

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

Anna E. Hughes^a, Anna Nowakowska^b, Alasdair D. F. Clarke¹

^a*Department of Psychology, University of Essex, Colchester, CO4 3SQ, UK*

^b*School of Psychology, University of Aberdeen, Aberdeen, AB24 3FX, UK*

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). Here, we
34 aim to replicate and extend this work both theoretically and empirically, to test the
35 generalisability of the TCS model, and to suggest ways in which the TCS model
36 could be modified to generate better predictions.

37 1.1. Previous Work

38 Many different forms of visual search models have been proposed. One well
39 developed class of models are the saliency models, which aim to predict eye move-
40 ments during scene viewing, including visual search. They rest on the assump-
41 tion that fixations are directed to objects or locations that are most dissimilar to
42 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. |
| 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.

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

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

138 We also extend the TCS model into a Bayesian framework, where we begin
139 with existing 'prior' beliefs that are updated with data to give 'posterior' beliefs
140 that can be used for inference (McElreath, 2020). We think this has a number
141 of advantages over frequentist approaches. Perhaps most importantly, Bayesian
142 models are highly flexible. We demonstrate how we are able to specify a model
143 that is able to more accurately represent the distribution of responses (for exam-
144 ple, by specifying a response distribution that avoids predicting negative reaction
145 times) with a relatively complex model structure, that can be fit to a relatively
146 small amount of pilot data: something that would be challenging within a fre-
147 quentist framework. We also believe that Bayesian models offer very intuitive
148 methods for model testing and comparison and straightforward interpretation of
149 results, and we hope that this manuscript can act as a demonstration of these ben-
150 efits, showing how they can be applied to real scientific questions beyond the
151 simplified examples often found in textbooks or tutorials.

152 In the current manuscript, we focus on replicating and extending findings from
153 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 (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,

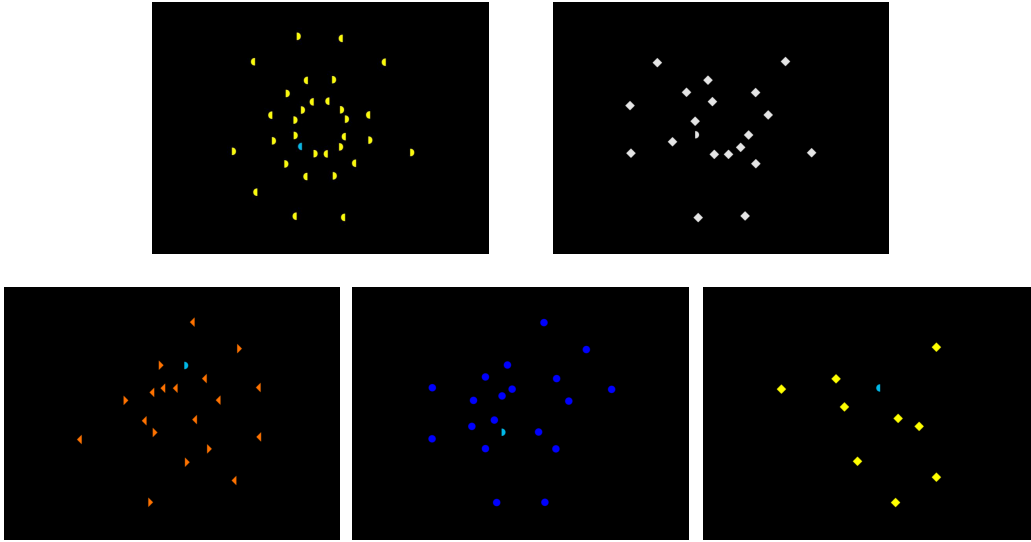


Figure 1: Example stimuli from Buetti et al. (2019) Top left: Expt 1A. Here, the target is a blue semicircle within a set of homogeneous (yellow semicircle) distractors. Top right: Expt 1B. The target is a grey semicircle in circular grey distractors. Bottom left: Expt 2A. The target is a blue semicircle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

