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## Original Articles

## Dynamics of visual attention revealed in foraging tasks

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## ABSTRACT

Visual search tasks play a key role in theories of visual attention. But single-target search tasks may provide only a snapshot of attentional orienting. Foraging tasks with multiple targets of different types arguably provide a closer analogy to everyday attentional processing. Set-size effects have in the literature formed the basis for inferring how attention operates during visual search. We therefore measured the effects of absolute set-size (constant target-distractor ratio) and relative set-size (constant set-size but target-distractor ratio varies) on foraging patterns during “feature” foraging (targets differed from distractors on a single feature) and “conjunction” foraging (targets differed from distractors on a combination of two features). Patterns of runs of same target-type selection were similar regardless of whether absolute or relative set-size varied: long sequential runs during conjunction foraging but rapid switching between target types during feature foraging. But although foraging strategies differed between feature and conjunction foraging, surprisingly, intertarget times throughout foraging trials did not differ much between the conditions. Typical response time by set-size patterns for single-target visual search tasks were only observed for the last target during foraging. Furthermore, the foraging patterns within trials involved several distinct phases, that may serve as markers of particular attentional operations. Foraging tasks provide a remarkably intricate picture of attentional selection, far more detailed than traditional single-target visual search tasks, and well-known theories of visual attention have difficulty accounting for key aspects of the observed foraging patterns. Finally, we discuss how theoretical conceptions of attention could be modified to account for these effects.

## 1. Introduction

At the supermarket, after the cashier rings up your purchases, you have to pay €4.58. Searching through your pockets you find a handful of coins. How do you pick the required ones? Do you grab a cent, then a 1 Euro coin, another cent and a fifty-cent coin in random order? As you pick the coins you perform a foraging task, where you search for multiple targets among distractors (the coins you will not need).

Foraging has typically been studied in animals (Bond, 1983; Dawkins, 1971; Tinbergen, 1960; see Scharf, Lubin, & Ovadia, 2011), but recently foraging has been used to investigate visual orienting and visual attention in humans (e.g. Wolfe, 2013; Kristjánsson, Jóhannesson, & Thornton, 2014; Kristjánsson & Kristjánsson, 2018; Gilchrist, North, & Hood, 2001; Hills, Kalf, & Wiener, 2013). Foraging tasks may provide insights into operational principles of visual attention, over and above single target visual search tasks, since the goals during daily interaction with the environment are typically unlikely to

involve only a single target (Cain, Vul, Clark, & Mitroff, 2012; Fougny, Cormiea, Zhang, Alvarez, & Wolfe, 2015; Gilchrist et al., 2001; Jóhannesson, Kristjánsson, & Thornton, 2017; Jóhannesson, Thornton, Smith, Chetverikov, & Kristjánsson, 2016; Wolfe, 2013).

Kristjánsson et al. (2014) introduced an easily administrable laboratory version of such foraging tasks. Observers foraged on iPads for 40 targets (e.g. 20 red and 20 green) among 40 distractor items (e.g. 20 blue and 20 yellow). They had to tap all targets, which disappeared once tapped, as quickly as possible while avoiding mistakes. During ‘feature’ foraging, the target categories were defined by different colors only, while during ‘conjunction’ foraging the target categories were defined by color and shape. Observers were, in general, able to switch repeatedly between different target types during feature foraging, while during conjunction foraging most observers selected the same target types repeatedly (see e.g. Williams, 1966). Increased target complexity has indeed been thought to increase the attentional load of foraging tasks (Dukas & Kamil, 2001; Kristjánsson et al., 2014; Vreven & Blough,

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**Table 1**  
Definitions of terms used to describe foraging patterns.

<i>Run behavior/Run number/Run length</i>	Do observers select the same target type repeatedly until all are gone or select different target types randomly? A run is the repeated consecutive selection of the same target type. For example, when a foraging task involves two target types, <i>run number</i> ranges from 2 (all targets of one type are tapped before participants switch to the other type) to the total number of targets (participants always switch between target types). <i>Run length</i> refers to how many targets of the same type are selected within a run.
<i>Run length distribution</i>	The number of runs on individual foraging trials is tallied in a histogram, revealing how often observers perform the foraging task using a particular number of runs. If observers forage randomly, the distribution should be roughly Gaussian around a mean of target number/number of target categories. If they forage systematically the distributions should be skewed.
<i>Collection rate</i>	A measure of how quickly target items are collected, typically measured as number of items per second.
<i>Intertarget times/<math>\Delta</math>ITTs</i>	The length of the interval between each target selection <i>within</i> a foraging trial. Note that $\Delta$ ITTs can also be calculated as the difference between an ITT and the previous ITT. Decreasing $\Delta$ ITTs indicate that the foraging becomes faster while positive $\Delta$ ITTs indicate that foraging is slowing down.
<i>Cruise phase</i>	The phase during foraging trials where intertarget times are low and constant from one selection to the next. Typically excludes the first and last target selection during the foraging trial.
<i>Mid-peaks</i>	Are seen in difficult foraging tasks (e.g. conjunction foraging) and reflect when observers switch between target categories.
<i>End-peaks</i>	End-peaks are seen at the end of foraging trials in tasks where observers must find all targets before the task finishes.
<i>Switch Costs</i>	The increase in ITTs when observers switch between target types.

1998). When load is high because targets are complex or hard to distinguish from distractors, such as during conjunction foraging, animals and humans have been shown to repeatedly select one target type even when another target type is closer to the focus of attention (Bond, 1982; Dukas, 2002; Kristjánsson et al., 2014). Such above-chance repeated selection from the same target category is referred to as ‘run behavior’ (Bond, 1983; Dawkins, 1971; Tinbergen, 1960; see definitions in Table 1).

But foraging patterns are not the only interesting aspect of such tasks. Intertarget times (ITTs; see Table 1), or the time between individual selections of the target, is another performance measure (related to collection rates in studies where observers can move to a new source of targets before all are finished, so-called ‘patch leaving’; e.g. Wolfe, 2013). In single-target search, response times reflect a single selection from the search array. During multi-target foraging, however, ITT’s change throughout the trial, providing additional information about attentional orienting (Ólafsdóttir, Kristjánsson, Gestsdóttir, Jóhannesson, & Kristjánsson, 2016). Ólafsdóttir et al. (2016, 2019) found that the intertarget times change in systematic ways as a function of when during the within-trial sequence each target selection occurred and also by the attentional load of the task, whether it involves foraging for targets defined by a single feature or by a conjunction of features. During both feature and conjunction foraging most selections were fast, during what has been called the *cruise phase* (see Table 1) except for the first and last trials of the foraging trial. These increases for the last selections have been called *end-peaks* (see Table 1) and may reflect that observers have trouble finding the last target. Finally, a difference in the foraging patterns were found between feature and conjunction foraging in that in the latter case there were distinct *mid-peaks* (see Table 1) where observers switched between target types, reflecting the cost of switching between the target types. No such mid-peaks occurred during feature foraging, and this is consistent with the run behavior since during feature foraging, observers seem to have no difficulty switching between target types. Those results call for a more thorough investigation of these patterns in the intertarget times since each characteristic in the foraging pattern may serve as a marker of particular attentional operations.

### 1.1. Set-size effects

It might be argued that many models of visual search specifically, and visual attention more broadly, were partly built to explain set-size effects. One finding in particular – that response times during feature search are minimally affected by increased set-size while conjunction search response times increase close to linearly with increased set-size – has generated much interest (Treisman & Gelade, 1980; Palmer, 1994; Wolfe, Cave, & Franzel, 1989; see Kristjánsson, 2015, 2016; Wolfe, 2016 for recent discussion). A theme in this literature is the two-stage

distinction between preattentive (parallel) and attentive (serial) processing (Egeth, 1966; Krummenacher, Grubert, & Müller, 2010; Neisser, 1963) and that if response times increase with set-size, this reflects that attention is required for the search. Foraging has many similarities with visual search, while there are also notable differences. Both tasks involve visual selection of predefined aspects of the presented stimuli but during foraging observers have more freedom as there are more targets. Because of this similarity in function, there is almost certainly considerable overlap in mechanisms, both functionally and in terms of neural mechanisms such as the mechanisms involved in top-down guidance of attention (Corbetta & Shulman, 2002; Desimone & Duncan, 1995), while foraging tasks may involve a more strategic component (Charnov, 1976; Kristjánsson, Ólafsdóttir, & Kristjánsson, 2019; Wolfe, 2013).

