

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 run a new fully within-subjects experiment to attempt to replicate the key original findings, and show that overall, TCS does a good job of predicting the data. However, we do not replicate the finding that the collinear combination model outperforms the other contrast combination models, instead finding that it may be difficult to conclusively distinguish between them.

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

4 developed that can generate testable predictions about how different types of dis-
5 tractors 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-
43 tion that fixations are directed to objects or locations that are most dissimilar to
44 the background or other objects in the visual display (Itti and Koch, 2000; Itti
45 et al., 1998; Koch and Ullman, 1987). While the original saliency model was
46 able to predict fixation allocation in a visual search task above chance (Parkhurst
47 et al., 2002), further research demonstrated that a comparable level of performance
48 could be achieved using a simple central fixation bias heuristic (Tatler, 2007). The
49 saliency models have since been extended and improved (see for example Zhang
50 et al. (2008)): however, the main issue with this family of models remains their
51 limited usability in complex real-life search arrays (Tatler et al., 2011; Koehler
52 et al., 2014), and even in abstract laboratory search arrays (Kotseruba et al., 2020).
53 In addition, in most instances of visual search, the target is clearly defined (i.e. the
54 goal is to find a specific object) and inspecting the most salient areas of the dis-
55 play may in these cases be inefficient. Finally, by focusing on eye movements,
56 these models do not necessarily provide a theoretical framework for the cognitive
57 processes underlying visual search.

58 Perhaps the most established class of models of visual search are based around
59 Feature Integration Theory (Treisman and Gelade, 1980), which has been modi-
60 fied and extended by Wolfe and colleagues in the Guided Search Model (Wolfe
61 et al., 1989; Wolfe, 2014). These theories have been developed using data from
62 visual search tasks with discrete sets of abstract items. These models combine
63 top-down influences (how closely an item resembles the observer’s goal) with
64 bottom-up image properties. For example, if one’s goal (top-down processing)
65 is to find a red horizontal bar, all the red and horizontal items in a visual search
66 display will be given greater weight than distractors (e.g. vertical and blue items)
67 in the model. The salience of a given object in the display (how distinctive it is
68 from the surrounding objects) also activates bottom-up processing. For instance, a
69 blue item among red items is ranked higher than red among orange items. In such
70 cases, a salient item can capture attention even without resembling the target.
71 Combining bottom-up and top-down sources of activation generates an activation
72 map which generates a prediction of the order in which stimuli are processed in
73 visual search. Other extensions to these models have been proposed, such as the
74 Dimension Weighting Account, in which saliency weightings are assigned to dif-
75 ferent target ‘dimensions’ (e.g. colour or shape), helping to explain results where
76 varying the target dimension within blocks of trials leads to longer reaction times

77 than where the dimension remains consistent within a block (Krummenacher and
78 Müller, 2012). Thus, these models aim to produce a representation of the visual
79 properties of the distractors at each location in the visual field. However, these
80 are predominantly qualitative models, and thus it is difficult to use them to make
81 specific quantitative predictions.

82 TCS falls under a class of models that take a different approach, in that they
83 focus solely on representing the difference between targets and distractors. For
84 example, in work on eye movement patterns, it has been proposed that perfor-
85 mance in inefficient (serial) visual search is mostly determined by the size of the
86 ‘functional viewing field’, whose size varies as a function of target-distractor sim-
87 ilarity (Hulleman and Olivers, 2017). Similarly, work on attention has proposed
88 the notion of ‘relative features’, where attention is tuned to feature relationships
89 i.e. the appearance of the target relative to distractors in the environment (Becker
90 et al., 2014; Becker, 2010). TCS also has features in common with other models
91 that propose parallel identification of all items in a scene, with diffusion based
92 mechanisms for identifying targets from distractors (Moran et al., 2013, 2016).
93 However, TCS (Lleras et al., 2020) aims to provide a unifying framework that can
94 make quantitative behavioural predictions for visual search based on this general
95 assumption. As such, it is an attractive candidate model for a formal registered
96 replication.

97 A key assumption of the TCS model is that behaviour is determined by com-
98 paring the target template (held in memory) with every element present in the
99 scene in parallel. This allows the visual system to reject peripheral non-targets
100 quickly; the speed at which items are evaluated is determined by how different the
101 item is from the template through an evidence accumulation process (formally,
102 the slope of the logarithmic function is assumed to be inversely proportional to the
103 overall magnitude of the contrast signal between the target and distractor). The
104 model thus focuses on an initial, efficient processing stage of search; if sufficient
105 evidence is not accumulated during this process, the model posits that a second
106 stage is entered, requiring a sequence of eye movements to search for the target
107 in a serial manner. TCS has been successful in predicting a number of empirical
108 results, including search performance in heterogeneous scenes based on param-
109 eters estimated in homogeneous scenes, both with artificial stimuli (Buetti et al.,
110 2016; Lleras et al., 2019) and with real-world objects visualised on a computer
111 display (Wang et al., 2017). Table 1 provides an overview of studies investigating
112 the TCS framework to date.

113 The original version of the TCS model is essentially a (natural) log-linear
114 model in the number of distractors. The full model contains a variable L , which

115 represents the number of different types of distractors present in the display. How-
 116 ever, in our paper, we will follow Buetti et al. (2019) and only consider the specific
 117 case of $L = 1$, of a target among a homogeneous set of distractors. In this case,
 118 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., 2022a).

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

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.

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

160 In the current manuscript, we focus on replicating and extending findings from
161 Buetti et al. (2019). In their study, participants searched for a target in a scene of
162 homogeneous distractors (see Figure 1). First, parallel search efficiency (mea-
163 sured by the logarithmic search slope) was estimated for cases where the distrac-
164 tors varied from the target in one dimension: either colour (e.g. a cyan target being
165 searched for in either yellow, blue or orange distractors) or shape (e.g. a semicir-
166 cle target in either circle, diamond or triangle distractors). New participants then
167 searched for the same targets in displays where the distractors were compounds,
168 differing from the target in both colour and shape (e.g. searching for a cyan semi-
169 circle in either blue circles, orange diamonds or yellow triangles). The logarithmic
170 search slopes in the initial experiments were then used to predict the logarithmic
171 slopes and reaction times using a number of models. The authors found that the
172 best model was a ‘collinear contrast integration model’ where the distinctiveness
173 scores were summed along each attribute in the unidimensional experiments, cre-
174 ating an overall contrast score that was used for compound stimuli predictions.
175 In our registered replication, we will attempt to verify the conclusions of Buetti
176 et al. (2019), that the collinear contrast integration model does indeed offer the
177 best characterisation of contrast signal combinations in visual search within the
178 TCS framework.

179 We begin by verifying the analysis of Buetti et al. (2019). We then describe
180 our proposed replication study, showing with pilot data how we are able to extend
181 their model of how multi-dimensional contrasts are calculated, both by incorpo-
182 rating a multi-level design to predict within-subjects effects and by utilising a
183 Bayesian generalised linear model framework to better represent the distribution
184 of responses (e.g. avoiding predicting negative reaction times, accounting for un-
185 certainty in model predictions).