188 with participants searching for the semicircular target within triangle, circle or di-
 189 amond distractors). In Experiments 2a, 2b and 2c, participants again searched for
 190 a cyan semicircle, but this time, the distractors differed in both shape and colour.
 191 We will refer to these conditions as *double features*. Note, unlike in standard con-
 192 junction searches, in this paradigm, the distractors are all identical with respect to
 193 these features (i.e, orange triangles). Examples of all these stimuli are shown in
 194 Figure 1. Buetti et al. (2019) also carried out a replication of their basic results
 195 using slightly different target and distractor stimuli (Experiments 3 and 4).

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

201 *2.1.1. Calculating the intercept, a , and the logarithmic slope parameter, D_i*

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

210 Fitting the model specified in Equation 1 to the data, we obtain the values for
 211 D_c and D_s given in Table 2. As can be seen, the more similar the distractors are to
 212 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.

213 *2.1.2. Estimating $D_{c,s}$, the logarithmic slope parameter for compound features*

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

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

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

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

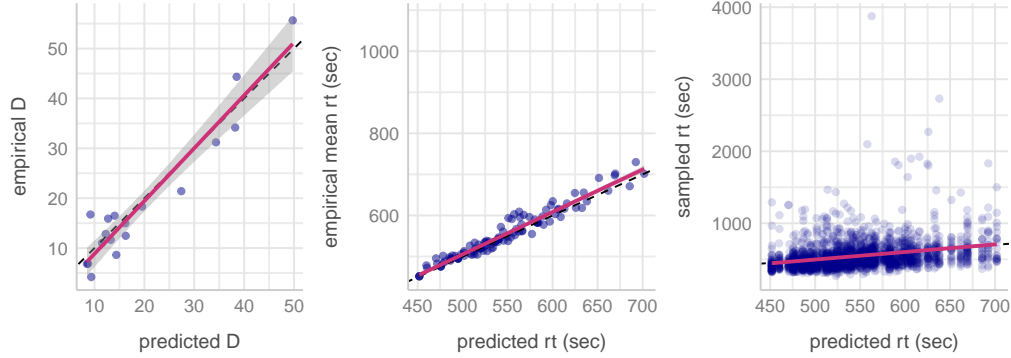


Figure 2: (left) The collinear method for calculating D offers a good prediction. (centre) Using the TCS to predict reaction times. (right) Each dot now represents a randomly sampled reaction time from an observer. Note that there is greater spread in the data points here, due to the fact that there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

225 Finally, the collinear contrast integration model also assumes independence of
 226 feature dimensions, but assumes that while the visual features create a multidimensional space, the contrast between them is unidimensional. As D is assumed
 227 to be inversely proportional to contrast, the equation can be written as follows:
 228

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

229 Buetti et al. (2019) found that with their dataset, the collinear contrast inte-
 230 gration model was best able to predict $D_{c,s}$ from D_c and D_s , with $R^2 = 0.915$.
 231 We verified we were able to replicate this result using the dataset available on
 232 OSF (<https://osf.io/f3m24/>)¹ and using the exclusion criteria originally applied;
 233 see Figure 2 (left panel) and *Supplementary Materials* for details. We show that
 234 we are able to do this using both the frequentist modelling approaches used in the
 235 original paper, and using Bayesian modelling.

236 2.1.3. Estimating a , the intercept parameter for compound features

237 As a is the intercept of the model, it represents how long observers take to find
 238 a target when $N_T = 0$, i.e., there are no distractors. As such, it should be inde-
 239 pendent of both shape and colour, and can be thought of as the role of non-search

¹downloaded on 28th August 2020

240 processes (such as motivation, motor preparation etc.) that influence reaction time.
241 In Buetti et al. (2019), a was calculated for each sub-experiment. Here, we follow
242 that method in order to replicate their results exactly.

