

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

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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 investigate modelling using normal and shifted-lognormal distributions, and show that the latter allows for a better fit to previously published data. We propose running a new fully within-subjects experiment to attempt to replicate the key original findings, with some changes to help distinguish between theories.

Keywords: Visual search, Efficient search, Parallel processing

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

6 has been between efficient (also referred to as parallel or pop-out) and inefficient
7 (serial) search. These are often studied in the context of the regression slope be-
8 tween the number of distractors and mean reaction time, which has been termed
9 the *search slope*. When the search slope is shallow (usually positive, but occasion-
10 ally negative e.g. (Rangelov et al., 2017)), the search is called efficient or parallel,
11 and the addition of more non-target distractors has little impact on an observers
12 difficulty in finding a target. When the slope is steeper, each additional distrac-
13 tor has a noticeable impact on increasing difficulty, and the search is described
14 as inefficient or serial. However, the distinction between these types of search is
15 often less clear in real experimental data, with a range of different search slopes
16 being seen for different types of targets and distractors (Duncan and Humphreys,
17 1989; Cave and Wolfe, 1990; Wolfe, 1998; Liesefeld et al., 2016). Recent work
18 has also attempted to model the variation in search slopes at the boundary between
19 inefficient and efficient search (Liesefeld et al., 2016).

20 In the current study, we are interested in what has traditionally been termed
21 efficient or parallel search, and the factors that affect search slope in these condi-
22 tions. Recent work has suggested that for efficient search, there is a logarithmic
23 relationship between distractor set size and reaction time, and that this relation-
24 ship can be modified by target-distractor similarity (Buetti et al., 2016), providing
25 evidence that search behaviour in parallel search is more complex than has pre-
26 viously been assumed. This observation has formed the basis of the ‘Target Con-
27 trast Signal (TCS) Theory’ (Lleras et al., 2020), which aims to provide a means
28 of predicting observer search slopes for new search arrays by quantifying target-
29 distractor differences. For example, by measuring search slopes for conditions in
30 which the distractors differ from the target along a *single feature* (e.g. colour *or*
31 shape), it has been shown that you can predict search times for arrays in which
32 the target differs from the distractors along two features (e.g., colour *and* shape)
33 which we refer to here as *double feature* search. (Buetti et al., 2019) (but simi-
34 lar paradigms have been known by other names e.g. ‘redundant feature search’
35 (Krummenacher and Müller, 2012; Mordkoff and Yantis, 1991)). Here, we aim
36 to replicate and extend this work both theoretically and empirically, to test the
37 generalisability of the TCS model, and to suggest ways in which the TCS model
38 could be modified to generate better predictions.

39 1.1. Previous Work

40 Many different forms of visual search models have been proposed. One well
41 developed class of models are the saliency models, which aim to predict eye move-
42 ments during scene viewing, including visual search. They rest on the assump-

tion 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), and even in abstract laboratory search arrays (Kotseruba et al., 2020). 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. Other extensions to these models have been proposed, such as the Dimension Weighting Account, in which saliency weightings are assigned to different target ‘dimensions’ (e.g. colour or shape), helping to explain results where varying the target dimension within blocks of trials leads to longer reaction times than where the dimension remains consistent within a block (Krummenacher and Müller, 2012). 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:

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

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

121 1.2. Rationale for proposed work

122 While many aspects of the TCS framework have been tested, with extremely
 123 promising results, there remains a great deal of scope for verification of some of
 124 the key findings to date, and extensions of aspects of the model. In all implementa-
 125 tions of TCS so far, predictions of search efficiency (e.g. in heterogeneous scenes)
 126 have been made on the average of a group of participants, using data from a dif-
 127 ferent group performing a different task (e.g. searching in homogeneous scenes).
 128 Thus, we know that TCS can replicate group-level averages between subjects in
 129 search well, but we do not know to what extent it is also able to make predictions
 130 at the individual level. This is particularly important given that conclusions based
 131 on aggregate data can be different from those that take individual differences into
 132 account; in one study where participants searched for a target in an array of ran-
 133 domly oriented line segments, aggregating the data suggested that participants
 134 were using a stochastic search model (Nowakowska et al., 2017). However, when
 135 considering each participant individually, it became clear that there was a high
 136 level of heterogeneity in responses, with some participants performing close to
 137 optimally, and others actually performing worse than chance (Nowakowska et al.,
 138 2017). Similarly striking variability has also been reported in other search studies
 139 (Irons and Leber, 2016, 2018; Clarke et al., 2020).