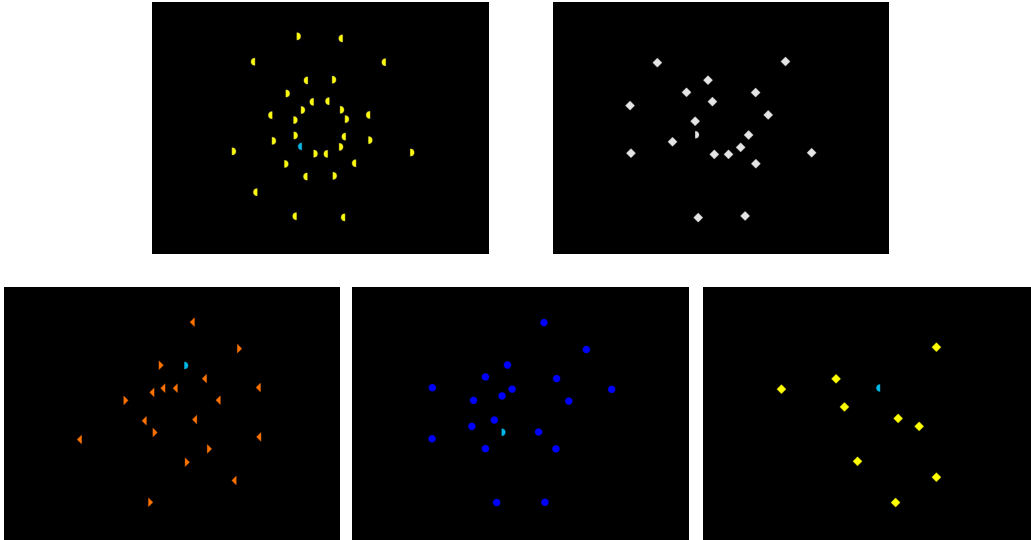


Figure 1: Example stimuli from Buetti et al. (2019) Top left: Expt 1A. Here, the target is a blue semicircle within a set of homogeneous (yellow semicircle) distractors. Top right: Expt 1B. The target is a grey semicircle in circular grey distractors. Bottom left: Expt 2A. The target is a blue semicircle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

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 - Computational Verification*).

2.1. TCS modelling overview

In Experiment 1a of Buetti et al. (2019), participants searched for a cyan semicircle target among blue, yellow or orange semicircular distractors i.e. they searched for a target that differed from the distractors by a *single feature* (colour). The experiment was then repeated (1b) using a different single feature (shape, with participants searching for the semicircular target within triangle, circle or diamond distractors). In Experiments 2a, 2b and 2c, participants again searched for a cyan semicircle, but this time, the distractors differed in both shape and colour.

We will refer to these conditions as *double features*. Note, unlike in standard conjunction searches, in this paradigm, the distractors are all identical with respect to these features (i.e, orange triangles). Examples of all these stimuli are shown in Figure 1. Buetti et al. (2019) also carried out a replication of their basic results using slightly different target and distractor stimuli (Experiments 3 and 4).

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

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

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

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

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 - Computational Verification* for full values for all experiments.

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

In the context of the current experiments, the core idea of TCS theory is that we can estimate the (natural) logarithmic slope parameter for a double feature visual search from the slopes parameters in the two independent single feature searches i.e., $D_{c,s} = f(D_c, D_s)$. Buetti et al. (2019) tested three different models for predicting D for compound colour-shape stimuli. The best feature guidance

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 inte-
 238 gration model was best able to predict $D_{c,s}$ from D_c and D_s , with $R^2 = 0.915$.
 239 We verified we were able to replicate this result using the dataset available on
 240 OSF (<https://osf.io/f3m24/>)¹ and using the exclusion criteria originally applied;
 241 see Figure 2 (left panel) and *Supplementary Materials - Computational Verification*
 242 for details. We show that we are able to do this using both the frequentist
 243 modelling approaches used in the original paper, and using Bayesian modelling.

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 inde-
 247 pendent of both shape and colour, and can be thought of as the role of non-search
 248 processes (such as motivation, motor preparation etc.) that influence reaction time.
 249 In Buetti et al. (2019), a was calculated for each sub-experiment. Here, we follow
 250 that method in order to replicate their results exactly.

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.

2.1.4. Estimating mean reaction times

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

2.1.5. Discussion

While TCS theory offers a good prediction of search slopes and corresponding mean reaction times for double feature search, there are two related limitations. Firstly, it is unable to account for individual differences between observers, only the changes to the sample average. Secondly, it cannot account for the distribution of reaction times over multiple trials. Figure 2 (right panel) shows clearly that these factors generate high levels of variability within the individual trial-level data. To address these issues, we propose adapting TCS to make use of multi-level modelling techniques. 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

271 this allows us to naturally account for the uncertainty in the model’s predictions.
272 However, switching from linear regression to a multi-level model raises the prob-
273 lem of which distribution to use for modelling reaction times. Using a normal
274 distribution is unlikely to be satisfactory, as it is unable to account for the skew
275 frequently seen in reaction time distributions, and also allows the possibility of
276 negative reaction times. We can account for both of these problems by using a
277 log-normal distribution. We will also test whether a slightly more complex ex-
278 tension of this model, the shifted lognormal model (which allows the distribution
279 to be offset to the right i.e. mimicking the patterns seen in reaction time data,
280 where valid responses begin at around 100ms) offers any improvement in model
281 fit. Note that a Wald, or inverse Gaussian distribution, would also be a reasonable
282 distribution choice for this data given that TCS is based on a diffusion process e.g.
283 (Moran et al., 2013), and this distribution has been argued to be psychologically
284 more plausible (e.g. Kieffaber et al. (2006), though see Matzke and Wagenmakers
285 (2009)): we chose not to use this distribution as it often leads to computational is-
286 sues, which would make it harder for others to reproduce or build on our approach
287 later.

288 3. Hypotheses

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

291 3.1. *Proposed Modifications to Experimental Design*

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

- 294 1. **Within-subjects design.** This modification should give us greater power to
295 detect differences between different models, as well as allowing us to in-
296 vestigate how individual differences in the single-feature task might explain
297 differences in the double-feature task.
298
- 299 2. **Increase target-distractor similarity.** If the distractors are a very differ-
300 ent colour from the target, they may not distinguish well between different
301 contrast models. We will therefore run a version of the experiment where
302 the target is a red semicircle, with distractors being either orange, purple or
303 pink.
304

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

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

3.3. Planned Explorations

We plan to investigate the effect of individual differences in this paradigm: to what extent performance in the single-feature task can predict performance in the double-feature task for a given individual (Buetti et al. (2019) were not able to investigate this due to the between-subjects design of their study). We plan to do this by specifying a more complex random effects structure for the model, that allows for individual differences across different slopes for different features. This

allows us to then study the random effect correlation structure. However, given these models can be challenging to fit, we will do this in an exploratory manner after carrying out our formally registered analysis.

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

3.4. Pilot Experiment

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

4. General Methods

4.1. Sample Size: Participants and Trials

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

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



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.

375 Finally, we have carried out a simulation experiment to estimate the confi-
 376 dence intervals on the mean when sampling from a log-normal distribution. We
 377 defined our distribution to have a mean-log of 6.135 and a standard deviation of
 378 0.32. These values were loosely based on the distributions of reaction times in
 379 Buetti et al. (2019). The results are shown in Figure 3. Based on these simula-
 380 tions, we find that a sample of $n = 20$ leads to a 95% confidence interval that is
 381 approximately 1.4 times larger than $n = 40$. We feel this is a suitable compromise
 382 given we will be collecting our data within-subjects.

383 4.2. Stimuli

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

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

397 shapes (triangles, circles and diamonds) in which case the target is a white semi-
398 circle.

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

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

406 4.3. Procedure

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

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

430 4.4. Data Pre-processing

431 Only participants who complete the full experiment will be considered candi-
432 dates for inclusion in the data analysis. We will apply the same inclusion criteria

433 as the original paper: participants will only be included if their search accuracy
434 is over 90% and their average response time is not smaller or larger than two
435 standard deviations from the group average response time.

436 For participants included in the analysis, we will apply the data cleaning used
437 in the pilot data analysis i.e. removing the top and bottom 1% of their data.²

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 mixed-effect models with either nor-
441 mal, 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/Riadsala/single_double_](https://github.com/Riadsala/single_double_feature_search)
444 [feature_search](https://github.com/Riadsala/single_double_feature_search)).