Set-size effects on foraging are yet to be systematically measured. There are studies where either the absolute set-size (e.g. Wolfe, 2013) or relative set-size (e.g. Cain et al., 2012; Fougny et al., 2015) have been varied. But studying either one in isolation entails a problem. Each tap on a target reduces set-size by one, but not only set-size changes. As a target is tapped and disappears, the ratio of targets versus distractors also changes. For example, in Jóhannesson et al. (2016) and Ólafsdóttir et al. (2016) there were 80 stimuli on the screen and 50% were targets. But for a set-size of 60 (after participants tap 20 targets) the target/distractor ratio dropped to 33.33% and down to 2.4% for the last target. Any changes in performance could therefore be explained by decreasing target to distractor ratio or with decreasing set-size. Furthermore, if similar set-size effects hold for foraging as for single-target search, these two factors should counteract one another, possibly masking any changes in foraging patterns or foraging speed: As set-size decreases, foraging should be faster on average, at least during conjunction foraging. But as target to distractor ratio decreases, foraging times per target should increase.

### 1.2. The current study

Our aim was to better understand the processes that underlie foraging by analyzing foraging patterns throughout trials, since previous results have indicated that these patterns show characteristic markers (Ólafsdóttir et al., 2016) that are discussed above and defined in Table 1. Our second aim was to investigate effects of set-size upon foraging performance for a more thorough understanding of the relation between foraging and findings from the visual search literature.

But as explained above, measuring set-size effects in visual foraging is not quite straightforward. We therefore measured the effects of both relative and absolute set-size on feature and conjunction foraging. In Experiment 1, we manipulated absolute set-size by using four different set-sizes. In Experiment 2, we manipulated relative set-size by using three different target/distractor ratios holding absolute set-size

constant.

In line with previous foraging results (Jóhannesson et al., 2016; Kristjánsson et al., 2014; Ólafsdóttir et al., 2016) and the single-target search literature (Treisman & Gelade, 1980; Wolfe, 1994), we predicted that ITTs during foraging would be faster for smaller initial set-sizes and faster for higher target to distractor starting ratios. We did not expect ITTs throughout each foraging trial to differ between the different set-size manipulations, however, as decreasing set-size and decreasing target to distractor ratio should cancel out. However, if either absolute or relative set-size affect foraging more than the other, larger interactions between condition and intertarget times might occur for one experiment over the other. We also assessed any changes in foraging patterns (i.e., run behavior, see Table 1) as a function of absolute or relative set-size. In line with previous results (2017; Jóhannesson et al., 2016; Kristjánsson et al., 2014; Ólafsdóttir et al., 2016) we expected that run number would, overall, be close to random during feature foraging, while during conjunction foraging, run number distributions should be highly positively skewed with a large peak at two runs. Finally, we measured any effects of the set-size manipulations upon intertarget times and the within-trial performance markers found in previous studies.

## 2. Experiment 1 – Absolute set-size

### 2.1. Method

#### 2.1.1. Participants

Thirteen unpaid volunteers from the University of Iceland (10 female; aged between 20 and 45 years old,  $M = 24.5$ ) participated. All reported normal or corrected to normal vision, were right handed and gave written, informed consent. All aspects of the experiment were approved by the appropriate ethical committee and conformed to the Declaration of Helsinki for testing human participants.

#### 2.1.2. Equipment

The stimuli were displayed on an iPad 2 with screen dimensions of  $20 \times 15$  cm and an effective resolution of  $1024 \times 768$  pixels. The iPad was placed on a table in front of participants in landscape mode, so that viewing distance was approximately 60 cm. Stimulus presentation and response collection were carried out with a custom iPad application written in Swift using Xcode.

#### 2.1.3. Stimuli

During feature-based foraging, targets were red and green disks and distractors were yellow and blue disks for half the participants while for the other half this was reversed. During conjunction foraging, the targets were red squares and green disks and the distractors were green squares and red disks for half the participants (reversed for the others). There were four different set-sizes, 80, 60, 40 and 20, and four stimulus groups, each consisting of  $\frac{1}{4}$  of the set-size, drawn on a black background (see Fig. 1). The diameter of targets and distractors was 20 pixels, approximately  $0.37^\circ$  of visual angle.

The items were randomly distributed across a non-visible  $10 \times 8$  grid offset from the edge of the screen by  $150 \times 100$  pixels. The whole viewing area therefore occupied  $15 \times 12$  cm (approximately  $14.3 \times 11.4^\circ$ ). The exact position of individual items within the grid was jittered by adding a random horizontal and vertical offset ( $x/2 - y*x$  where  $x$  is the maximal jitter and  $y$  a random value from 0 to 1) to create less uniform appearance. Gaps between rows and columns ensured that items never approached or occluded one another. The overall spatial layout and location of targets and distractors was generated independently for each trial.

#### 2.1.4. Procedure

The experiments were run in a small room with minimal distraction from overhead lighting. On each trial, participants were instructed to

tap all targets as quickly as possible using the index finger of their dominant hand. A counter at the bottom of the screen indicated the number of completed trials. Participants were to finish eight blocks of 20 trials. One trial refers to a completed sequence where all 10, 20, 30 or 40 targets were tapped (for set-sizes 20, 40, 60 and 80 respectively). They could take a break between any of the blocks. They started with two practice trials, to familiarize themselves with the iPad and the stimuli and the iPad touch screen. After initial set up, the experiment started and participants pressed a “play” button on the screen when ready, and the stimuli subsequently appeared. The targets disappeared immediately once tapped. If participants tapped a distractor, the trial ended, an error message was given, and they could start a new trial by pressing the play button. When all targets had been tapped, a smiley face appeared along with feedback about total trial time. Participants started the next trial by tapping the “play” button. Condition order was counterbalanced so that half the participants started with conjunction foraging and the other half started with feature foraging. Within the two conditions the set-size order was counterbalanced so that half the participants performed the conditions in an increasing-decreasing order (20-40-60-80-80-60-40-20) while the other half performed them in decreasing-increasing order.

#### 2.1.5. Data analysis

We measured the total number of runs on each trial, which can range from 2 (all targets of one type are tapped before participants switch to the other type) to the total number of targets (where participants always switch between target types, see Table 1). The total number of targets ranged from 10 to 40 depending on the set-size. If observers forage randomly (pick targets regardless of type) we should expect the number of runs to be normally distributed around target number/2 (Kristjánsson et al., 2014). We also measured intertarget times (ITTs) the time between taps on each target, which allow assessment of the cruise phase, mid-peaks and end-peaks (these dependent variables are defined in Table 1). For Experiment 1, if nothing else is stated, the independent variables in the repeated measures ANOVAs were condition (feature vs conjunction) and set-size (20, 40, 60 and 80). When variables had more than two levels, the Greenhouse-Geisser correction was used for the degrees of freedom to correct for non-sphericity. Before analysis, taps on empty areas of the iPad screen and all taps on incomplete trials were filtered out. For each dependent variable, averages were calculated for each participant for each condition ( $4 \times 2$  in Experiment 1 and  $3 \times 2$  in Experiment 2) and all outliers (more than 3 SDs away from the mean for each participant in each condition) were removed.