243 2.1.4. *Estimating mean reaction times*

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

247 2.1.5. *Discussion*

248 While TCS theory offers a good prediction of search slopes and corresponding
249 mean reaction times for double feature search, there are two related limitations.
250 Firstly, it is unable to account for individual differences between observers, only
251 the changes to the sample average. Secondly, it cannot account for the distribution
252 of reaction times over multiple trials. Figure 2 (right panel) shows clearly that
253 these factors generate high levels of variability within the individual trial-level
254 data. To address these issues, we propose adapting TCS to make use of multi-
255 level modelling techniques. Multi-level models allow us to take into account the
256 hierarchical structure of the data (i.e. that each participant completes multiple
257 trials) in a way that does not require averaging, meaning that we are able to model
258 participant variability as well as group-level effects (Gelman and Hill, 2006).

259 2.2. *A multi-level TCS*

260 Switching from a linear regression model to a multi-level model will allow
261 us to compute D for each participant, while simultaneously estimating the trial-
262 to-trial variance. We also switch from a frequentist to Bayesian framework, as
263 this allows us to naturally account for the uncertainty in the model’s predictions.
264 However, switching from linear regression to a multi-level model raises the prob-
265 lem of which distribution to use for modelling reaction times. Using a normal
266 distribution is unlikely to be satisfactory, as it is unable to account for the skew
267 frequently seen in reaction time distributions, and also allows the possibility of
268 negative reaction times. We can account for both of these problems by using a
269 log-normal distribution. We will also test whether a slightly more complex ex-
270 tension of this model, the shifted lognormal model (which allows the distribution
271 to be offset to the right i.e. mimicking the patterns seen in reaction time data,
272 where valid responses begin at around 100ms) offers any improvement in model
273 fit. Note that a Wald, or inverse Gaussian distribution, would also be a reasonable
274 distribution choice for this data given that TCS is based on a diffusion process e.g.

275 (Moran et al., 2013), and this distribution has been argued to be psychologically
276 more plausible (e.g. Kieffaber et al. (2006), though see Matzke and Wagenmakers
277 (2009)): we chose not to use this distribution as it often leads to computational is-
278 sues, which would make it harder for others to reproduce or build on our approach
279 later.

280 3. Hypotheses

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

283 3.1. *Proposed Modifications to Experimental Design*

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

- 286 1. **Within-subjects design.** This modification should give us greater power to
287 detect differences between different models, as well as allowing us to in-
288 vestigate how individual differences in the single-feature task might explain
289 differences in the double-feature task.
- 290
- 291 2. **Increase target-distractor similarity.** If the distractors are a very differ-
292 ent colour from the target, they may not distinguish well between different
293 contrast models. We will therefore run a version of the experiment where
294 the target is a red semicircle, with distractors being either orange, purple or
295 pink.
- 296

297 3.2. *Registered Hypothesis*

- 298 1. **Shifted lognormal model.** We hypothesise that a shifted lognormal model
299 will give the best fit to our single-feature data, when compared to a lognor-
300 mal and a normal model.
- 301
- 302 2. **Log-linear effect of N_T .** We will test the TCS model assumption that N_T
303 has a log-linear effect by testing models with and without the log of this
304 term. We expect that this will confirm the results previously seen in papers
305 testing TCS i.e. that the log-linear approach will be best.
- 306

- 307 **3. Contrast model comparisons.** We will test the hypothesis proposed by
308 (Buetti et al., 2019): specifically, that the *collinear contrast ingratiation*
309 *model* outperforms the *best feature guidance*, and *orthogonal contrast com-*
310 *bination models* for the calculation of D , by calculating and comparing the
311 mean absolute prediction error for each model.
312
- 313 **4. Reaction time predictions.** We will further test the hypothesis proposed by
314 (Buetti et al., 2019) by testing which model gives the best prediction at the
315 trial-by-trial RT level.