445 4.6. *Registered Report*

446 The original Stage 1 registered report for this manuscript is available at <https://osf.io/f9sua/>. All study data, materials and analysis code for both Stage 1
447 and Stage 2 are available at [https://github.com/Riadsala/single_double_](https://github.com/Riadsala/single_double_feature_search)
448 [feature_search](https://github.com/Riadsala/single_double_feature_search).

449 We report how we determined our sample size (see Section 4.1), all data exclu-
450 sions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria
451 were established prior to data analysis (see Section 4.4) all manipulations, and all
452 measures in the study (see Section 4.2).

454 5. Results

455 All 40 participants had accuracy over 90% (minimum 93.1%). One participant
456 had an average response time (1100ms) over two standard deviations from the
457 group average response time (781ms) and was removed. Incorrect trials were
458 then removed, and the data was trimmed (only including response times between
459 the 1% and 99% quantiles) leaving us with 39 participants completing a total of
460 59,587 trials.

²See *Supplementary Materials - Pilot Analysis* and *Supplementary Materials - Registered Anal-
ysis* for full details of data cleaning.

461 All Bayesian models were fit to the new data using exactly the same proce-
 462 dure³ as the pilot data presented in the Stage One review process. We checked
 463 for convergence of our models by visually inspecting the chains as well as ver-
 464 ifying that the \hat{R} was close to 1 for all parameters of all the fitted models (see
 465 *Supplementary Material - Main Analysis* for full model fit information).

466 5.1. Hypothesis 1: Shifted-lognormal model

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

472 After each of these models had been fit to the data, leave-one-out (LOO) model
 473 comparison was used to calculate posterior probabilities for each. The results of
 474 this procedure allocated $\sim 100\%$ of the weight to the shifted-lognormal model, so
 475 we can conclude that, in accordance with our registered hypothesis, it is the best
 476 distribution (out of the three we tested⁴) to use for modelling response times in
 477 this paradigm. This model is shown in Figure 2.2 of the *Supplementary Materials*
 478 - *Registered Analysis*.

479 5.2. Hypothesis 2: log-linear effect of N_T

480 We then used the same methods to verify that using $\log N_T$ for the search slope
 481 does indeed give a better fit to the data than simply using N_T . The results are again
 482 conclusive with $\sim 100\%$ of the model weight being assigned to the model that is
 483 log-linear in N_T , again in accordance with our original hypothesis.

484 5.3. Hypothesis 3: Contrast Model Comparison

485 Now that we have confirmed that the shifted-lognormal multilevel model (with
 486 a log-linear effect of N_T) is indeed the best fit to the data we will extract the search
 487 slopes for each feature. These are summarised in Table 3. We can see that we have
 488 successfully obtained a range of values for both D_c and D_s . As with Buetti et al.
 489 (2019) we find that the values for D_s are larger than D_c (see Table 2), meaning
 490 that search slopes for colour features are shallower than shape.

³The only departure was an increase in iterations from 5000 to 80000 for the model predicting reaction times, based on advice given in the Stan forums, to enable the bridge sampling process to work properly.

⁴See discussion for Wald, Weibull, etc.

feature	D_c	95%HDCI	feature	D_s	95%HDCI
orange	0.156	[0.139 , 0.173]	triangle	0.253	[0.230 , 0.275]
pink	0.042	[0.028 , 0.057]	diamond	0.187	[0.171 , 0.205]
purple	0.015	[0.002 , 0.030]	circle	0.191	[0.175 , 0.204]

Table 3: A summary of the posterior estimates of D_c and D_s values from our Experiment. Note that our values are reported in seconds, in contrast to Table 2, which follows (Buetti et al., 2019) and reports the slopes in milliseconds.

491 We now combine the *single-feature* search slopes, D_c and D_s , to predict the
492 *double-feature* conditions ($D_{c,s}$) using Equations 2, 3 and 4 and above. The results
493 are summarised in Figure 4. We find that while the collinear contrast model has
494 the highest R^2 (0.922, compared to $R^2 = 0.884$ for best feature, and $R^2 = 0.916$ for
495 orthogonal contrast), the orthogonal contrast model is the most accurate, both in
496 terms of mean absolute error (0.165, compared to 0.185 for best feature and 0.271
497 for collinear) and having a regression slope closest to 1 (1 compared to 0.753 and
498 1.48). Therefore, Hypothesis 3 does not hold: orthogonal contrast rather than
499 collinear contrast offers the best prediction of search slopes in the double-feature
500 condition.

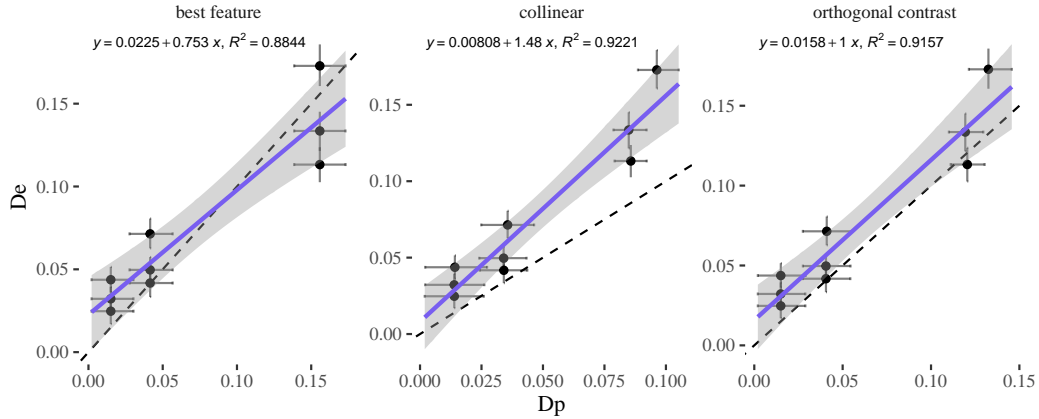


Figure 4: Predicting $D_{c,s}$ from D_c and D_s . The x-axis shows our predictions, D_p , using the best feature, collinear contrast, and orthogonal contrast models.

501 5.4. Hypothesis 4: Reaction Time Predictions

502 Upon reflection, the approach to model comparison we outlined in our reg-
503 istered analysis was limited in a number of ways. Our original plan was to use

the posterior predictions from a model trained on the single-feature data to act as a prior for the double-feature data. While we initially thought this would be an elegant approach, there are a large number of parameters that are outside the main focus of this paper yet still require priors (intercepts, group level variance and residual variance). Furthermore, while the methods for estimating $D_{c,s}$ presented above give good predictions in terms of the mean value, it is not clear that the standard deviation for these distributions will be accurate. As such, we have developed a new, simpler method for this final comparison. To maintain full transparency, we present both methods here.

5.4.1. Registered Method

Our final hypothesis concerns how well the different feature combination models perform when predicting reaction times. We find very little difference between the three methods in terms of LOO model weights: 0.318 for best feature, 0.346 for collinear and 0.336 for orthogonal contrast. Thus, according to this analysis, we find no conclusive answer to hypothesis 4: all models give similar predictions at the trial-by-trial RT level.

5.4.2. Updated Method

Our new method for exploring this hypothesis involves taking $n = 100$ samples of the fixed effects from both the model fitted to the single-feature data and the model fitted to the double-feature data. Each of these samples includes an intercept (a), slope (D), non-decision time (ndt), and residual variance (σ). We then take the parameters from the double-feature model, but replace the D values with our predicted D using the single-feature model. Finally the predicted mean $\log(rt)$ is calculated for each feature and number of distractors. These are then compared to the empirical reaction times and we compute the absolute error.

We can also calculate an upper-bound by carrying out the above process, but without replacing the fitted $D_{c,s}$ with the predicted. This allows us to report ‘relative absolute error’. As all of the methods under consideration make identical predictions for trials with no distractors, these are omitted from this calculation.