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

146 We also extend the TCS model into a Bayesian framework, where we begin
 147 with existing 'prior' beliefs that are updated with data to give 'posterior' beliefs
 148 that can be used for inference (McElreath, 2020). We think this has a number
 149 of advantages over frequentist approaches. Perhaps most importantly, Bayesian
 150 models are highly flexible. We demonstrate how we are able to specify a model
 151 that is able to more accurately represent the distribution of responses (for exam-
 152 ple, by specifying a response distribution that avoids predicting negative reaction

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.
Buetti et al. (2019)	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.

times) with a relatively complex model structure, that can be fit to a relatively small amount of pilot data: something that would be challenging within a frequentist framework. We also believe that Bayesian models offer very intuitive methods for model testing and comparison and straightforward interpretation of results, and we hope that this manuscript can act as a demonstration of these benefits, showing how they can be applied to real scientific questions beyond the simplified examples often found in textbooks or tutorials.

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.

We begin by verifying the analysis of Buetti et al. (2019). We then describe our proposed replication study, showing with pilot data 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).

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



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.

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

191 2.1. TCS modelling overview

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

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

209 2.1.1. Calculating the intercept, a , and the logarithmic slope parameter, D_i

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

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

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 Materials* for full values for all experiments.

221 2.1.2. Estimating $D_{c,s}$, the logarithmic slope parameter for compound features

222 In the context of the current experiments, the core idea of TCS theory is that
 223 we can estimate the (natural) logarithmic slope parameter for a double feature
 224 visual search from the slopes parameters in the two independent single feature
 225 searches i.e., $D_{c,s} = f(D_c, D_s)$. Buetti et al. (2019) tested three different models
 226 for predicting D for compound colour-shape stimuli. The best feature guidance
 227 model (Equation 2) suggests that when the target and lures differ in two dimen-
 228 sions, participants will choose to attend to whichever feature dimension is the
 229 most discriminable (i.e. has the smallest D value):

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

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

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

233 Finally, the collinear contrast integration model also assumes independence of
 234 feature dimensions, but assumes that while the visual features create a multidimensional space, the contrast between them is unidimensional. As D is assumed
 235 to be inversely proportional to contrast, the equation can be written as follows:
 236

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

237 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 $R^2 = 0.915$.
 238 We verified we were able to replicate this result using the dataset available on
 239 OSF (<https://osf.io/f3m24/>)¹ and using the exclusion criteria originally applied;
 240 see Figure 2 (left panel) and *Supplementary Materials* for details. We show that
 241 we are able to do this using both the frequentist modelling approaches used in the
 242 original paper, and using Bayesian modelling.
 243

244 2.1.3. Estimating a , the intercept parameter for compound features

245 As a is the intercept of the model, it represents how long observers take to find
 246 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
 247 processes (such as motivation, motor preparation etc.) that influence reaction time.
 248 In Buetti et al. (2019), a was calculated for each sub-experiment. Here, we follow
 249 that method in order to replicate their results exactly.
 250