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

326 3.3. *Planned Explorations*

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

336 One of the benefits of using a multi-level modelling approach is that it is rel-
337 atively easy to extend to incorporate other factors that may contribute to reaction
338 times, such as eccentricity and inter-item distance, which may help to explain
339 behaviour further. To demonstrate this, we will also run exploratory analyses in-
340 cluding a factor for which ring the target is in to assess whether this improves
341 model fit or affects any of the conclusions that can be drawn from the model.

342 3.4. Pilot Experiment

343 Full details of a pilot experiment with $n = 4$ participants (960 trials each) using
344 our proposed analyses can be found in *Supplementary Materials*. This suggests
345 that even with a small sample, we can convincingly demonstrate H1 and H2. How-
346 ever, more data will be required to discriminate between the models, particularly
347 for H4. Given that our methods are within-subject, we have reduced the num-
348 ber of trials per condition compared to Buetti et al. (2019) (12 in our proposed
349 study, compared to 40 in theirs). It is therefore possible that the increased noise
350 in our estimated D single-feature parameters will make it more difficult to predict
351 double-feature Ds accurately. However, we think this is unlikely to be the case for
352 several reasons. Firstly, we can see that even in a small amount of pilot data, we
353 can verify H3, with the collinear model having the lowest mean absolute predic-
354 tion error. Secondly, while the pilot data does not give a strong weighting to the
355 collinear model in H4, it is still the most probable model. Finally, we have carried
356 out simulations to estimate our measurement error....

357 4. General Methods

358 4.1. Sample Size: Participants and Trials

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

364 4.2. Stimuli

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

371 **Distractor and target types:** we will replicate the distractor types used in
372 Buetti et al. (2019), apart from that we will change one distractor colour (from
373 blue to pink) to allow us to discriminate better between different models of the
374 data (see above). There are six single-feature conditions (purple, orange and pink
375 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 (60 in total, with 12 being the white semicircle target and the remainder the red semicircle target).

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

4.3. Procedure

Participants will complete the experiment in the laboratory, sitting at a viewing distance of 45cm from the screen (viewing distance will be fixed by using a chin rest). They 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 (either a red semicircle or a white semicircle, depending on the block) 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 120 trials. Participants will complete 8 blocks of trials (960 trials overall i.e. 192 trials in each of 5 experiments, consisting of 5 set sizes x 3 distractor conditions x 12 repeats + 12 zero distractor trials). The trials where the distractors are single-feature shapes (i.e. the target is a white semicircle - Experiment 1b in Buetti et al. (2019)) will all appear in one block (which will appear at a randomly selected position within the experiment). All other trials (where the target is red semicircle) will be fully randomised i.e. all different conditions will be completely intermixed. This approach will be taken as TCS requires the participant to have a well-defined target template in mind in order to compare this to the stimuli in the display. Thus, participants will be cued to search for the relevant target at the beginning of each block.

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.

410 4.4. Data Pre-processing

411 Only participants who complete the full experiment will be considered candi-
412 dates for inclusion in the data analysis. We will apply the same inclusion criteria
413 as the original paper: participants will only be included if their search accuracy
414 over 90% and their average response time is not smaller or larger than two stan-
415 dard deviations from the group average response time.

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

418 4.5. Analysis Plan

419 All analysis will be carried out using R (vx.xx)², brms (v.xx.xx) and rStan
420 (vx.xxxx) As discussed above, we will use a mixed-effect models with either nor-
421 mal, lognormal or shifted lognormal distributions.

422 Please see the analysis of our pilot data for a full implementation of our anal-
423 ysis pipeline, including all code (available on Github at https://github.com/scienceanna/TCS_Bayesian).
424

425 5. Results

426 *– blank –*

427 6. General Discussion

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429 Conflict of interest

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

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²Version numbers will be recorded upon completion of final analysis.