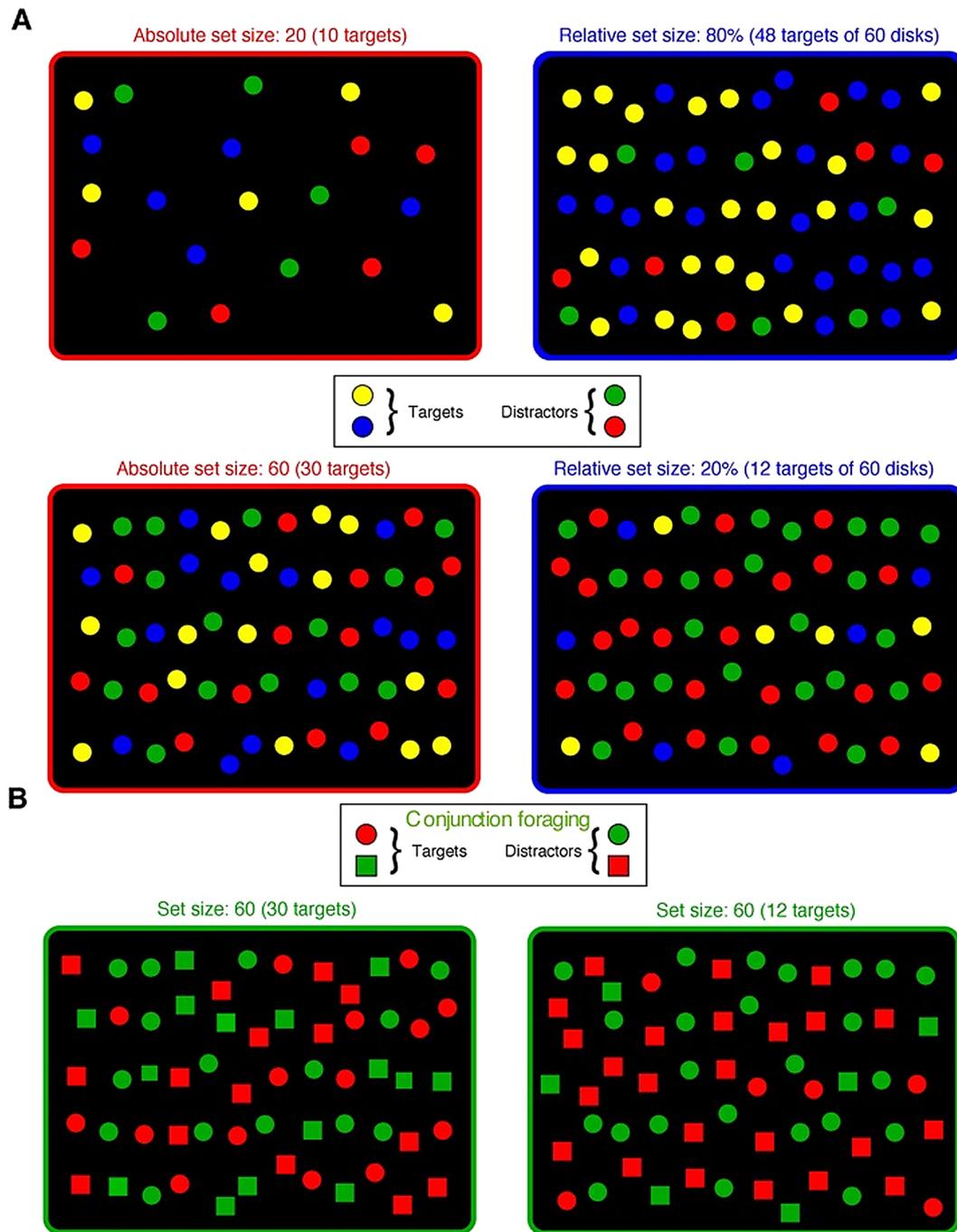
## 3. Results

Note that key concepts we use in assessing foraging performance are explained in Table 1.

### 3.1. Run behavior

Histograms showing the run numbers within each foraging trial are shown in Fig. 2 for the two conditions (descriptive statistics shown in Table 2). Two things are particularly notable: During feature foraging, run numbers separate into four distinct distributions by set-size. This is to be expected if run number is random, as target numbers (50% of the set-size) differ for each set-size. Secondly, during conjunction foraging, run number distributions do not vary by set-size, rather, distributions for all set-sizes are highly skewed with a peak at two runs, regardless of set-size.

A 2 (feature and conjunction)  $\times$  4 (set-size 20, 40, 60 and 80) repeated measures ANOVA on the average run number confirmed significant main effects of both condition,  $F(1,11) = 107.05$   $p < .001$   $\eta_p^2 = 0.91$ , and set-size,  $F(1.33,14.58) = 42.66$   $p < .001$   $\eta_p^2 = 0.80$ . The



**Fig. 1.** Examples of the stimuli and the manipulations of absolute set-size (Experiment 1) and relative set-size (Experiment 2). Panel A shows examples of feature foraging and Panel B shows examples of conjunction foraging. Note that for illustrative purposes the set-sizes shown do not correspond directly to the ones used in the experiments (see methods).

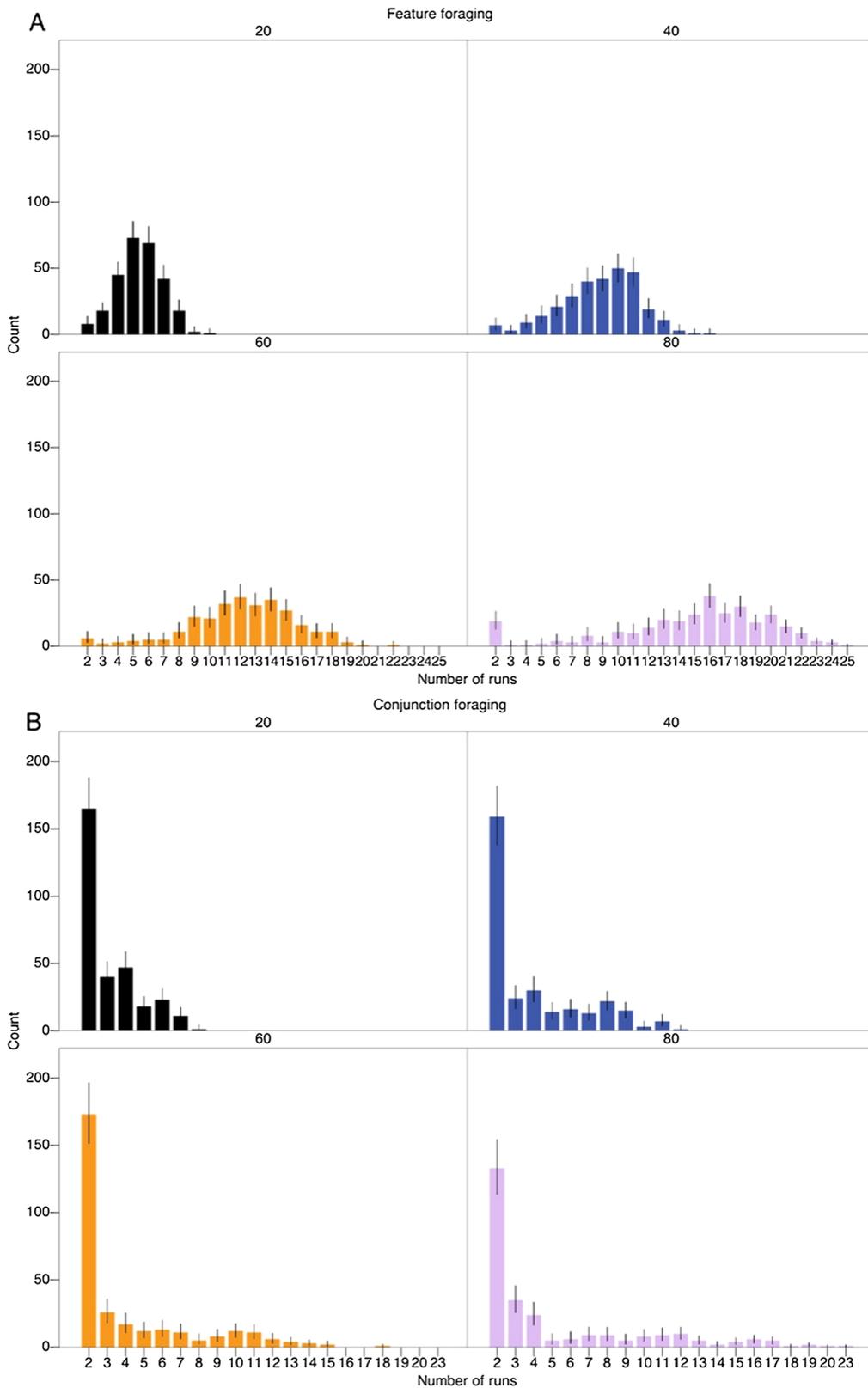
interaction was also significant,  $F(1.59,17.45) = 34.32 p < .001 \eta_p^2 = 0.80$ . Since Fig. 2 suggests that the effect of set-size on run number is mostly driven by the feature foraging condition, separate univariate ANOVAs were also conducted. The difference in run number as a function of set-size during feature foraging was significant,  $F(3,52) = 60.16 p < .001 \eta_p^2 = 0.790$  but not during conjunction foraging,  $F(3,52) = 1.23 p = .309 \eta_p^2 = 0.073$ , confirming the pattern in Fig. 2.

This result would be expected, even if there is no difference in deviation from randomness during feature foraging due to the different target numbers for each set-size. The same repeated-measures ANOVA, using *proportional* run number as the dependent variable (the average

run number for each participant in each condition divided by the number of targets in each condition), confirmed significant main effects of condition,  $F(1,11) = 120.89 p < .001 \eta_p^2 = 0.917$ , and set-size  $F(2.15,23.65) = 65.55 p < .001 \eta_p^2 = 0.856$  on proportional run number. The interaction, however, was not significant  $F(1.95,21.46) = .41 p = .663 \eta_p^2 = 0.036$ .