251 2.1.4. Estimating mean reaction times

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

¹downloaded on 28th August 2020

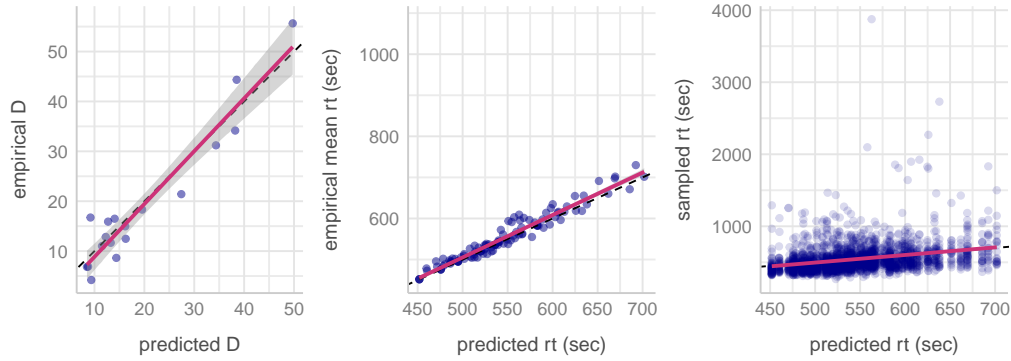


Figure 2: (left) The collinear method for calculating D offers a good prediction. (centre) Using the TCS to predict reaction times. (right) Each dot now represents a randomly sampled reaction time from an observer. Note that there is greater spread in the data points here, due to the fact that there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

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. Multi-level models allow us to take into account the hierarchical structure of the data (i.e. that each participant completes multiple trials) in a way that does not require averaging, meaning that we are able to model participant variability as well as group-level effects (Gelman and Hill, 2006).

2.2. A multi-level TCS

Switching from a linear regression model to a multi-level model will allow us to compute D for each participant, while simultaneously estimating the trial-to-trial variance. We also switch from a frequentist to Bayesian framework, as this allows us to naturally account for the uncertainty in the model's predictions. However, switching from linear regression to a multi-level model raises the problem of which distribution to use for modelling reaction times. Using a normal distribution is unlikely to be satisfactory, as it is unable to account for the skew

frequently seen in reaction time distributions, and also allows the possibility of negative reaction times. We can account for both of these problems by using a log-normal distribution. We will also test whether a slightly more complex extension of this model, the shifted lognormal model (which allows the distribution to be offset to the right i.e. mimicking the patterns seen in reaction time data, where valid responses begin at around 100ms) offers any improvement in model fit. Note that a Wald, or inverse Gaussian distribution, would also be a reasonable distribution choice for this data given that TCS is based on a diffusion process e.g. (Moran et al., 2013), and this distribution has been argued to be psychologically more plausible (e.g. Kieffaber et al. (2006), though see Matzke and Wagenmakers (2009)): we chose not to use this distribution as it often leads to computational issues, which would make it harder for others to reproduce or build on our approach later.

3. Hypotheses

We plan an experiment to test the extent to which the original results in Buetti et al. (2019) replicate and generalise, using our new modelling approach.

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.** If the distractors are a very different colour from the target, they may 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, purple or pink.

3.2. *Registered Hypotheses*

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.

- 310 **2. Log-linear effect of N_T .** We will test the TCS model assumption that N_T
 311 has a log-linear effect by testing models with and without the log of this
 312 term. We expect that this will confirm the results previously seen in papers
 313 testing TCS i.e. that the log-linear approach will be best.
 314
- 315 **3. Contrast model comparisons.** We will test the hypothesis proposed by
 316 (Buetti et al., 2019): specifically, that the *collinear contrast integration*
 317 *model* outperforms the *best feature guidance*, and *orthogonal contrast com-*
 318 *bination models* for the calculation of D , by calculating and comparing the
 319 mean absolute prediction error for each model.
 320
- 321 **4. Reaction time predictions.** We will further test the hypothesis proposed by
 322 (Buetti et al., 2019) by testing which model gives the best prediction at the
 323 trial-by-trial RT level.