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.
- John Duncan and Glyn W Humphreys. Visual search and stimulus similarity. *Psychological review*, 96(3):433, 1989.
- Andrew Gelman and Jennifer Hill. *Data analysis using regression and multi-level/hierarchical models*. Cambridge university press, 2006.
- 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.

- 465 Laurent Itti and Christof Koch. A saliency-based search mechanism for overt and
466 covert shifts of visual attention. *Vision research*, 40(10-12):1489–1506, 2000.
- 467 Laurent Itti, Christof Koch, and Ernst Niebur. A model of saliency-based visual
468 attention for rapid scene analysis. *IEEE Transactions on pattern analysis and*
469 *machine intelligence*, 20(11):1254–1259, 1998.
- 470 Paul D Kieffaber, Emily S Kappenman, Misty Bodkins, Anantha Shekhar, Brian F
471 O’Donnell, and William P Hetrick. Switch and maintenance of task set in
472 schizophrenia. *Schizophrenia research*, 84(2-3):345–358, 2006.
- 473 Christof Koch and Shimon Ullman. Shifts in selective visual attention: towards
474 the underlying neural circuitry. In *Matters of intelligence*, pages 115–141.
475 Springer, 1987.
- 476 Kathryn Koehler, Fei Guo, Sheng Zhang, and Miguel P Eckstein. What do
477 saliency models predict? *Journal of vision*, 14(3):14–14, 2014.
- 478 Heinrich René Liesefeld and Hermann J Müller. A theoretical attempt to revive
479 the serial/parallel-search dichotomy. *Attention, Perception, & Psychophysics*,
480 82(1):228–245, 2020.
- 481 Heinrich René Liesefeld, Rani Moran, Marius Usher, Hermann J Müller, and
482 Michael Zehetleitner. Search efficiency as a function of target saliency: The
483 transition from inefficient to efficient search and beyond. *Journal of Experi-*
484 *mental Psychology: Human Perception and Performance*, 42(6):821, 2016.
- 485 Alejandro Lleras, Zhiyuan Wang, Anna Madison, and Simona Buetti. Predicting
486 search performance in heterogeneous scenes: Quantifying the impact of homo-
487 geneity effects in efficient search. *Collabra: Psychology*, 5(1), 2019.
- 488 Alejandro Lleras, Zhiyuan Wang, Gavin Jun Peng Ng, Kirk Ballew, Jing Xu, and
489 Simona Buetti. A target contrast signal theory of parallel processing in goal-
490 directed search. *Attention, Perception, & Psychophysics*, pages 1–32, 2020.
- 491 Anna Madison, Alejandro Lleras, and Simona Buetti. The role of crowding in par-
492 allel search: Peripheral pooling is not responsible for logarithmic efficiency in
493 parallel search. *Attention, Perception, & Psychophysics*, 80(2):352–373, 2018.
- 494 Dora Matzke and Eric-Jan Wagenmakers. Psychological interpretation of the ex-
495 gaussian and shifted wald parameters: A diffusion model analysis. *Psycho-*
496 *nomics bulletin & review*, 16(5):798–817, 2009.