### 3.2. Intertarget times

Fig. 3 shows the intertarget times (ITT) in milliseconds for each target as a function of when each target was selected within the trial. Three distinct phases (see Table 1 for definitions) emerged that we



**Fig. 2.** Run numbers on each foraging trial for different set-sizes in Experiment 1. Panel A shows histograms for feature foraging. Panel B shows histograms for conjunction foraging. The number above each graph shows the set-size in each case.

analyze separately: i) a ‘cruise-phase’ which involves all ITT’s except the last ITT and the middle peak ITT, ii) the end-peak, involving the last ITT on each trial and iii) the mid-point reflecting the ITT after half of the targets had been tapped ( $N/2 + 1$ ; where N is the number of targets). The figure shows that ITTs remain relatively flat (with a slight,

but significant upwards slope, see below) throughout the cruise phase during feature foraging with a small rise in ITTs for the last two targets. This can be captured with the intercept and the change in the ITTs ( $\Delta$ ITTs) throughout the trial, shown in Table 3.  $\Delta$ ITT was calculated as the difference between an ITT and the previous ITT so that negative

**Table 2**  
Descriptive statistics for the run number (RN) for different set-sizes in both foraging conditions.

	Set-size	Mean RN	Median RN	SD	Skewness
Feature Foraging	20	5.46	5	1.44	0.007
	40	8.88	9	2.55	-0.434
	60	12.43	13	3.43	-0.483
Conjunction foraging	20	3.1	2	1.52	1.239
	40	3.87	2	2.62	1.244
	60	4.11	2	3.45	1.643
	80	5.11	2	4.77	1.534

$\Delta$ ITTs represent shorter ITTs (downward slope on average as the trial progresses) and positive  $\Delta$ ITTs represent longer ITTs over time (upward slope on average throughout trials). Table 4 shows the ITTs for the mid-peaks and end-peaks.

A 2 (condition: feature, conjunction)  $\times$  4 (set-size) repeated measures ANOVA was conducted for each of the phases. For the cruise-phase,  $\Delta$ ITTs for each participant in each condition were the dependent variable, while mean ITT for either the mid-point or the end-peak for each participant in each condition was the dependent variable for those respective phases.

During the cruise phase, there was a significant effect of condition  $F(1,11) = 17.37 p = .002 \eta_p^2 = 0.612$  but not of set-size,  $F(1.29,14.24) = 2.74 p = .114 \eta_p^2 = 0.199$ , and their interaction was not significant,  $F(1.78,19.56) = 1.05 p = .362 \eta_p^2 = 0.087$ . The  $\Delta$ ITTs were larger for conjunction than feature foraging, but the difference between the different set-sizes was not significant, although the trend, as seen in Table 2 is that smaller set-sizes yield larger  $\Delta$ ITTs. This is interesting in comparison with results from the visual search literature where response times are larger with increased set-size.

For the mid-points there was a significant effect of condition,  $F(1,11) = 132.63 p < .001 \eta_p^2 = 0.923$ . The effect of set-size was not significant, nor was the interaction significant, set-size:  $F(2.15,23.66) = 0.37 p = .711 \eta_p^2 = 0.032$ ; interaction:  $F(1.99,21.90) = 1.03 p = .375 \eta_p^2 = 0.085$ . As Fig. 3 shows, there are no mid-peaks during feature foraging, but these are clearly visible during conjunction foraging, and mostly seem to reflect switches between target types.

For the end-peaks, there were main-effects of both condition,  $F(1,11) = 34.83 p < .001 \eta_p^2 = 0.760$ , and set-size,  $F(2.32,25.56) = 4.54 p = .017 \eta_p^2 = 0.292$ . However, as Fig. 3 shows, the set-size pattern

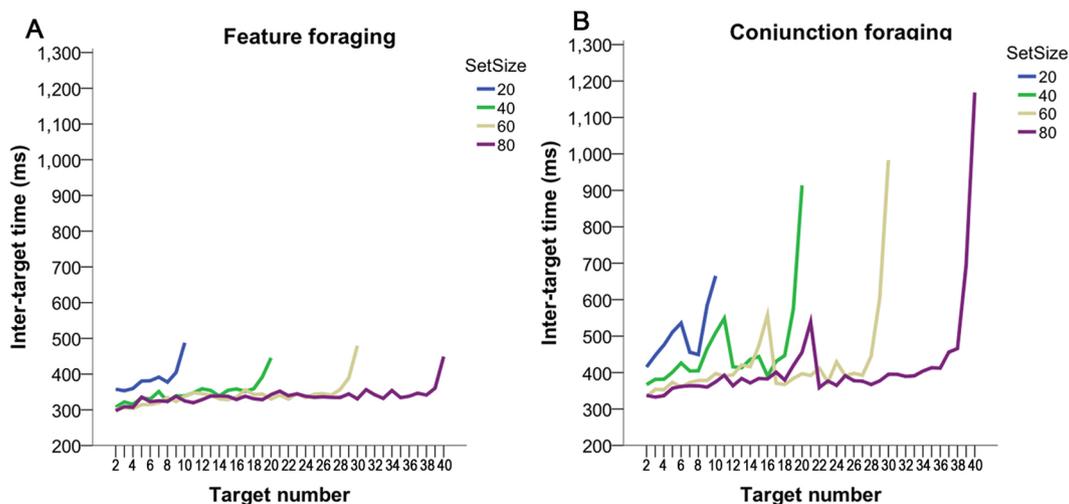
**Table 3**  
Parameters of the “cruise-phase” during feature and conjunction foraging.  $\Delta$ ITT is the average change in ITTs from a previous tap, so a positive  $\Delta$ ITT denotes slowing throughout the trial.

	Set-size	Cruise Intercept	$\Delta$ ITT
Feature	20	340.09	6.85
	40	309.59	4.06
	60	309.23	2.48
Conjunction	20	317.82	1.87
	40	405.47	15.79
	60	372.38	6.87
Foraging	60	345.77	9.71
	80	330.95	7.49

**Table 4**  
Mid and end-peaks during feature and conjunction foraging.

	Position	Set-size	Mean (ms)	Std. Deviation
Feature foraging	Mid-peaks	20	381.74	57.51
		40	378.30	118.23
		60	337.33	30.05
	End-peaks	80	354.43	77.75
		20	487.85	77.13
		40	445.26	78.27
		60	479.28	93.51
		80	449.01	72.13
		20	535.81	130.12
		40	548.77	104.75
Conjunction foraging	Mid-peaks	60	558.17	111.08
		80	538.75	96.47
	End-peaks	20	665.12	286.90
		40	913.72	417.59
		60	982.94	451.97
		80	1168.49	461.41

needs to be interpreted in light of the significant condition  $\times$  set-size interaction,  $F(2.66,29.23) = 5.90 p = .004 \eta_p^2 = 0.349$ . While end-peaks are clearly visible in both conditions, they are substantially larger for conjunction foraging, and increase as a function of set-size in this condition only. It is highly notable how these end-peaks mirror the mean RT's typically seen in for single-target conjunction search tasks (Egeth, Virzi, & Garbart, 1984; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1998).



**Fig. 3.** Intertarget times (ITT) in milliseconds for each target within a trial, as a function of when each target was selected within the trial (on the abscissa). Each line represents a different set-size. Panel A shows the results for feature foraging while Panel B shows the results for conjunction foraging.

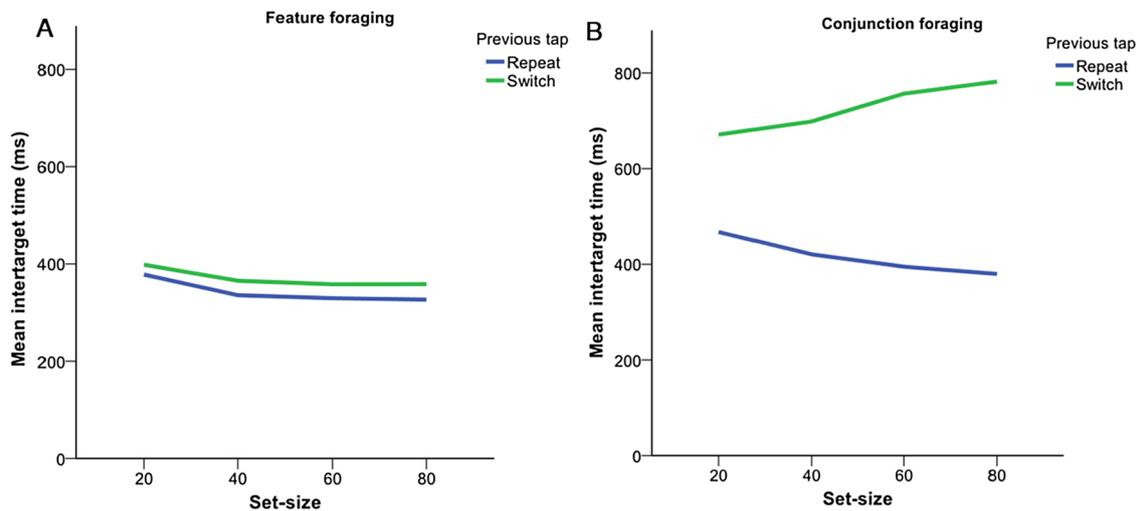


Fig. 4. Switch costs from Experiment 1 for feature (panel A) and conjunction foraging (panel B). Differences between the lines represent the differences in ITTs when a target is from the same target category or from a different target category than the previous target (switch cost).