324 We will test each of these hypotheses by calculating the marginal likelihood
 325 of the relevant models, and then calculating the posterior probabilities. This will
 326 give us a probability for each model that represents the likelihood that the model
 327 gives the best prediction. We will consider there to be evidence for one model over
 328 the others if a given model has a probability above 90%. We will consider there
 329 to be strong evidence for one model over the others if that model has a posterior
 330 probability above 99%. This approach is most appropriate for our model: other
 331 measures of model fit, such as AIC, require an assumption of flat priors (which is
 332 not valid for multi-level models) and are based on point estimates (which is not
 333 valid for Bayesian models) (McElreath, 2020).

334 3.3. *Planned Explorations*

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

344 One of the benefits of using a multi-level modelling approach is that it is rel-
 345 atively easy to extend to incorporate other factors that may contribute to reaction

346 times, such as eccentricity and inter-item distance, which may help to explain
347 behaviour further. To demonstrate this, we will also run exploratory analyses in-
348 cluding a factor for which ring the target is in to assess whether this improves
349 model fit or affects any of the conclusions that can be drawn from the model.

350 3.4. Pilot Experiment

351 Full details of a pilot experiment with $n = 4$ participants (960 trials each) using
352 our proposed analyses can be found in *Supplementary Materials*. This suggests
353 that even with a small sample, we can convincingly demonstrate H1 and H2. How-
354 ever, more data will be required to discriminate between the models, particularly
355 for H4. Given that our methods are within-subject, we have reduced the number
356 of trials per condition compared to Buetti et al. (2019) (12 in our pilot study, 20 in
357 our proposed, compared to 40 in theirs). It is therefore possible that the increased
358 noise in our estimated D single-feature parameters will make it more difficult to
359 predict double-feature Ds accurately. However, we think this is unlikely to be the
360 case as we can see that even in a small amount of pilot data, we can verify H3,
361 with the collinear model having the lowest mean absolute prediction error.

362 4. General Methods

363 4.1. Sample Size: Participants and Trials

364 We plan to test 40 participants during the experiment. Our pilot experiment
365 shows that H1 and H2 are easily demonstrated with 10 times less data, and Buetti
366 et al. (2019) used 20 participants per experiment. Our sample size will therefore be
367 in line with previous work testing H3 and H4. Ethical approval for the study was
368 granted by the University of Aberdeen (application number PEC/4677/2021/2).

369 Our pilot study above suggests that just 12 trials per condition may be suffi-
370 cient to fit our models. To be conservative, we propose using 20 in our experiment.
371 We have demonstrated that using just half the data (20/40 trials per condition)
372 from Buetti et al. (2019) makes no difference to our computational verification
373 (see *Supplementary Materials*).

374 Finally, we have carried out a simulation experiment to estimate the confi-
375 dence intervals on the mean when sampling from a log-normal distribution. We
376 defined our distribution to have a mean-log of 6.135 and a standard deviation of
377 0.32. These values were loosely based on the distributions of reaction times in
378 Buetti et al. (2019). The results are shown in Figure 3. Based on these simula-
379 tions, we find that a sample of $n = 20$ leads to a 95% confidence interval that is



Figure 3: (left) The dark line shows the distribution we sampled from. The blue lines show distributions fitted to different samples of 20 data points. (right) Plot showing how the distribution of sample means vary with n . Shaded regions indicate the 50%, 80% and 95% confidence intervals.

380 approximately 1.4 times larger than $n = 40$. We feel this is a suitable compromise
 381 given we will be collecting our data within-subjects.

382 4.2. Stimuli

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

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

398 **Set sizes:** we will run all the distractor set sizes used in Buetti et al. (2019) (1,
 399 4, 9, 19 and 31). We will also run target-only 'zero distractor' trials (60 in total,
 400 with 12 being the white semicircle target and the remainder the red semicircle
 401 target).

402 The experiments were programmed in PsychoPy and Pavlovia (Peirce et al.,
403 2019). Stimuli were pre-made to generate search array images with 1920×1080
404 resolution.