The results of this procedure are in-line with the registered analysis presented above: all three methods perform well relative to our baseline (see Table 4), and thus we cannot make any strong conclusions related to hypothesis 4. All three contrast combination methods do a good job of accounting for the reaction time data collected.

metric	abs error		
	lower	median	upper
orthogonal	0.994	1.00	1.02
collinear	0.990	1.01	1.05
best feature	0.999	1.01	1.02

Table 4: How well can we predict RTs using D_p (collinear, best feature or orthogonal contrast) compared to using D_e ? A value of 1 means that our estimates of D derived from the single-feature trials does an equally good job at predicting the double-feature trials as using the D fit to the data.

6. Planned Explorations

Our interpretation of the null/neutral results for Hypothesis 4 (the prediction of reaction times) is that the differences in predictions from the three contrast combination methods are small relative to the (i) individual differences between participants and (ii) trial-to-trial variability due to target eccentricity. Thus, in our exploratory analysis, we investigate how incorporating these factors affects our conclusions.

6.1. Individual Differences

We start this exploratory analysis looking at how the D_c and D_s values vary from participant to participant. From Figure 5 (*left*) we can see that there is considerable variation between observers - in fact, the variation from one observer to the next is often larger than the variation across features. To investigate this further we calculated the correlations between each of the features, by calculating Pearson's r for each sample from our posterior, which gives us a full posterior distribution for the correlations. We can see in Figure 5 (*right*) that while both the D_c and D_s are correlated within feature classes (~ 0.75), there is no correlation of any of the colour features with any of the shape features. The individual differences for the *double-feature* conditions are much less pronounced - these conditions are easy and the search slopes are quite close to flat. Hence, the correlations are all much weaker, presumably due to range restriction.

Given these results, it is perhaps unsurprising that our analysis for Hypothesis 4 leads to an inconclusive result for distinguishing between the three contrast combination methods. Perhaps taking these individual differences into account when we predict reaction times will lead to improved power to discriminate between the models. However, before we do so, we will also investigate incorporating information about target eccentricity into the model.

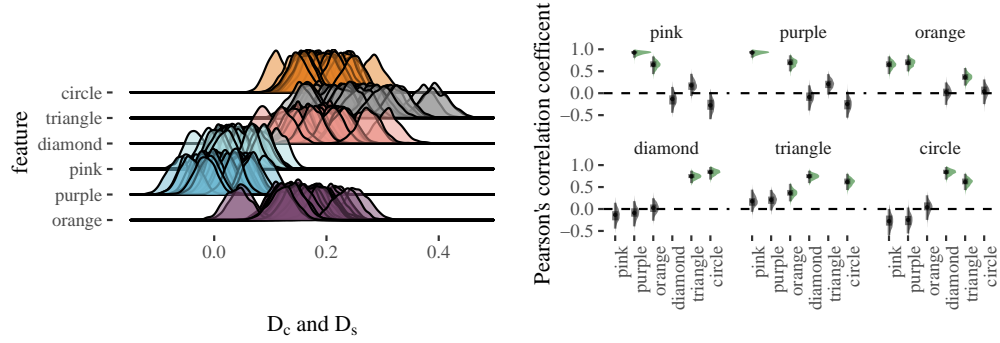


Figure 5: Individual differences in D_c and D_s . (left) Posterior probability distributions for D_c and D_s for each individual. (right) Estimated correlations between each of the D_c and D_s .

6.2. Target Eccentricity

It is well known that there are eccentricity effects in visual search, with reaction times being longer for targets that are further away from fixation (Carrasco et al., 1995; Wang et al., 2017). To investigate this in our dataset, we will use the same methods as above (fitting a multi-level shifted-lognormal model) but now including an additional factor that represents how far the target was from the fixation cross. This is coded as a three-level categorical factor representing which ring contained the target (see stimulus details, above). Allowing for interactions with the *feature* and $\log N_T$ increases the number of fixed effect parameters in the model from 8 to 22, with the model equation becoming the following:

$$y \sim 0 + r + r : f : \log(N_T) + (1|id) \quad (5)$$

We experimented with including r in the random effect structure, but this proved difficult to fit. We also had to revise the priors used in our registered analysis, in order to lower the intercept. Full details can be found in *Supplementary Materials - Planned Explorations*.

After obtaining a model that passed all convergence checks, we examined the posterior distribution for the effect of *ring*. Figure 6 paints an interesting and complex picture in which some features (e.g. some colours, particularly those that are more distinct from the target colour) are clearly leading to ‘pre-attentive search’ in which response times are unaffected by either the number of distractors or target eccentricity. However, shape features seem to be strongly affected by eccentricity, particularly when there are multiple distractors in the stimulus.

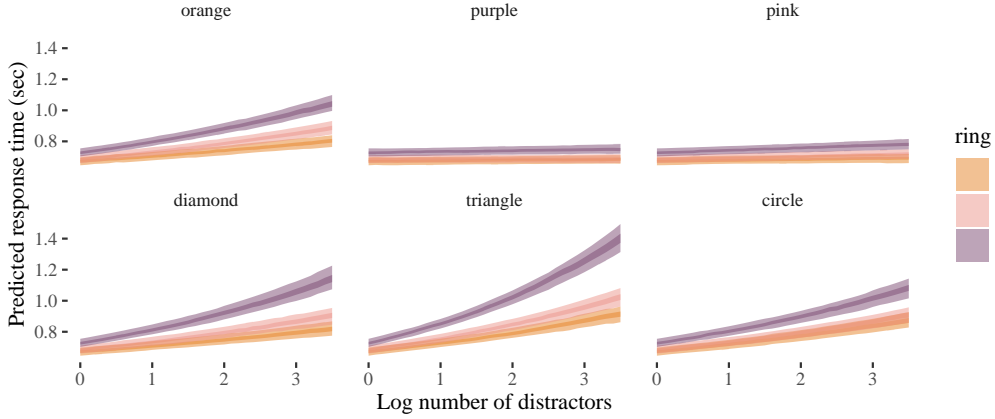


Figure 6: Fixed effects for predicting the effect of ring, feature and number of distractors on response times. Shaded regions represent the 53% and 97% HDICs. We can see that *ring* has an effect on search slopes, and that this effect is more pronounced for some features (i.e., triangles) than others.

585 We can now compute our predictions (D_p) for $D_{c,s}$ taking the *ring* into ac-
 586 count. Doing so leads us to a similar result as before with orthogonal contrast
 587 outperforming the best feature and collinear measures in terms of absolute error
 588 (0.023 compared to 0.025 (best feature) and 0.034 (collinear)). However, the re-
 589 gression slopes are all relatively similar (0.90 for best feature, 1.58 for collinear
 590 and 1.15 for orthogonal contrast). Thus, adding ring into the model does not dras-
 591 tically change our overall conclusions, with the orthogonal contrast model still
 592 giving the best prediction of search slopes in the double-feature condition.

593 6.3. Predicting Response Times

594 We will now test to see if we can discriminate between the three contrast
 595 combination methods when we take target eccentricity (ring) and individual-level
 596 slopes into account. We use the same model comparison as before (see *Supple-*
 597 *mentary Materials - Planned Explorations* for full code) and find orthogonal con-
 598 trast performs best, closely followed by best feature.

