a better understanding of parallel visual processing in human vision: Evidence for exhaustive analysis of visual information. *Journal of Experimental Psychology: General*, 145(6):672, 2016.
- Simona Buetti, Jing Xu, and Alejandro Lleras. Predicting how color and shape combine in the human visual system to direct attention. *Scientific reports*, 9(1): 1–11, 2019.
- Kyle R Cave and Jeremy M Wolfe. Modeling the role of parallel processing in visual search. *Cognitive psychology*, 22(2):225–271, 1990.
- Alasdair DF Clarke, JL Irons, Warren James, Andrew B Leber, and Amelia R Hunt. Stable individual differences in strategies within, but not between, visual search tasks. *Quarterly Journal of Experimental Psychology*, 2020.
- Johan Hulleman and Christian NL Olivers. On the brink: The demise of the item in visual search moves closer. *Behavioral and Brain Sciences*, 40, 2017.
- Jessica L Irons and Andrew B Leber. Choosing attentional control settings in a dynamically changing environment. *Attention, Perception, & Psychophysics*, 78(7):2031–2048, 2016.
- Jessica L Irons and Andrew B Leber. Characterizing individual variation in the strategic use of attentional control. *Journal of Experimental Psychology: Human Perception and Performance*, 44(10):1637, 2018.



- Laurent Itti and Christof Koch. A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision research*, 40(10-12):1489–1506, 2000.
- Laurent Itti, Christof Koch, and Ernst Niebur. A model of saliency-based visual attention for rapid scene analysis. *IEEE Transactions on pattern analysis and machine intelligence*, 20(11):1254–1259, 1998.
- Christof Koch and Shimon Ullman. Shifts in selective visual attention: towards the underlying neural circuitry. In *Matters of intelligence*, pages 115–141. Springer, 1987.
- Kathryn Koehler, Fei Guo, Sheng Zhang, and Miguel P Eckstein. What do saliency models predict? *Journal of vision*, 14(3):14–14, 2014.
- Heinrich René Liesefeld and Hermann J Müller. A theoretical attempt to revive the serial/parallel-search dichotomy. *Attention, Perception, & Psychophysics*, 82(1):228–245, 2020.
- Alejandro Lleras, Zhiyuan Wang, Anna Madison, and Simona Buetti. Predicting search performance in heterogeneous scenes: Quantifying the impact of homogeneity effects in efficient search. *Collabra: Psychology*, 5(1), 2019.
- Alejandro Lleras, Zhiyuan Wang, Gavin Jun Peng Ng, Kirk Ballew, Jing Xu, and Simona Buetti. A target contrast signal theory of parallel processing in goal-directed search. *Attention, Perception, & Psychophysics*, pages 1–32, 2020.
- Anna Madison, Alejandro Lleras, and Simona Buetti. The role of crowding in parallel search: Peripheral pooling is not responsible for logarithmic efficiency in parallel search. *Attention, Perception, & Psychophysics*, 80(2):352–373, 2018.
- Xiao-Li Meng and Wing Hung Wong. Simulating ratios of normalizing constants via a simple identity: a theoretical exploration. *Statistica Sinica*, pages 831–860, 1996.
- Rani Moran, Michael Zehetleitner, Hermann J Mueller, and Marius Usher. Competitive guided search: Meeting the challenge of benchmark rt distributions. *Journal of Vision*, 13(8):24–24, 2013.
- Rani Moran, Michael Zehetleitner, Heinrich René Liesefeld, Hermann J Müller, and Marius Usher. Serial vs. parallel models of attention in visual search: accounting for benchmark rt-distributions. *Psychonomic bulletin & review*, 23(5): 1300–1315, 2016.

- Rani Moran, Heinrich René Liesefeld, Marius Usher, and Hermann J Muller. An appeal against the item’s death sentence: Accounting for diagnostic data patterns with an item-based model of visual search. *Behavioral and Brain Sciences*, 40:e148, 2017.
- Gavin JP Ng, Simona Buetti, Trisha N Patel, and Alejandro Lleras. Prioritization in visual attention does not work the way you think it does. *Journal of Experimental Psychology: Human Perception and Performance*, 2020.
- Gavin Jun Peng Ng, Alejandro Lleras, and Simona Buetti. Fixed-target efficient search has logarithmic efficiency with and without eye movements. *Attention, Perception, & Psychophysics*, 80(7):1752–1762, 2018.
- Anna Nowakowska, Alasdair DF Clarke, and Amelia R Hunt. Human visual search behaviour is far from ideal. *Proceedings of the Royal Society B: Biological Sciences*, 284(1849):20162767, 2017.
- Derrick Parkhurst, Klinto Law, and Ernst Niebur. Modeling the role of salience in the allocation of overt visual attention. *Vision research*, 42(1):107–123, 2002.
- Jonathan Peirce, Jeremy R Gray, Sol Simpson, Michael MacAskill, Richard Höchenberger, Hiroyuki Sogo, Erik Kastman, and Jonas Kristoffer Lindeløv. Psychopy2: Experiments in behavior made easy. *Behavior research methods*, 51(1):195–203, 2019.
- Benjamin W Tatler. The central fixation bias in scene viewing: Selecting an optimal viewing position independently of motor biases and image feature distributions. *Journal of vision*, 7(14):4–4, 2007.
- Benjamin W Tatler, Mary M Hayhoe, Michael F Land, and Dana H Ballard. Eye guidance in natural vision: Reinterpreting salience. *Journal of vision*, 11(5): 5–5, 2011.
- Anne M Treisman and Garry Gelade. A feature-integration theory of attention. *Cognitive psychology*, 12(1):97–136, 1980.
- Zhiyuan Wang, Simona Buetti, and Alejandro Lleras. Predicting search performance in heterogeneous visual search scenes with real-world objects. *Collabra: Psychology*, 3(1), 2017.

- Jeremy M Wolfe. Approaches to visual search: Feature integration theory and guided search. *Oxford handbook of attention*, pages 11–55, 2014.
- Jeremy M Wolfe, Kyle R Cave, and Susan L Franzel. Guided search: an alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human perception and performance*, 15(3):419, 1989.
- Jeremy M Wolfe, Evan M Palmer, and Todd S Horowitz. Reaction time distributions constrain models of visual search. *Vision research*, 50(14):1304–1311, 2010.
- Zoe Jing Xu, Alejandro Lleras, and Simona Buetti. Predicting how surface texture and shape combine in the human visual system to direct attention. *Scientific reports*, 11(1):1–13, 2021.
- Lingyun Zhang, Matthew H Tong, Tim K Marks, Honghao Shan, and Garrison W Cottrell. Sun: A bayesian framework for saliency using natural statistics. *Journal of vision*, 8(7):32–32, 2008.