- 497 Richard McElreath. *Statistical rethinking: A Bayesian course with examples in R*
498 *and Stan*. Chapman and Hall/CRC, 2020.
- 499 Rani Moran, Michael Zehetleitner, Hermann J Mueller, and Marius Usher. Com-
500 petitive guided search: Meeting the challenge of benchmark rt distributions.
501 *Journal of Vision*, 13(8):24–24, 2013.
- 502 Rani Moran, Michael Zehetleitner, Heinrich René Liesefeld, Hermann J Müller,
503 and Marius Usher. Serial vs. parallel models of attention in visual search: ac-
504 counting for benchmark rt-distributions. *Psychonomic bulletin & review*, 23(5):
505 1300–1315, 2016.
- 506 Rani Moran, Heinrich René Liesefeld, Marius Usher, and Hermann J Muller. An
507 appeal against the item’s death sentence: Accounting for diagnostic data pat-
508 terns with an item-based model of visual search. *Behavioral and Brain Sci-*
509 *ences*, 40:e148, 2017.
- 510 Gavin JP Ng, Simona Buetti, Trisha N Patel, and Alejandro Lleras. Prioritiza-
511 tion in visual attention does not work the way you think it does. *Journal of*
512 *Experimental Psychology: Human Perception and Performance*, 2020.
- 513 Gavin Jun Peng Ng, Alejandro Lleras, and Simona Buetti. Fixed-target efficient
514 search has logarithmic efficiency with and without eye movements. *Attention,*
515 *Perception, & Psychophysics*, 80(7):1752–1762, 2018.
- 516 Anna Nowakowska, Alasdair DF Clarke, and Amelia R Hunt. Human visual
517 search behaviour is far from ideal. *Proceedings of the Royal Society B: Biolog-*
518 *ical Sciences*, 284(1849):20162767, 2017.
- 519 Derrick Parkhurst, Klinto Law, and Ernst Niebur. Modeling the role of salience
520 in the allocation of overt visual attention. *Vision research*, 42(1):107–123, 2002.
- 521 Jonathan Peirce, Jeremy R Gray, Sol Simpson, Michael MacAskill, Richard
522 Höchenberger, Hiroyuki Sogo, Erik Kastman, and Jonas Kristoffer Lindeløv.
523 Psychopy2: Experiments in behavior made easy. *Behavior research methods*,
524 51(1):195–203, 2019.
- 525 Dragan Rangelov, Hermann J Müller, and Michael Zehetleitner. Failure to pop
526 out: Feature singletons do not capture attention under low signal-to-noise ratio
527 conditions. *Journal of Experimental Psychology: General*, 146(5):651, 2017.

- 528 Benjamin W Tatler. The central fixation bias in scene viewing: Selecting an op-
529 timal viewing position independently of motor biases and image feature distri-
530 butions. *Journal of vision*, 7(14):4–4, 2007.
- 531 Benjamin W Tatler, Mary M Hayhoe, Michael F Land, and Dana H Ballard. Eye
532 guidance in natural vision: Reinterpreting salience. *Journal of vision*, 11(5):
533 5–5, 2011.
- 534 Anne M Treisman and Garry Gelade. A feature-integration theory of attention.
535 *Cognitive psychology*, 12(1):97–136, 1980.
- 536 Zhiyuan Wang, Simona Buetti, and Alejandro Lleras. Predicting search perfor-
537 mance in heterogeneous visual search scenes with real-world objects. *Collabra:*
538 *Psychology*, 3(1), 2017.
- 539 Jeremy M Wolfe. What can 1 million trials tell us about visual search? *Psycho-*
540 *logical Science*, 9(1):33–39, 1998.
- 541 Jeremy M Wolfe. Approaches to visual search: Feature integration theory and
542 guided search. *Oxford handbook of attention*, pages 11–55, 2014.
- 543 Jeremy M Wolfe, Kyle R Cave, and Susan L Franzel. Guided search: an alterna-
544 tive to the feature integration model for visual search. *Journal of Experimental*
545 *Psychology: Human perception and performance*, 15(3):419, 1989.
- 546 Jeremy M Wolfe, Evan M Palmer, and Todd S Horowitz. Reaction time distri-
547 butions constrain models of visual search. *Vision research*, 50(14):1304–1311,
548 2010.
- 549 Zoe Jing Xu, Alejandro Lleras, and Simona Buetti. Predicting how surface texture
550 and shape combine in the human visual system to direct attention. *Scientific*
551 *reports*, 11(1):1–13, 2021.
- 552 Lingyun Zhang, Matthew H Tong, Tim K Marks, Honghao Shan, and Garrison W
553 Cottrell. Sun: A bayesian framework for saliency using natural statistics. *Jour-*
554 *nal of vision*, 8(7):32–32, 2008.