405 4.3. Procedure

406 Participants will complete the experiment in the laboratory, sitting at a view-
407 ing distance of 45cm from the screen (viewing distance will be fixed by using a
408 chin rest). They will view a fixation cross before viewing a search array: they
409 will press the space bar to continue to the trial. Participants will be told to search
410 for the target among distractors (either a red semicircle or a white semicircle, de-
411 pending on the block) and report if the semicircle target points to the left or right,
412 by pressing either the left or right button on a button box (Cedrus RB-540). They
413 will first complete 16 practice trials where they will receive feedback immediately
414 after completing each trial. In the real experimental trials, participants will receive
415 feedback on their average accuracy and reaction time after each block of 320 tri-
416 als. Participants will complete 5 blocks of trials (1600 trials overall i.e. 320 trials
417 in each of 5 experiments, consisting of 5 set sizes x 3 distractor conditions x 20 re-
418 peats + 20 zero distractor trials). The trials where the distractors are single-feature
419 shapes (i.e. the target is a white semicircle - Experiment 1b in Buetti et al. (2019))
420 will all appear in one block (which will appear at a randomly selected position
421 within the experiment). All other trials (where the target is red semicircle) will
422 be fully randomised i.e. all different conditions will be completely intermixed.
423 This approach will be taken as TCS requires the participant to have a well-defined
424 target template in mind in order to compare this to the stimuli in the display. Thus,
425 participants will be cued to search for the relevant target at the beginning of each
426 block.

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

429 4.4. Data Pre-processing

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

435 For participants included in the analysis, we will apply the data cleaning used
436 in the pilot data analysis i.e. *removing incorrect trials* and removing the top and
437 bottom 1% of their data.

438 4.5. Analysis Plan

439 All analysis will be carried out using R (v4.2.0), brms (v2.17.0) and rStan
440 (v2.26.11). As discussed above, we will use a mixed-effect models with either
441 normal, lognormal or shifted lognormal distributions.

442 Please see the analysis of our pilot data for a full implementation of our anal-
443 ysis pipeline, including all code (available on Github at https://github.com/scienceanna/TCS_Bayesian).
444

445 5. Results

446 5.1. Pre-Processing

447 All 40 participants had accuracy over 90% (minimum 93.1%). One participant
448 had an average response time (1100ms) over two standard deviations from the
449 group average response time (781ms) and was removed. Incorrect trials were
450 then removed, and the data was trimmed (only including response times between
451 the 1% and 99% quantiles) leaving us with 39 participants completing a total of
452 59,587 trials.

453 5.2. Planned Analysis

454 All Bayesian models were fit to the new data using exactly the same proce-
455 dure² as the pilot data presented in the Stage One review process. All models
456 converged with WHAT CRITERIA DO WE WANT TO SAY HERE? \hat{R}

457 5.2.1. Hypothesis 1: Shifted-lognormal model

458 Our first hypothesis concerns which distribution best fits the single feature
459 response time data. We fit multi-level models with a i) normal, ii) lognormal, and
460 iii) shifted-lognormal distribution. The models all used the same model formula
461 that estimated search slopes in terms of $\log N_i$ for each feature. Maximal random
462 effect structures were used.

463 After each of these models had been fit to the data, leave-one-out model com-
464 parison was used to calculate posterior probabilities for each. The results of this
465 procedure are shown in Table 3 and we can conclude that the shifted-lognormal
466 is indeed the best distribution (out of the three we tested) to use for these models.
467 This model is shown in Figure 4.

²the only departure was an increase in samples in the bridgesampling procedure from xxxx to xxxx. Based on advice given in the Stan forums

model	LOO	WAIC
shifted-lognormal	1	1
lognormal	0	0
normal	0	0
linear in $\log N_T$	1	1
linear in N_T	0	0

Table 3: Model comparison results for Hypotheses 1 and 2.

Figure 4: The shifted-lognormal model fits for the single-feature data.