599 6.3.1. Issues with the Collinear Contrast method

600 In the previous model, the upper bound on the error in the collinear contrast
 601 method is high (see Table 5). To explain this, we can look back at Equation 4:
 602 when search slopes are close to 0, it is possible that we will observe negative
 603 values in the empirical data. Breaking down our data to compute search slopes

metric	abs error		
	lower	median	upper
orthogonal	1.01	1.00	1.04
collinear	1.03	1.00	5.15
best feature	1.03	1.00	1.07

Table 5: How well can we predict RTs using D_p (collinear, best feature or orthogonal contrast) compared to using D_e when using a model containing the ring of the target? A value of 1 means that our estimates of D derived from the single-feature trials does an equally good job at predicting the double-feature trials as using the D fit to the data.

for each person and each target eccentricity increases the chances of this being observed. Looking at Equation 4 we can see that in the case where both D_1 and D_2 are small but one is negative (i.e. $D_1 \sim -D_2$), then $1/D_1 + 1/D_2 \sim 0$. This leads to our estimated $D = \frac{1}{1/D_1 + 1/D_2} \gg D_1, D_2$ i.e. our estimated D is much larger than the slopes that were used to generate it, which is clearly incorrect. However, we do note that the main conclusions of our analyses still hold even if we remove these negative slopes (by restricting our analyses only to certain colours and rings of the data - see *Supplementary Materials: Suggestions from Reviewers* for more details), suggesting that addressing this mathematical issue may not necessarily lead to the collinear contrast method being preferred.

7. General Discussion

In this paper, we aimed to test the extent to which the results of Buetti et al. (2019) replicate and generalise, using a new modelling approach. Our results allow us to confirm our pre-registered hypotheses 1 and 2. Firstly, a shifted-lognormal distribution of response times outperforms normal and lognormal distributions, demonstrating that reaction time data are best modelled by a skewed distribution with an offset. Similarly, we confirmed that the number of distractors has a log-linear effect in this model, in line with the predictions of TCS theory. We also replicated other aspects of the original Buetti et al. (2019) paper with a different experimental set up, such as to observing shallower search slopes for colour features compared to shape features.

We do not find support for our pre-registered hypotheses 3 and 4. For predicting D in the double-feature conditions, our analyses found that the orthogonal contrast model was favoured over collinear, which is not in line with the registered hypothesis, which predicted that the collinear contrast model would be best (in line with Buetti et al. (2019)). Similarly, for hypothesis 4, we found that

630 there was relatively little difference between the three combination methods for
631 prediction of trial-by-trial reaction times. Our exploratory analyses suggest that
632 incorporating additional factors (e.g. individual differences in participant D_c and
633 D_s values, and the eccentricity of the target) allows better discrimination between
634 models, but again suggests that the orthogonal contrast combination method gives
635 the best predictions.

636 7.1. *Modelling of reaction times*

637 In much of the literature on visual search, mean reaction times are modelled
638 using a simple linear model $\bar{y} = bN_T + a$ (e.g. Treisman and Gormican (1988);
639 Rosenholtz et al. (2012); Hughes et al. (2016)). The b coefficients are often re-
640 ferred to as “search slopes” and are often treated as measurements of theoretical
641 importance. Our results indicate that a shifted-lognormal model that is loglinear
642 in N_T offers a much better fit to the data ($\log(y) - ndt = b \log(N_T) + a$), which
643 is perhaps not surprising, given the properties of reaction time data, where valid
644 responses normally begin at around 100ms, and the distribution often has a long
645 “tail” of slower responses.

646 However, there have been concerted efforts within the literature to model re-
647 action time distributions more effectively: indeed, Buetti et al. (2019) use $\log N_T$
648 when computing their search slopes. In terms of reaction time distributions, log
649 transformations are frequently taught as a way to normalise reaction time data (al-
650 though often with caveats regarding how this can change the interpretation of the
651 results e.g. Osborne (2002)) and are frequently used in analysing reaction time
652 data e.g. (Clarke et al., 2022b). Researchers have also looked at other distribu-
653 tions to assess which offer the best fit to empirical response times in visual search.
654 For example, Palmer et al. (2011) compared ex-Gaussian, ex-Wald, Gamma, and
655 Weibull distributions and found that the distributions with exponential compo-
656 nents offer a better fit to the data. Our results are in line with this. However,
657 we opted to use a shifted-lognormal distribution in our analysis above for mostly
658 pragmatic reasons, as these more complex distributions are often computationally
659 difficult to fit⁵. It has also been argued that trying to select a “correct” distribu-
660 tion is likely to be problematic for empirical data, which is probably a mixture
661 of multiple components (Wolfe et al., 2010). Similarly, some recent approaches
662 make use of drift-diffusion methods (e.g. Wolfe and Van Wert (2010); Yu et al.
663 (2022); Corbett and Smith (2020)), though again these models can be challenging,

⁵See: <https://discourse.mc-stan.org/t/model-fails-to-converge-when-using-brms/9062>

664 particularly when considering how to interpret the parameters (Evans and Wagen-
665 makers, 2019; Bompas et al., 2023). While important, these debates are outside
666 the scope of the present Registered Report.

667 Despite these previous findings, the use of linear search slopes is still prevalent
668 in the visual search literature. Our work shows that these choices of distribution
669 can influence results and conclusions (see section 7.2 below), and therefore we
670 recommend that other researchers consider carefully how they want to model their
671 data. Even in the case where the search slopes are the primary outcome measure
672 of interest (as opposed to the potentially more 'cognitive' parameters of e.g. Wald
673 distributions, or drift diffusion models), we demonstrate that approaches that bet-
674 ter account for the data distribution can be taken with relative ease. While trying
675 to decide on the best model may be a challenging task, our view is that the better
676 the underlying statistical model does in accounting for the data, the more credence
677 we can give to the inferences we draw from model parameters such as the slope.

678 7.2. *Discriminating between combination methods*

679 In Buetti et al. (2019), the collinear contrast integration model was found to
680 provide the best fit for their data, providing a more precise prediction than the
681 orthogonal contrast combination model (as measured by both the closeness of
682 the slope of the regression line to one, and the mean average prediction error).
683 Accepting this model of how the combination process works has theoretical im-
684 plications e.g. it implies that colour and shape contrasts independently contribute
685 to attentional guidance. However, we did not find strong support for this model,
686 instead finding that the orthogonal contrast combination model provides the best
687 fit with the data.

688 One possibility is that our small modifications to the experimental stimuli
689 changed the strategy that participants used. However, this seems unlikely given
690 that we only made changes to the colour of the stimuli, a manipulation that Buetti
691 et al. (2019) also used, with no changes to their overall conclusions. In addition,
692 our reanalysis of the original Buetti et al. (2019) data using our new methods also
693 suggested that the orthogonal contrast model was best supported. Thus, we sug-
694 gest that the choice of modelling distribution (e.g. shifted-lognormal v.s. lognor-
695 mal) affects the conclusions drawn, and thus we should aim to use the models that
696 best align with the data in order to better understand the theoretical implications
697 of our findings.

698 We also modified the way stimuli were presented in our experiment com-
699 pared to Buetti et al. (2019): rather than running each experiment separately, we
700 (mostly) intermixed conditions. Models of attention presume that we hold a target

template in our memory (Duncan and Humphreys, 1989), and thus we ensured that the trials where the target was the white semicircle were blocked separately from the trials where the target was the red semicircle, to try to avoid conflict between maintaining multiple target templates in memory. However, the distractors could change from trial to trial in all other blocks, unlike in Buetti et al. (2019). In their experiments, it is possible participants used strategies such as shifting the target representation away from the distractors, or generally using relational strategies (Navalpakkam and Itti, 2007; Becker, 2010; Yu et al., 2023), which would be more challenging in our experimental set up. In relation to the models, this type of target representation shift could occur more strongly for one feature dimension (e.g. colour) than the other, perhaps changing the relationship between the contrasts for different feature dimensions and therefore the preferred model. If future work were to confirm this hypothesis, it would suggest that observers are able to cognitively shift their strategy based on the information available in the task.

Another possibility is that because some participants had negative search slopes, the collinear contrast model predicts implausibly large reaction times, due to the mathematical formulation of this model, leading to worse predictions. Despite the fact that our exploratory analyses suggested that removing these negative slopes would not change our conclusions, we suggest that a future improvement for the collinear contrast integration model would be to modify it to be able to give sensible predictions in these situations, given that negative search slopes do occur in some situations (Utochkin, 2013).