### 3.3. Switch costs

Fig. 4 shows switch costs in Experiment 1, for the different absolute set-sizes. Switch costs reflect increases in ITTs when observers pick a different target type than they last did. While ITTs increase, for both feature and conjunction foraging, indicating switch costs, this switch cost is far higher during conjunction ( $M = 188$  ms,  $SD = 119.9$  ms) than feature foraging ( $M = 20$  ms,  $SD = 24.7$  ms). Two  $2 \times 4$  (switch (yes, no)  $\times$  set-size (20, 40, 60, 80)) repeated measures ANOVAs, one for feature foraging, the other for conjunction foraging, were performed on the ITTs. This revealed significant main effects and an interaction during conjunction foraging but not feature foraging (set-size:  $F(1.98, 23.79) = 11.74$   $p < .001$   $\eta_p^2 = 0.494$ ; repeat/switch:  $F(1, 12) = 80.29$   $p < .001$   $\eta_p^2 = 0.870$ ; interaction:  $F(2.08, 24.99) = .91$   $p = .421$   $\eta_p^2 = 0.070$  during feature foraging. Set-size:  $F(1.80, 19.79) = 0.79$   $p = .457$   $\eta_p^2 = 0.067$ ; repeat/switch:  $F(1, 12) = 158.14$   $p < .001$   $\eta_p^2 = 0.935$ ; interaction:  $F(1.62, 17.83) = 12.51$   $p = .001$   $\eta_p^2 = 0.532$  during conjunction foraging). This interaction for conjunction foraging shows how switches become harder with increased set-size which is opposite to the pattern for repeats.

## 4. Discussion

Run behavior clearly differed between the two conditions in Experiment 1, with long runs during conjunction foraging but frequent switches during feature foraging, replicating our previous results (Kristjánsson et al., 2014). An examination of the ITT patterns revealed distinct phases during the foraging trials. Firstly, there was a 'cruise phase' throughout the trial, where observers quickly selected targets, much faster than typically seen in single-target visual searches. There were also mid-point peaks during conjunction, but not feature foraging that seem to represent switches between the target categories. Finally, there were peaks at the ends of the foraging trials for both conditions. Strikingly, these end-peaks mirror typical results from single target searches in that the peaks are the same height regardless of set-size for feature foraging, but increase by set-size, approximately linearly, for conjunction foraging. Indeed, for the cases where only a single target (the last one) is to be found, the task is effectively reduced to a single target search.

We measured whether the end-peaks might reflect increased switching rates for the last target (since no choice is involved for the last target, the likelihood of a switch could be higher). But during feature foraging, the likelihood that the last target was a switch was not higher than for other targets (43% that the last target was a switch vs

40.5% that other targets were a switch from the previous target). During conjunction foraging this difference was slightly larger (21.5% vs 11%), but this alone cannot explain the peak at the end of the trial. Firstly, the end-peaks are larger than the switch-costs, second, the peak is much larger at the end than in the middle where more switches are actually made and third, since there was no difference in the likelihood that the last target was a switch during feature foraging, we should not see a peak at the end there, if the peak reflects only switch costs. While the end-peaks may reflect a combination of several factors such as inhibition of return (if participants missed a target; Wang & Klein, 2010), low target/distractor ratios, that the last target is far away from the focus of attention, or that before tapping the final target, participants are searching for the next target or making a final check for any remaining targets, the simplest explanation seems to be that finding the last target, during a foraging task, simply reduces to a single target search. The data are certainly consistent with this interpretation. Finally, the change in ITTs throughout the trial ( $\Delta$ ITTs) was not significantly affected by set-size, although there was a clear trend towards lower  $\Delta$ ITTs at higher set-sizes which indicates that the upwards slope through the cruise-phase flattens, the higher the set-size.

Overall, the foraging patterns reveal highly interesting within-trial dynamics, a cruise phase where selections are surprisingly fast even during conjunction foraging, middle peaks during conjunction foraging, reflecting switches between target categories and end-peaks that mirror the results seen for feature and conjunction searches for different set-sizes. This finding highlights the additional information provided with foraging tasks compared to single-target visual searches. In the general discussion we address potential theoretical implications of these findings. In Experiment 2, we address effects of relative rather than absolute set-size on foraging performance.

## 5. Experiment 2 – Relative set-size

### 5.1. Methods

#### 5.1.1. Participants

Fourteen unpaid volunteers from the University of Iceland participated (13 females; aged between 21 and 40 years old,  $M = 24.2$ ). All reported normal, or corrected to normal vision, were right handed and gave written, informed consent. None had taken part in Experiment 1. All aspects of the experiment were approved by the appropriate ethical committee, and conformed to the Declaration of Helsinki for testing human participants.

**Table 5**  
Descriptive statistics for the number of runs for different proportions during both foraging conditions in Experiment 2.

	Proportion	Mean run number	Median run number	SD	Skewness
Feature	25	8.83	9	2.40	-0.540
	50	14.75	15	4.48	-0.451
	75	22.52	23	5.73	-0.920
Conjunction	25	3.55	2	2.33	1.589
	50	3.57	2	3.09	2.431
	75	4.65	2	4.80	1.891

### 5.1.2. Stimuli & procedure

Set-size was always 80 with three ratios of targets versus distractors (25/75, 50/50, 75/25). For example, in the 25% condition, there were 20 targets, 10 from each target category and 60 distractors, 30 from each distractor category. There were 6 blocks of 20 trials (a completed trial refers to successful tapping on all 20, 40 or 60 targets). Otherwise, methods and analyses were identical to Experiment 1.

## 6. Results

Fig. 4 shows run numbers in Experiment 2 as a function of different relative set-sizes. As for absolute set-size, the different conditions separate into approximately normal distributions for feature foraging while the distributions are highly skewed for conjunction foraging (see Table 5 for descriptive statistics).

A 2 (condition)  $\times$  3 (proportions) repeated measures ANOVA on the average run numbers confirmed significant main effects of both condition,  $F(1,13) = 186.10$   $p < .001$   $\eta_p^2 = 0.94$ , and proportion,  $F(1.73,22.53) = 182.84$   $p < .001$   $\eta_p^2 = 0.934$  and a significant interaction,  $F(1.67,21.74) = 198.49$   $p < .001$   $\eta_p^2 = 0.939$ . As in Experiment 1, Fig. 5 shows that the effect of proportion on run number is mostly driven by feature foraging. Separate univariate ANOVAs showed that target proportions affected run number for feature foraging, both when the independent variables were run number  $F(2, 39) = 141.86$   $p < .001$   $\eta_p^2 = 0.879$  and proportional run number  $F(2, 39) = 9.87$   $p < .001$   $\eta_p^2 = 0.336$ , but not for conjunction foraging ( $F(2, 39) = 0.72$   $p = .494$   $\eta_p^2 = 0.035$ ).

Fig. 6 shows intertarget times throughout trials in Experiment 2. The pattern was similar to Experiment 1 for feature foraging, with a slight positive slope throughout the cruise-phase and small peaks at the end of trials. During conjunction foraging, the results differ in several respects from the patterns in Experiment 1. The increases in ITT's at the end of the trials during conjunction foraging were larger (roughly 600–2180 ms for relative set-size versus 650–1190 ms for absolute set-size). The middle peaks, presumably reflecting switching between target categories, were also larger for relative set-size. While in Experiment 1 these peaks were constant, regardless of set-size, in Experiment 2 they differed by relative set-size. The same parameters for the cruise-phase and the mid and end-peaks were calculated (Tables 6 and 7).

A 2 (condition)  $\times$  3 (proportion) repeated measures ANOVA was conducted for each of the phases. During the cruise phase, there was a main effect of condition  $F(1,13) = 28.57$   $p < .001$   $\eta_p^2 = 0.687$ , and a main effect of proportion,  $F(1.10,14.34) = 17.65$   $p = .001$   $\eta_p^2 = 0.576$  on  $\Delta$ ITTs. The interaction between condition and proportion was also significant  $F(1.14,14.85) = 12.40$   $p = .002$   $\eta_p^2 = 0.488$ . Unlike absolute set-size in Experiment 1, where the effect of set-size on  $\Delta$ ITTs was not quite significant, manipulating relative set-size (target proportion) significantly affected  $\Delta$ ITTs, where the ITT's were fastest for the largest set-sizes.