468 5.2.2. Hypothesis 2: log-linear effect of N_T

469 We then used the same methods to verify that using $\log N_T$ for the search
470 slope does indeed give a better fit to the data than simply using N_T . The results
471 are shown in Table 3 and again, our hypothesis is

472 5.2.3. Summary of search slopes

473 Now that we have confirmed that the shifted-lognormal multilevel model (with
474 a log-linear effect of N_T) is indeed the best fit to the data we will extract the search
475 slopes for each feature. These are summarised in Table 4
476 feature D .lower .upper

feature	D_c	95%HDCI
orange	0.161	[0.144 , 1.110]
pink	0.039	[-0.061 , 0.053]
purple	0.019	[0.005 , 0.537]
	D_c	
circle	0.188	[-0.065 , 0.202]
diamond	0.190	[0.174 , 1.168]
triangle	0.258	[0.237 , 0.849]

Table 4: A table of D_c and D_s values from our Experiment

477 5.2.4. Hypothesis 3: Contrast Model Comparison

478 5.2.5. Reaction Time Predictions

479 5.3. Exploratory Analysis

480 Does taking target location into account help with the reaction time predic-
481 tions?

482 6. General Discussion

483 – blank –

484 Conflict of interest

485 The authors declare that they have no conflict of interest.

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489 References

- 490 Stefanie I Becker. The role of target–distractor relationships in guiding attention
491 and the eyes in visual search. *Journal of Experimental Psychology: General*,
492 139(2):247, 2010.
- 493 Stefanie I Becker, Christian Valuch, and Ulrich Ansorge. Color priming in pop-
494 out search depends on the relative color of the target. *Frontiers in psychology*,
495 5:289, 2014.
- 496 Simona Buetti, Deborah A Cronin, Anna M Madison, Zhiyuan Wang, and Ale-
497 jandro Lleras. Towards a better understanding of parallel visual processing in
498 human vision: Evidence for exhaustive analysis of visual information. *Journal*
499 *of Experimental Psychology: General*, 145(6):672, 2016.
- 500 Simona Buetti, Jing Xu, and Alejandro Lleras. Predicting how color and shape
501 combine in the human visual system to direct attention. *Scientific reports*, 9(1):
502 1–11, 2019.
- 503 Kyle R Cave and Jeremy M Wolfe. Modeling the role of parallel processing in
504 visual search. *Cognitive psychology*, 22(2):225–271, 1990.
- 505 Alasdair DF Clarke, JL Irons, Warren James, Andrew B Leber, and Amelia R
506 Hunt. Stable individual differences in strategies within, but not between, visual
507 search tasks. *Quarterly Journal of Experimental Psychology*, 2020.
- 508 John Duncan and Glyn W Humphreys. Visual search and stimulus similarity.
509 *Psychological review*, 96(3):433, 1989.

- 510 Andrew Gelman and Jennifer Hill. *Data analysis using regression and multi-*
511 *level/hierarchical models*. Cambridge university press, 2006.
- 512 Johan Hulleman and Christian NL Olivers. On the brink: The demise of the item
513 in visual search moves closer. *Behavioral and Brain Sciences*, 40, 2017.
- 514 Jessica L Irons and Andrew B Leber. Choosing attentional control settings in a
515 dynamically changing environment. *Attention, Perception, & Psychophysics*,
516 78(7):2031–2048, 2016.
- 517 Jessica L Irons and Andrew B Leber. Characterizing individual variation in the
518 strategic use of attentional control. *Journal of Experimental Psychology: Hu-*
519 *man Perception and Performance*, 44(10):1637, 2018.
- 520 Laurent Itti and Christof Koch. A saliency-based search mechanism for overt and
521 covert shifts of visual attention. *Vision research*, 40(10-12):1489–1506, 2000.
- 522 Laurent Itti, Christof Koch, and Ernst Niebur. A model of saliency-based visual
523 attention for rapid scene analysis. *IEEE Transactions on pattern analysis and*
524 *machine intelligence*, 20(11):1254–1259, 1998.
- 525 Paul D Kieffaber, Emily S Kappenman, Misty Bodkins, Anantha Shekhar, Brian F
526 O’Donnell, and William P Hetrick. Switch and maintenance of task set in
527 schizophrenia. *Schizophrenia research*, 84(2-3):345–358, 2006.
- 528 Christof Koch and Shimon Ullman. Shifts in selective visual attention: towards
529 the underlying neural circuitry. In *Matters of intelligence*, pages 115–141.
530 Springer, 1987.
- 531 Kathryn Koehler, Fei Guo, Sheng Zhang, and Miguel P Eckstein. What do
532 saliency models predict? *Journal of vision*, 14(3):14–14, 2014.
- 533 Iuliia Kotseruba, Calden Wloka, Amir Rasouli, and John K Tsotsos. Do saliency
534 models detect odd-one-out targets? new datasets and evaluations. *arXiv*
535 *preprint arXiv:2005.06583*, 2020.
- 536 Joseph Krummenacher and Hermann J Müller. Dynamic weighting of feature di-
537 mensions in visual search: behavioral and psychophysiological evidence. *Fron-*
538 *tiers in psychology*, 3:221, 2012.