Finally, we would argue that it is difficult from these results to definitively make a decision about which model is best: all three models give very similar predictive weights during our model evaluation process. One challenge is that in general, the double feature searches are easy, and therefore the search slopes are fairly flat and there is not much variability to allow different models to make different predictions. For the current paradigm, a fruitful approach for future research could be to consider using different feature sets, and in particular, moving away from colour as feature, which may be a particularly salient cue (see Section 7.2.3 below).

7.2.1. Individual differences

Our (planned) exploratory analysis of the individual differences in search slopes suggests that there are large differences from one observer to the next. Indeed in some cases, these are larger than the differences from one feature to another. The difference between the steepest and shallowest search slopes (fixed effects) is 0.238 ($D_{triangle} = 0.253$, while $D_{purple} = 0.015$). If we compare this to the range

of observer search slopes within a feature, we find this varies from 0.242 ($D_{triangle}$ per-observer ranges from 0.395 to 0.152) to 0.149 (D_{pink} ranges from -0.065 to 0.092). This suggests a challenge for modelling based on average performance: can we be sure that averages represent a meaningful summary of the data, given that we see very clear individual differences? It could certainly be argued that observers might be using different strategies, and thus some members of the sample population might use (for example) a collinear combination strategy, while others use an orthogonal contrast strategy (and we can see some hints of this when we plot the predictions of D separately for each participant in the *Supplementary Materials - Planned Explorations*). Variable strategies have been found for other search behaviour (Clarke et al., 2022a; Kristjánsson et al., 2014; Proulx, 2011; Li et al., 2022), highlighting the importance of considering individual differences when understanding behaviour.

We also found that search slopes were correlated within feature, but not between: i.e, knowing that an observer’s search slope for a colour condition allows us to predict their search slopes for the other colour conditions, but not any of the shape conditions. However, given the block design of our experiment, it is possible that this reflects a type of priming effect: knowing the search slope for a feature in the first block tells allows us to predict the search slopes of the other features in that block, but tells us nothing of the observer’s behaviour in the second block. Post-hoc analyses looking at correlations within the colour condition by block suggest that this seems unlikely to explain our results fully, as we still observe good correlations between different colour search slopes across blocks (see *Supplementary Materials - Suggestions from Reviewers* for further details). However, to test this fully we would need to design the experiment differently in order to avoid block confounds, allowing us to disentangle whether these correlations reflect something about an observer’s behaviour with different features, or instead how an observer’s behaviour changes over time.

7.2.2. Eccentricity

Buetti et al. (2019) argues that the processing undertaken in this type of task can be done in parallel, with observers using peripheral vision to distinguish between target and distractors, and that there is systematic variation in reaction times as a function of set size associated with parallel processing. Target Contrast Signal Theory incorporates eccentricity effects into this type of parallel processing via a time-out parameter (T_0) (Lleras et al., 2020; Wang et al., 2018; Ng et al., 2018). Here, we confirm in our exploratory analyses that we are able to detect relatively strong eccentricity effects, as a model with target ring number included

775 was a better predictor of the data than one without. However, including this factor
776 did not change our overall conclusions about which model best predicted D in the
777 double-feature condition, or which model best predicted reaction times.

778 In our experiment we followed Buetti et al. (2019)’s original methods, with
779 participants freely viewing the displays. It is therefore likely that in some cases,
780 observers felt that peripheral information was insufficient to make judgements,
781 and thus made eye movements, moving into a more serial, focused-attention pro-
782 cessing stage. Future work could more exclusively investigate peripheral effects
783 in parallel processing by ensuring fixation when viewing the displays.

784 7.2.3. *Limitations*

785 One limitation of the experimental approach may be the feature dimensions
786 chosen. We kept these the same as in Buetti et al. (2019) (colour and shape), but
787 there is good evidence that colour may in some ways be a ‘basic’ feature dimen-
788 sion that is particularly salient, especially in peripheral vision, whereas guidance
789 of attention by shape may be more complex (Wolfe, 2021). Mathematically, it
790 would be better to have features where the slope values across the two dimensions
791 are more similar, as all of the contrast combination formulae essentially consist of
792 sums of inverse values, and if the slope values are highly dissimilar, the inverse
793 sums will be disproportionately determined by one feature. This may indeed re-
794 flect how participants are approaching this task, as it may be the case that they
795 preferentially attend to the more discriminating feature (colour) and the contribu-
796 tion of shape to their behaviour in the double-feature condition may be negligible.
797 However, for the purposes of discriminating between the models, it would be ben-
798 efcial in future experiments to adjust the target set, perhaps by making the shape
799 dimension more salient (e.g. by increasing the size of the targets), or by selecting
800 a different pair of features (e.g. shape and orientation).

801 7.3. *Conclusions and future directions*

802 In the current paper, we have independently reproduced the findings of Buetti
803 et al. (2019) by extending their modelling to a multi-level framework. We have
804 used a Bayesian approach, but note that this is in many ways entirely arbitrary: all
805 of the modelling decisions we have taken would be possible within a frequentist
806 framework as well. We also aimed to replicate the previous findings by running
807 a within-subjects experiment, and broadly find that the Target Contrast Signal
808 Theory does a good job of predicting the data. When using single-feature search
809 slopes to predict double-feature search slopes, we do not replicate the previous
810 finding that the collinear contrast integration method outperforms other options,

811 but instead find that all combination methods do reasonably well, and in this par-
812 ticular experimental design, it may be difficult to conclusively distinguish between
813 them.

814 One of the clear benefits of Target Contrast Signal Theory (Lleras et al., 2020)
815 is its quantitative nature, allowing it to be empirically tested in a straightforward
816 manner. Here, we demonstrate that we can independently replicate many aspects
817 of TCS, while also offering extensions to the model that we hope will stimulate
818 more research and refinement of this theory. Some suggestions for possible future
819 directions and hypotheses that could be tested include:

- 820 1. It is relatively straightforward to make predictions about the mean reaction
821 time per participant in the double-feature search condition: however, we
822 have not attempted to predict an individual’s trial-to-trial variance for dif-
823 ferent features, which could improve the model fit further.
824
- 825 2. We find correlations within feature classes (i.e. D_c and D_s) but not between:
826 however, these may be a side-effect of the block design of the experiment.
827 A future experiment could randomise trial type in order to more fully un-
828 derstand the nature of these correlations.
829
- 830 3. To more fully explore which combination model best predicts the data, we
831 suggest a) modifying the collinear contrast model to accommodate negative
832 search slopes b) attempting to find experimental conditions that best dif-
833 ferentiate between the models, perhaps by using feature dimensions other
834 than colour and c) modifying the experimental design to enforce parallel
835 processing e.g. by making the display gaze contingent.

836 Computational modelling approaches alongside detailed, quantitative theory
837 building has been argued to be one way to improve the reliability of psycho-
838 logical research (Oberauer and Lewandowsky, 2019; Guest and Martin, 2021).
839 By combining this approach with fully open datasets and analysis scripts, we
840 can hopefully begin to take a more “distributed collaborative network” approach
841 (Moshontz et al., 2018) to our scientific questions. As such, we would like to
842 conclude by encouraging other researchers to critique, build on and improve the
843 approach we have taken in this manuscript, in order to further improve our ability
844 to model performance in visual search tasks.

845 **Conflict of interest**

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

847 **Acknowledgements**

848 This work was supported by an Economic and Social Research Council grant
849 (ES/S016120/1) to ADFC and employing AN. We thank the reviewers for their
850 helpful comments which greatly improved the manuscript.