For the end-peaks, there were main-effects of both condition,  $F(1,13) = 51.23$   $p < .001$   $\eta_p^2 = 0.798$ , and proportion,  $F$

$(1.44,18.69) = 30.85$   $p < 0.001$   $\eta_p^2 = 0.704$ . As in Experiment 1, there was a significant interaction  $F(1.43,18.59) = 19.45$   $p < .001$   $\eta_p^2 = 0.599$ . While end-peaks are, again, clearly visible in both conditions (Fig. 6), they are larger the smaller the target proportion is in both conditions, but far larger for conjunction foraging.

For the mid-peaks there was a significant effect of both condition,  $F(1,13) = 102.63$   $p < .001$   $\eta_p^2 = 0.887$  and target proportion,  $F(1.67,21.65) = 19.10$   $p < .001$   $\eta_p^2 = 0.595$ , and a significant condition  $\times$  proportion interaction.  $F(1.57,20.45) = 6.36$   $p = .011$   $\eta_p^2 = 0.328$ . As in Experiment 1 there were no mid-peaks during feature foraging, but clear mid-peaks during conjunction foraging. Unlike Experiment 1, the mid-peaks during conjunction foraging are not of the same size, instead they become larger, the smaller the target proportion.

### 6.1. Switch costs

In Experiment 2, the same switch-cost analyses as in Experiment 1 were performed (Fig. 7). The switch-costs during feature foraging (Fig. 7A) were much smaller than for conjunction foraging (Fig. 7B). Also, while switch-costs were constant for the different proportions during feature foraging there was a clear interaction during conjunction foraging, reflecting increasing switch costs as target proportion decreased. Two, 2 (switch (yes, no))  $\times$  3 (proportion (25, 50, 75)) repeated measures ANOVAs, one for each condition, were conducted. The results mirror the results from Experiment 1, during feature foraging, there were significant effects of switching  $F(1,13) = 18.39$   $p < .001$   $\eta_p^2 = 0.586$  and proportion  $F(1.36,17.72) = 28.73$   $p < .001$   $\eta_p^2 = 0.688$ . As the parallel lines in Fig. 7A suggest, there was no interaction between switches and proportion  $F(1.17,15.18) = 1.25$   $p = .290$   $\eta_p^2 = 0.088$ . During conjunction foraging both the main effects and the interaction between them were significant (Switch:  $F(1,13) = 101.44$   $p < .001$   $\eta_p^2 = 0.886$ ; proportion:  $F(1.51,19.61) = 62.76$   $p < .001$   $\eta_p^2 = 0.828$ ; interaction:  $F(1.62,21.00) = 19.51$   $p < .001$   $\eta_p^2 = 0.600$ ).

## 7. Discussion – Experiment 2

The run behavior in Experiment 2 was similar to Experiment 1 and our previous findings. For the intertarget time analysis, there were similar 'phases' within foraging trials as in Experiment 1, a cruise-phase with a positive slope, a rise in ITTs at the mid-peaks of conjunction foraging trials, but not during feature foraging, and a rise at the end of trials during both feature and conjunction foraging, although the rise was substantially larger for conjunction foraging.

The results differ from Experiment 1 when it comes to the mid-peaks during conjunction foraging, in that their size is constant for different set-sizes in Experiment 1 but they become larger in Experiment 2 with smaller relative set-size, probably reflecting that there are fewer targets on the screen. Also, in Experiment 2, relative set-size affects the average  $\Delta$ ITTs during the cruise-phase, while this was not significant in Experiment 1.

As in Experiment 1, switches were no more likely for the last target than at any other point during feature foraging (39.7% for the last target vs 38.3% for the rest of the trial). The last target during conjunction foraging was however more likely to be a switch (18.7% for the last target vs 6.3% for the other targets). But this increased likelihood of switches at the end cannot alone explain the end-peaks, since although a switch is more likely at the end of a trial, the target is still more likely to be a repeat of a previous target than a switch, and the end-peaks are far larger than any switch costs (for example, at the mid-peaks during conjunction foraging).

During foraging for multiple targets, the trials essentially collapse to single target searches when only one target is left. For the highest relative set-size, the distractor number was the smallest and indeed this is where the end-peaks were the lowest. In other words, in both

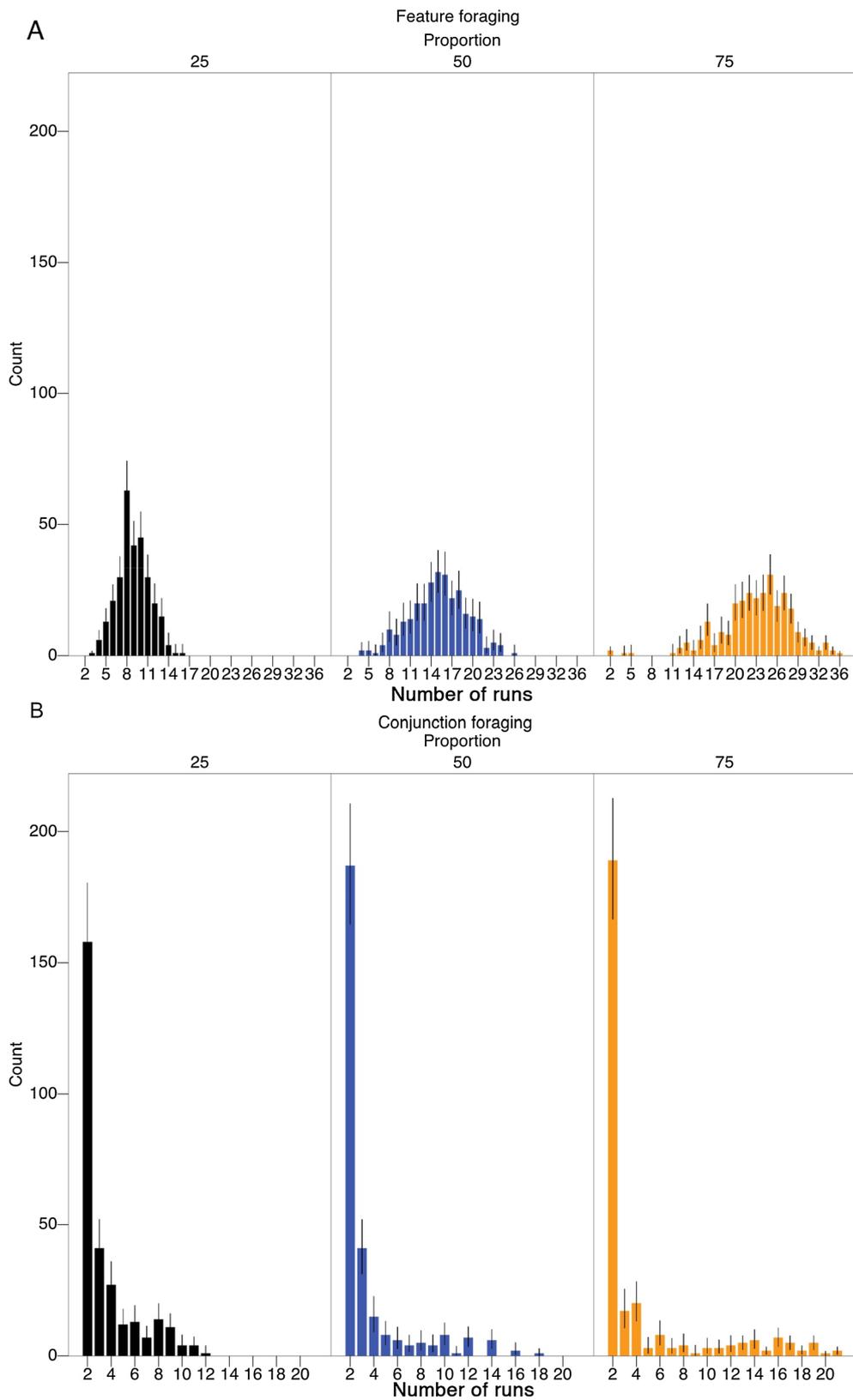


Fig. 5. Run numbers for different target proportions in Experiment 2. Panel A shows feature foraging. Panel B shows conjunction foraging. Different bar colors denote different target proportions.