- 539 Heinrich René Liesefeld and Hermann J Müller. A theoretical attempt to revive
540 the serial/parallel-search dichotomy. *Attention, Perception, & Psychophysics*,
541 82(1):228–245, 2020.
- 542 Heinrich René Liesefeld, Rani Moran, Marius Usher, Hermann J Müller, and
543 Michael Zehetleitner. Search efficiency as a function of target saliency: The
544 transition from inefficient to efficient search and beyond. *Journal of Experi-*
545 *mental Psychology: Human Perception and Performance*, 42(6):821, 2016.
- 546 Alejandro Lleras, Zhiyuan Wang, Anna Madison, and Simona Buetti. Predicting
547 search performance in heterogeneous scenes: Quantifying the impact of homo-
548 geneity effects in efficient search. *Collabra: Psychology*, 5(1), 2019.
- 549 Alejandro Lleras, Zhiyuan Wang, Gavin Jun Peng Ng, Kirk Ballew, Jing Xu, and
550 Simona Buetti. A target contrast signal theory of parallel processing in goal-
551 directed search. *Attention, Perception, & Psychophysics*, pages 1–32, 2020.
- 552 Anna Madison, Alejandro Lleras, and Simona Buetti. The role of crowding in par-
553 allel search: Peripheral pooling is not responsible for logarithmic efficiency in
554 parallel search. *Attention, Perception, & Psychophysics*, 80(2):352–373, 2018.
- 555 Dora Matzke and Eric-Jan Wagenmakers. Psychological interpretation of the ex-
556 gaussian and shifted wald parameters: A diffusion model analysis. *Psycho-*
557 *nomic bulletin & review*, 16(5):798–817, 2009.
- 558 Richard McElreath. *Statistical rethinking: A Bayesian course with examples in R*
559 *and Stan*. Chapman and Hall/CRC, 2020.
- 560 Rani Moran, Michael Zehetleitner, Hermann J Mueller, and Marius Usher. Com-
561 petitive guided search: Meeting the challenge of benchmark rt distributions.
562 *Journal of Vision*, 13(8):24–24, 2013.
- 563 Rani Moran, Michael Zehetleitner, Heinrich René Liesefeld, Hermann J Müller,
564 and Marius Usher. Serial vs. parallel models of attention in visual search: ac-
565 counting for benchmark rt-distributions. *Psychonomic bulletin & review*, 23(5):
566 1300–1315, 2016.
- 567 Rani Moran, Heinrich René Liesefeld, Marius Usher, and Hermann J Muller. An
568 appeal against the item’s death sentence: Accounting for diagnostic data pat-
569 terns with an item-based model of visual search. *Behavioral and Brain Sci-*
570 *ences*, 40:e148, 2017.