851 **References**

- 852 Stefanie I Becker. The role of target–distractor relationships in guiding attention
853 and the eyes in visual search. *Journal of Experimental Psychology: General*,
854 139(2):247, 2010.
- 855 Stefanie I Becker, Christian Valuch, and Ulrich Ansorge. Color priming in pop-
856 out search depends on the relative color of the target. *Frontiers in psychology*,
857 5:289, 2014.
- 858 Aline Bompas, Petroc Sumner, and Craig Hedge. Non-decision time: the higg’s
859 boson of decision. *bioRxiv*, pages 2023–02, 2023.
- 860 Simona Buetti, Deborah A Cronin, Anna M Madison, Zhiyuan Wang, and Ale-
861 jandro Lleras. Towards a better understanding of parallel visual processing in
862 human vision: Evidence for exhaustive analysis of visual information. *Journal*
863 *of Experimental Psychology: General*, 145(6):672, 2016.
- 864 Simona Buetti, Jing Xu, and Alejandro Lleras. Predicting how color and shape
865 combine in the human visual system to direct attention. *Scientific reports*, 9(1):
866 1–11, 2019.
- 867 Marisa Carrasco, Denise L Evert, Irene Chang, and Svetlana M Katz. The eccen-
868 tricity effect: Target eccentricity affects performance on conjunction searches.
869 *Perception & psychophysics*, 57:1241–1261, 1995.
- 870 Kyle R Cave and Jeremy M Wolfe. Modeling the role of parallel processing in
871 visual search. *Cognitive psychology*, 22(2):225–271, 1990.

- 872 Alasdair DF Clarke, Jessica L Irons, Warren James, Andrew B Leber, and
873 Amelia R Hunt. Stable individual differences in strategies within, but not be-
874 tween, visual search tasks. *Quarterly Journal of Experimental Psychology*, 75
875 (2):289–296, 2022a.
- 876 Alasdair DF Clarke, Anna Nowakowska, and Amelia R Hunt. Visual search habits
877 and the spatial structure of scenes. *Attention, Perception, & Psychophysics*, 84
878 (6):1874–1885, 2022b.
- 879 Elaine A Corbett and Philip L Smith. A diffusion model analysis of target detec-
880 tion in near-threshold visual search. *Cognitive Psychology*, 120:101289, 2020.
- 881 John Duncan and Glyn W Humphreys. Visual search and stimulus similarity.
882 *Psychological review*, 96(3):433, 1989.
- 883 Nathan J Evans and Eric-Jan Wagenmakers. Evidence accumulation models: Cur-
884 rent limitations and future directions. 2019.
- 885 Andrew Gelman and Jennifer Hill. *Data analysis using regression and multi-*
886 *level/hierarchical models*. Cambridge university press, 2006.
- 887 Olivia Guest and Andrea E Martin. How computational modeling can force theory
888 building in psychological science. *Perspectives on Psychological Science*, 16
889 (4):789–802, 2021.
- 890 Anna E Hughes, Rosy V Southwell, Iain D Gilchrist, and David J Tolhurst. Quan-
891 tifying peripheral and foveal perceived differences in natural image patches to
892 predict visual search performance. *Journal of vision*, 16(10):18–18, 2016.
- 893 Johan Hulleman and Christian NL Olivers. On the brink: The demise of the item
894 in visual search moves closer. *Behavioral and Brain Sciences*, 40, 2017.
- 895 Jessica L Irons and Andrew B Leber. Choosing attentional control settings in a
896 dynamically changing environment. *Attention, Perception, & Psychophysics*,
897 78(7):2031–2048, 2016.
- 898 Jessica L Irons and Andrew B Leber. Characterizing individual variation in the
899 strategic use of attentional control. *Journal of Experimental Psychology: Hu-*
900 *man Perception and Performance*, 44(10):1637, 2018.
- 901 Laurent Itti and Christof Koch. A saliency-based search mechanism for overt and
902 covert shifts of visual attention. *Vision research*, 40(10-12):1489–1506, 2000.

- 903 Laurent Itti, Christof Koch, and Ernst Niebur. A model of saliency-based visual
 904 attention for rapid scene analysis. *IEEE Transactions on pattern analysis and*
 905 *machine intelligence*, 20(11):1254–1259, 1998.
- 906 Paul D Kieffaber, Emily S Kappenman, Misty Bodkins, Anantha Shekhar, Brian F
 907 O’Donnell, and William P Hetrick. Switch and maintenance of task set in
 908 schizophrenia. *Schizophrenia research*, 84(2-3):345–358, 2006.
- 909 Christof Koch and Shimon Ullman. Shifts in selective visual attention: towards
 910 the underlying neural circuitry. In *Matters of intelligence*, pages 115–141.
 911 Springer, 1987.
- 912 Kathryn Koehler, Fei Guo, Sheng Zhang, and Miguel P Eckstein. What do
 913 saliency models predict? *Journal of vision*, 14(3):14–14, 2014.
- 914 Iuliia Kotseruba, Calden Wloka, Amir Rasouli, and John K Tsotsos. Do saliency
 915 models detect odd-one-out targets? new datasets and evaluations. *arXiv*
 916 *preprint arXiv:2005.06583*, 2020.
- 917 Árni Kristjánsson, Ómar I Jóhannesson, and Ian M Thornton. Common attentional
 918 constraints in visual foraging. *PloS one*, 9(6):e100752, 2014.
- 919 Joseph Krummenacher and Hermann J Müller. Dynamic weighting of feature di-
 920 mensions in visual search: behavioral and psychophysiological evidence. *Fron-*
 921 *tiers in psychology*, 3:221, 2012.
- 922 Walden Y Li, Molly R McKinney, Jessica L Irons, and Andrew B Leber. As-
 923 sessing the generality of strategy optimization across distinct attentional tasks.
 924 *Journal of Experimental Psychology: Human Perception and Performance*, 48
 925 (6):582, 2022.
- 926 Heinrich René Liesefeld and Hermann J Müller. A theoretical attempt to revive
 927 the serial/parallel-search dichotomy. *Attention, Perception, & Psychophysics*,
 928 82(1):228–245, 2020.
- 929 Heinrich René Liesefeld, Rani Moran, Marius Usher, Hermann J Müller, and
 930 Michael Zehetleitner. Search efficiency as a function of target saliency: The
 931 transition from inefficient to efficient search and beyond. *Journal of Experi-*
 932 *mental Psychology: Human Perception and Performance*, 42(6):821, 2016.

- 933 Alejandro Lleras, Zhiyuan Wang, Anna Madison, and Simona Buetti. Predicting
934 search performance in heterogeneous scenes: Quantifying the impact of homo-
935 geneity effects in efficient search. *Collabra: Psychology*, 5(1), 2019.
- 936 Alejandro Lleras, Zhiyuan Wang, Gavin Jun Peng Ng, Kirk Ballew, Jing Xu, and
937 Simona Buetti. A target contrast signal theory of parallel processing in goal-
938 directed search. *Attention, Perception, & Psychophysics*, pages 1–32, 2020.
- 939 Anna Madison, Alejandro Lleras, and Simona Buetti. The role of crowding in par-
940 allel search: Peripheral pooling is not responsible for logarithmic efficiency in
941 parallel search. *Attention, Perception, & Psychophysics*, 80(2):352–373, 2018.
- 942 Dora Matzke and Eric-Jan Wagenmakers. Psychological interpretation of the ex-
943 gaussian and shifted wald parameters: A diffusion model analysis. *Psycho-*
944 *nomic bulletin & review*, 16(5):798–817, 2009.
- 945 Richard McElreath. *Statistical rethinking: A Bayesian course with examples in R*
946 *and Stan*. Chapman and Hall/CRC, 2020.
- 947 Rani Moran, Michael Zehetleitner, Hermann J Mueller, and Marius Usher. Com-
948 petitive guided search: Meeting the challenge of benchmark rt distributions.
949 *Journal of Vision*, 13(8):24–24, 2013.
- 950 Rani Moran, Michael Zehetleitner, Heinrich René Liesefeld, Hermann J Müller,
951 and Marius Usher. Serial vs. parallel models of attention in visual search: ac-
952 counting for benchmark rt-distributions. *Psychonomic bulletin & review*, 23(5):
953 1300–1315, 2016.
- 954 Rani Moran, Heinrich René Liesefeld, Marius Usher, and Hermann J Muller. An
955 appeal against the item’s death sentence: Accounting for diagnostic data pat-
956 terns with an item-based model of visual search. *Behavioral and Brain Sci-*
957 *ences*, 40:e148, 2017.
- 958 J Toby Mordkoff and Steven Yantis. An interactive race model of divided at-
959 tention. *Journal of Experimental Psychology: Human Perception and Perform-*
960 *ance*, 17(2):520, 1991.
- 961 Hannah Moshontz, Lorne Campbell, Charles R Ebersole, Hans IJzerman,
962 Heather L Urry, Patrick S Forscher, Jon E Grahe, Randy J McCarthy, Erica D
963 Musser, Jan Antfolk, et al. The psychological science accelerator: Advancing