Experiments 1 and 2 we replicate well-known patterns of feature versus conjunction search, but only for the last target in the set during foraging. This highlights the additional insights foraging paradigms can provide regarding attentional selection over traditional visual search.

We address this point in more detail in the General Discussion.

Note that effect sizes were typically larger in Experiment 2 than in Experiment 1. This may suggest that manipulating target proportion affects foraging to a larger extent than manipulating absolute set-size

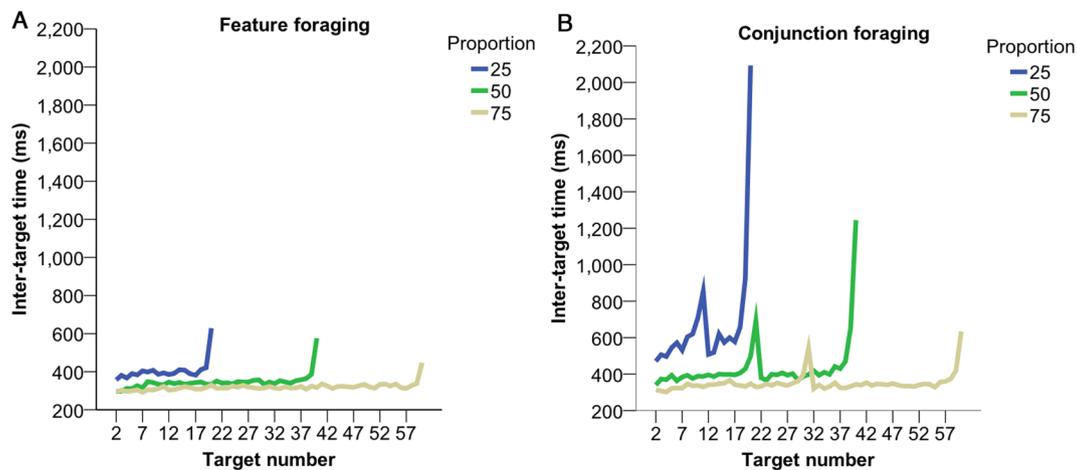


Fig. 6. Intertarget times in milliseconds for each target within a trial from Experiment 2. Panel A shows the results for feature foraging and Panel B the results for conjunction foraging, with each colored line representing a different relative set-size.

Table 6  
Parameters of the cruise-phase during feature and conjunction foraging.

	Target proportion	Cruise Intercept	$\Delta$ ITT
Feature Foraging	25	372.18	4.02
	50	315.89	2.53
	75	303.67	0.76
Conjunction Foraging	25	467.90	28.23
	50	358.87	8.70
	75	327.79	1.90

Table 7  
Mid and end-peaks during feature and conjunction foraging.

Condition	Condition	Target proportion	Mean (ms)	Std. Deviation
Feature foraging	Mid-peaks	25	393.84	58.68
		50	351.22	56.10
		75	323.26	55.96
	End-peaks	25	628.56	212.00
		50	575.97	283.81
		75	446.83	130.46
Conjunction foraging	Mid-peaks	25	853.79	172.40
		50	690.87	171.51
		75	541.77	222.60
	End-peaks	25	2093.00	993.38
		50	1244.65	500.07
		75	633.75	198.38

does, and may reflect that target proportion plays a larger role in set-size effects in traditional visual search than often thought, which has implications for theoretical accounts of visual attention. While this result is certainly suggestive, it should be supported with further experiments before firm conclusions can be drawn.

### 8. General discussion

Foraging tasks are increasingly being used to assess human visual attention. Set-size effects play a large role in how visual search tasks are used to make inferences about the function of visual attention and slopes of set-size against response times have been considered markers of attention for decades (see discussion in Kristjánsson, 2015, 2016; see also Wolfe, 2016). Understanding how set-size affects visual foraging is therefore important for casting light on how foraging tasks relate to visual search tasks, for further understanding of visual attention. We therefore measured the effects of variation in absolute and relative set-size upon foraging performance. Manipulating absolute and relative set-size independently can also help address an inherent problem with

interpreting foraging results since absolute and relative set-size change constantly throughout the tasks.

The run behavior, which has been the main outcome variable of several foraging studies (e.g. Kristjánsson et al., 2014; Ólafsdóttir et al., 2016; Kristjánsson & Kristjánsson, 2018), mirrored previous findings but there were no striking differences between absolute and relative set-size for run behavior. But the results from the analyses of the intertarget times (ITTs) are novel, and highly interesting since they reveal a remarkably intricate picture of how attention is deployed across the visual scene from moment-to-moment. Because of this detail, foraging tasks can provide important additional information above single-target visual search for understanding visual attention and visual orienting (see section on theoretical implications below).

Strikingly, the characteristic differences between the feature and conjunction conditions in single-target visual search tasks, were only seen for the last targets of foraging trials. This suggests that traditional single-target visual search tasks reflect only what might be called a special case of attentional selection. Furthermore, even if the typical single-target search patterns are seen, in that selection times for the last feature target are flat by set-size, but increase with set-size during conjunction foraging, these selection times for the last target are far higher than the other selection times. This argues that basing models of visual attention and visual search solely on data from a single paradigm has limitations. Note also that a target that is distinguished from distractors by color should, strictly speaking, pop-out, but the rise in response times at the end of trials during feature foraging indicates that such targets do not pop out if it takes observers such a long time to find the singleton target. We should acknowledge that these end-peaks may possibly reflect that this location has been discounted when other nearby targets were previously selected (Thornton & Horowitz, 2004), but this does not change the fact that these singletons do not seem to pop-out. Secondly, the ITTs are relatively flat (but increase slightly) throughout the foraging task (during the “cruise phase”) but only rise substantially at the end of the foraging trials, and in the middle of the trial during conjunction foraging. This pattern is more nuanced than two-stage conceptions (see introduction) predict, again highlighting how foraging paradigms can provide a more detailed picture of attentional orienting than traditional visual search tasks.

During the ‘cruise-phase’, the intertarget selection times (ITTs) were very low, lower than in most, if not all, single-target searches. Remarkably, they were also comparable between feature and conjunction foraging, although the run pattern differed strongly between those conditions. During conjunction foraging participants selected the same target repeatedly, which may therefore benefit from priming (Kristjánsson & Ásgeirsson, 2019), while during feature foraging they

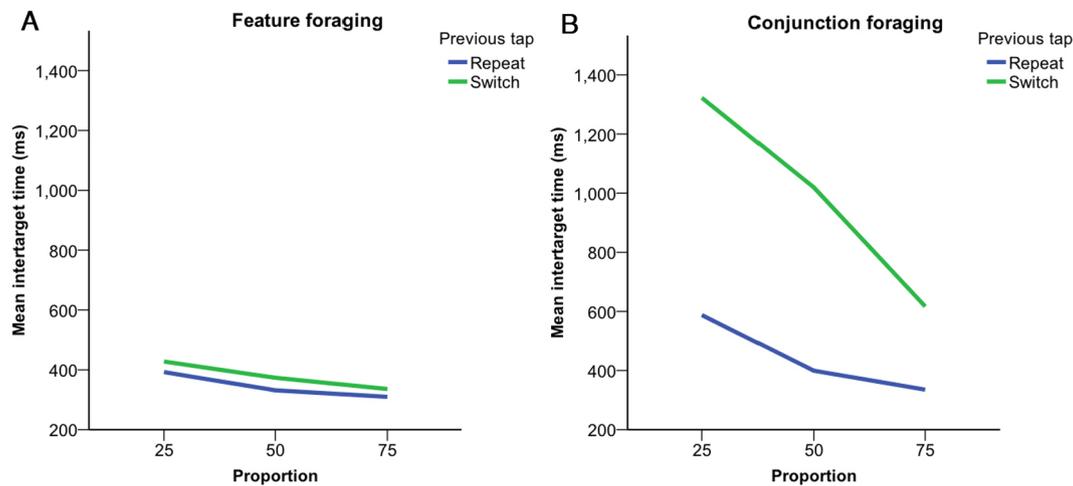


Fig. 7. Switch-costs in Experiment 2, measured as the difference in intertarget times when a target was from the same target category or from a different target category than the previous target. Panel A shows the switch costs during feature foraging and Panel B shows the switch costs for conjunction foraging.

switched far more often. These fast target selections during the cruise phase, provide an interesting challenge for theoretical accounts of visual attention. It is possible that the cruise phase reflects that observers have already attentionally selected the next target. This does, however, not alter the fact that there is remarkable similarity for the selection times for feature and conjunction foraging. Related to this, it is possible that observers performed ‘subset’ foraging for only one target category at a time (see e.g. Friedman-Hill & Wolfe, 1995; Kaptein, Theeuwes, & van der Heijden, 1995 for some examples from the visual search literature). Overall, our results from the assessment of set-size effects upon visual foraging clearly do not fit a classic two-stage distinction between “parallel” feature search and “serial” conjunction search (Egeth, 1966; Neisser, 1963; Sternberg, 1967; Treisman & Gelade, 1980). The patterns are simply too multifaceted for that, and they provide challenges for other accounts of visual attention (e.g. Duncan & Humphreys, 1989; Wolfe, 1994; Hulleman & Olivers, 2017).