- 571 J Toby Mordkoff and Steven Yantis. An interactive race model of divided at-
572 tention. *Journal of Experimental Psychology: Human Perception and Perfor-*
573 *mance*, 17(2):520, 1991.
- 574 Gavin JP Ng, Simona Buetti, Trisha N Patel, and Alejandro Lleras. Prioritiza-
575 tion in visual attention does not work the way you think it does. *Journal of*
576 *Experimental Psychology: Human Perception and Performance*, 2020.
- 577 Gavin Jun Peng Ng, Alejandro Lleras, and Simona Buetti. Fixed-target efficient
578 search has logarithmic efficiency with and without eye movements. *Attention,*
579 *Perception, & Psychophysics*, 80(7):1752–1762, 2018.
- 580 Anna Nowakowska, Alasdair DF Clarke, and Amelia R Hunt. Human visual
581 search behaviour is far from ideal. *Proceedings of the Royal Society B: Biolog-*
582 *ical Sciences*, 284(1849):20162767, 2017.
- 583 Derrick Parkhurst, Klinto Law, and Ernst Niebur. Modeling the role of salience
584 in the allocation of overt visual attention. *Vision research*, 42(1):107–123, 2002.
- 585 Jonathan Peirce, Jeremy R Gray, Sol Simpson, Michael MacAskill, Richard
586 Höchenberger, Hiroyuki Sogo, Erik Kastman, and Jonas Kristoffer Lindeløv.
587 Psychopy2: Experiments in behavior made easy. *Behavior research methods*,
588 51(1):195–203, 2019.
- 589 Dragan Rangelov, Hermann J Müller, and Michael Zehetleitner. Failure to pop
590 out: Feature singletons do not capture attention under low signal-to-noise ratio
591 conditions. *Journal of Experimental Psychology: General*, 146(5):651, 2017.
- 592 Benjamin W Tatler. The central fixation bias in scene viewing: Selecting an op-
593 timal viewing position independently of motor biases and image feature distri-
594 butions. *Journal of vision*, 7(14):4–4, 2007.
- 595 Benjamin W Tatler, Mary M Hayhoe, Michael F Land, and Dana H Ballard. Eye
596 guidance in natural vision: Reinterpreting salience. *Journal of vision*, 11(5):
597 5–5, 2011.
- 598 Anne M Treisman and Garry Gelade. A feature-integration theory of attention.
599 *Cognitive psychology*, 12(1):97–136, 1980.
- 600 Zhiyuan Wang, Simona Buetti, and Alejandro Lleras. Predicting search perfor-
601 mance in heterogeneous visual search scenes with real-world objects. *Collabra:*
602 *Psychology*, 3(1), 2017.

- 603 Jeremy M Wolfe. What can 1 million trials tell us about visual search? *Psycho-*
604 *logical Science*, 9(1):33–39, 1998.
- 605 Jeremy M Wolfe. Approaches to visual search: Feature integration theory and
606 guided search. *Oxford handbook of attention*, pages 11–55, 2014.
- 607 Jeremy M Wolfe, Kyle R Cave, and Susan L Franzel. Guided search: an alterna-
608 tive to the feature integration model for visual search. *Journal of Experimental*
609 *Psychology: Human perception and performance*, 15(3):419, 1989.
- 610 Jeremy M Wolfe, Evan M Palmer, and Todd S Horowitz. Reaction time distri-
611 butions constrain models of visual search. *Vision research*, 50(14):1304–1311,
612 2010.
- 613 Zoe Jing Xu, Alejandro Lleras, and Simona Buetti. Predicting how surface texture
614 and shape combine in the human visual system to direct attention. *Scientific*
615 *reports*, 11(1):1–13, 2021.
- 616 Lingyun Zhang, Matthew H Tong, Tim K Marks, Honghao Shan, and Garrison W
617 Cottrell. Sun: A bayesian framework for saliency using natural statistics. *Jour-*
618 *nal of vision*, 8(7):32–32, 2008.