- 964 psychology through a distributed collaborative network. *Advances in Methods*
965 *and Practices in Psychological Science*, 1(4):501–515, 2018.
- 966 Vidhya Navalpakkam and Laurent Itti. Search goal tunes visual features optimally.
967 *Neuron*, 53(4):605–617, 2007.
- 968 Gavin JP Ng, Simona Buetti, Trisha N Patel, and Alejandro Lleras. Prioritiza-
969 tion in visual attention does not work the way you think it does. *Journal of*
970 *Experimental Psychology: Human Perception and Performance*, 2020.
- 971 Gavin Jun Peng Ng, Alejandro Lleras, and Simona Buetti. Fixed-target efficient
972 search has logarithmic efficiency with and without eye movements. *Attention,*
973 *Perception, & Psychophysics*, 80(7):1752–1762, 2018.
- 974 Anna Nowakowska, Alasdair DF Clarke, and Amelia R Hunt. Human visual
975 search behaviour is far from ideal. *Proceedings of the Royal Society B: Biolog-*
976 *ical Sciences*, 284(1849):20162767, 2017.
- 977 Klaus Oberauer and Stephan Lewandowsky. Addressing the theory crisis in psy-
978 chology. *Psychonomic bulletin & review*, 26:1596–1618, 2019.
- 979 Jason Osborne. Notes on the use of data transformations. *Practical assessment,*
980 *research, and evaluation*, 8(1):6, 2002.
- 981 Evan M Palmer, Todd S Horowitz, Antonio Torralba, and Jeremy M Wolfe. What
982 are the shapes of response time distributions in visual search? *Journal of ex-*
983 *perimental psychology: human perception and performance*, 37(1):58, 2011.
- 984 Derrick Parkhurst, Klinto Law, and Ernst Niebur. Modeling the role of salience
985 in the allocation of overt visual attention. *Vision research*, 42(1):107–123, 2002.
- 986 Jonathan Peirce, Jeremy R Gray, Sol Simpson, Michael MacAskill, Richard
987 Höchenberger, Hiroyuki Sogo, Erik Kastman, and Jonas Kristoffer Lindeløv.
988 Psychopy2: Experiments in behavior made easy. *Behavior research methods,*
989 *51(1):195–203*, 2019.
- 990 Michael J Proulx. Individual differences and metacognitive knowledge of visual
991 search strategy. *PLoS One*, 6(10):e27043, 2011.
- 992 Dragan Rangelov, Hermann J Müller, and Michael Zehetleitner. Failure to pop
993 out: Feature singletons do not capture attention under low signal-to-noise ratio
994 conditions. *Journal of Experimental Psychology: General*, 146(5):651, 2017.

- 995 Ruth Rosenholtz, Jie Huang, Alvin Raj, Benjamin J Balas, and Livia Ilie. A sum-
 996 mary statistic representation in peripheral vision explains visual search. *Journal*
 997 *of vision*, 12(4):14–14, 2012.
- 998 Benjamin W Tatler. The central fixation bias in scene viewing: Selecting an op-
 999 timal viewing position independently of motor biases and image feature distri-
 1000 butions. *Journal of vision*, 7(14):4–4, 2007.
- 1001 Benjamin W Tatler, Mary M Hayhoe, Michael F Land, and Dana H Ballard. Eye
 1002 guidance in natural vision: Reinterpreting salience. *Journal of vision*, 11(5):
 1003 5–5, 2011.
- 1004 Anne Treisman and Stephen Gormican. Feature analysis in early vision: evidence
 1005 from search asymmetries. *Psychological review*, 95(1):15, 1988.
- 1006 Anne M Treisman and Garry Gelade. A feature-integration theory of attention.
 1007 *Cognitive psychology*, 12(1):97–136, 1980.
- 1008 Igor S Utochkin. Visual search with negative slopes: The statistical power of
 1009 numerosity guides attention. *Journal of vision*, 13(3):18–18, 2013.
- 1010 Zhiyuan Wang, Simona Buetti, and Alejandro Lleras. Predicting search perfor-
 1011 mance in heterogeneous visual search scenes with real-world objects. *Collabra:*
 1012 *Psychology*, 3(1), 2017.
- 1013 Zhiyuan Wang, Alejandro Lleras, and Simona Buetti. Parallel, exhaustive process-
 1014 ing underlies logarithmic search functions: Visual search with cortical magni-
 1015 fication. *Psychonomic bulletin & review*, 25:1343–1350, 2018.
- 1016 Jeremy M Wolfe. What can 1 million trials tell us about visual search? *Psycho-*
 1017 *logical Science*, 9(1):33–39, 1998.
- 1018 Jeremy M Wolfe. Approaches to visual search: Feature integration theory and
 1019 guided search. *Oxford handbook of attention*, pages 11–55, 2014.
- 1020 Jeremy M Wolfe. Guided search 6.0: An updated model of visual search. *Psy-*
 1021 *chonomic Bulletin & Review*, 28(4):1060–1092, 2021.
- 1022 Jeremy M Wolfe and Michael J Van Wert. Varying target prevalence reveals two
 1023 dissociable decision criteria in visual search. *Current biology*, 20(2):121–124,
 1024 2010.

- 1025 Jeremy M Wolfe, Kyle R Cave, and Susan L Franzel. Guided search: an alterna-
1026 tive to the feature integration model for visual search. *Journal of Experimental*
1027 *Psychology: Human perception and performance*, 15(3):419, 1989.
- 1028 Jeremy M Wolfe, Evan M Palmer, and Todd S Horowitz. Reaction time distri-
1029 butions constrain models of visual search. *Vision research*, 50(14):1304–1311,
1030 2010.
- 1031 Zoe Jing Xu, Alejandro Lleras, and Simona Buetti. Predicting how surface texture
1032 and shape combine in the human visual system to direct attention. *Scientific*
1033 *reports*, 11(1):1–13, 2021.
- 1034 Xinger Yu, Timothy D Hanks, and Joy J Geng. Attentional guidance and match
1035 decisions rely on different template information during visual search. *Psycho-*
1036 *logical science*, 33(1):105–120, 2022.
- 1037 Xinger Yu, Zhiheng Zhou, Stefanie I Becker, Sage EP Boettcher, and Joy J Geng.
1038 Good-enough attentional guidance. *Trends in Cognitive Sciences*, 2023.
- 1039 Lingyun Zhang, Matthew H Tong, Tim K Marks, Honghao Shan, and Garrison W
1040 Cottrell. Sun: A bayesian framework for saliency using natural statistics. *Jour-*
1041 *nal of vision*, 8(7):32–32, 2008.