Interestingly, the effects on foraging were typically larger for relative than absolute set-size. This suggests that relative set-size has a larger effect on foraging than absolute set-size. This may provide an alternative explanation for classic set-size effects in conjunctive visual search, although firm conclusions on this would require stronger evidence. As set-size increases in single target searches, the target/distractor ratio decreases, and this may be the actual reason for increased response times with larger set-sizes, rather than the increased number of distractors per se. This is quite speculative, however and experiments involving search where the number of targets and distractors are varied would be needed to settle this question for visual search (Thornton & Gilden, 2007; Ward & McClelland, 1989). Further questions also remain regarding the effects of relative set-size, such as regarding what might be called effective set-size. In a search where there are 8 targets among 72 distractors the effective set-size is 1/8, in other words the same effective set-size as for a single target among 7 distractors. Direct manipulations of effective set-size in future foraging studies may therefore be called for.

Note also that another feature of the task that might affect foraging patterns is that targets disappear when tapped, which has been found to affect performance when searching for multiple targets (Cain & Mitroff, 2013). Cain and Mitroff argued that this may free up resources (such as working memory) for other tasks. But note that this conclusion may be in direct contrast with the results of Thornton & Horowitz (2008). It would therefore be interesting to investigate performance in a task similar to here where the targets would *not* disappear once tapped. Studies are underway in our laboratory that address these questions.

### 8.1. Theoretical implications

Many of our findings are difficult to explain within standard theoretical accounts of visual attention based on visual search tasks. Models of attention that are based on single-target searches may therefore reflect undersampling of the operational characteristics of visual attention and may not explain visual attention in a general sense but merely reflect the characteristics of the particular task chosen to measure it. If these theories are supposed to be general models of visual attention, and not only single-target searches, they should both predict and explain results from other visual attention tasks including foraging tasks. While we do not wish to claim that existing theories of visual search cannot account for our results, we clearly require modification.

One obvious puzzle is that the typical response time patterns from visual search tasks are only seen for the last target within a foraging trial. These selections are also much slower than the majority of other selections (such as during the cruise phase). We speculate that this reflects how observers plan ahead how to organize their selections, which may allow very efficient selection. Such preplanning of attention shifts could in fact be a useful feature of visual attention, one that is not encapsulated in current theories of attention. This is of course reminiscent of findings on how attention may move to the location of upcoming locations for visual or manual selection (Baldauf & Deubel, 2010; Deubel & Schneider, 1996; see Kristjánsson, 2011 for review). Such moment-by-moment preplanning might therefore need to find its way into theoretical conceptions of visual attention.

Another key issue is that targets that are distinguishable from distractors by a single color should pop-out in a feature map, a concept central to theoretical accounts such as Guided Search (Wolfe, 1994) and Feature Integration theory (Treisman & Gelade, 1980). The rise in response times at the end of trials during feature foraging in our current findings indicates however that such targets do *not* pop-out as such. When only one target is left, the task essentially reduces to a single-target search task, and the target should pop out in the feature task. But the RT's (measured with intertarget times, ITT's here) for these last targets are very high which seems inconsistent with results from the visual search literature. This may argue for a lessened emphasis on preattentive versus attentive processing within visual search theories.

A third issue is that intertarget time were comparable for feature and conjunction foraging for the vast majority of trials, while the run pattern differed strongly between those conditions. This may tell us something about strategies of attending within different environments that have different demands. The fact that observers select the same target-type repeatedly during conjunction foraging may suggest that

they rely on attentional priming (Kristjánsson & Ásgeirsson, 2019) to a larger degree than is included in current visual search theories. Priming has been shown to play a large role in attentional orienting (see e.g. Awh, Belopolsky, & Theeuwes, 2012; Kristjánsson, 2006; Lamy & Kristjánsson, 2013) and can, in many cases have a dominating influence on attention, overriding our top-down goals (Belopolsky, Schreij, & Theeuwes, 2010; Brascamp, Blake, & Kristjánsson, 2011; Kristjánsson, Wang, & Nakayama, 2002; Shurygina, Kristjánsson, Tudge, & Chetverikov, 2019; Theeuwes, Reimann, & Mortier, 2006). Somewhat surprisingly in light of previous findings, priming appears not to be as dominant during feature foraging and we speculate that this casts light on the capacity of attention for different sorts of templates for foraging and search, and that this differs as a function of the features and feature relationships that are involved. This may also mean that theoretical accounts that are not as bound to preattentive versus attentive processing, such as TVA (Bundesen, 1990) may fare better in accounting for our results

A fourth issue is that theoretical accounts of attention will have to allow for individual differences in capacity and in strategy. One-size-fits-all theories are unlikely to work. Some observers seem to be able to switch easily between conjunction targets within foraging trials (Kristjánsson et al., 2014). Additionally the results of Kristjánsson, Thornton, and Kristjánsson (2018) show how most observers seem to be able to switch to a strategy of switching between conjunction targets if they have limited time to collect as many targets as they can, with short bursts of high concentration where they briefly load working memory with complex templates. This last point may therefore also have implications for conceptions of visual working memory in addition to theories of visual attention, in particular theories proposing that only a single VWM representation can control attention at any given time (e.g. Olivers, Peters, Houtkamp, & Roelfsema, 2011; Huang & Pashler, 2007).

Finally, we note that our results suggest that attentional selection during foraging may have particular markers, potentially useful for future research as indices of particular attentional functions, such as the mid- and end-peaks and the cruise phase.

Our goals during daily interaction with the environment are typically unlikely to involve only a single target. We argue that theories of visual attention will need to allow more flexibility in attending and theories where different weightings are given to items based on goals and conditions that are best suited to meet the task demands at each point. The hope for a single mechanism or principle that can explain attention may have been somewhat illusory – in the end theories based on visual search studies may explain only visual search.

## 9. Conclusions

Visual foraging is increasingly being used to assess the function of human visual attention. Our current results provide a very intricate picture of visual attention as we interact with the environment. Foraging performance involves highly interesting intertrial patterns, that carry specific markers that can be important for further understanding of visual attention. Set-size effects have played a major role in conceptions of visual attention, so it is important to understand how they function in foraging paradigms. Our results indicate that there are similarities but also differences between effects of set-size on visual search and visual foraging that reflect different attentional demands of the two tasks. Interestingly the set-size patterns for single-target search tasks are seen in the foraging results, but only for the last target in the foraging sequence suggesting that visual search tasks provide only a snapshot of attentional processing as we interact with the environment.

## Supplementary material

Data used in the analysis can be accessed at <https://data.mendeley.com/datasets/2k4kg723cn/draft?a=ee84ead3-010b-4092-bf60-f7308cb82278>.

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## References

- Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, 16(8), 437–443.
- Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. *Vision Research*, 50(11), 999–1013.
- Belopolsky, A. V., Schreij, D., & Theeuwes, J. (2010). What is top-down about contingent capture? *Attention, Perception, & Psychophysics*, 72(2), 326–341.
- Bond, A. B. (1982). The bead game: Response strategies in free assortment. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 24(1), 101–110.
- Bond, A. B. (1983). Visual search and selection of natural stimuli in the pigeon: The attention threshold hypothesis. *Journal of Experimental Psychology: Animal Behavior*, 9, 292–306.
- Brascamp, J. W., Blake, R., & Kristjánsson, Á. (2011). Deciding where to attend: Priming of pop-out drives target selection. *Journal of Experimental Psychology: Human Perception and Performance*, 37(6), 1700–1707.
- Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, 97(4), 523–547.
- Cain, M. S., & Mitroff, S. R. (2013). Memory for found targets interferes with subsequent performance in multiple-target visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 39(5), 1398.
- Cain, M. S., Vul, E., Clark, K., & Mitroff, S. R. (2012). A Bayesian optimal foraging model of human visual search. *Psychological Science*, 23(9), 1047–1054.
- Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, 9, 129–136.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3(3), 201–215.
- Dawkins, M. (1971). Shifts of 'attention' in chicks during feeding. *Animal Behavior*, 19, 575–582.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, 18(1), 193–222.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, 36(12), 1827–1837.
- Dukas, R. (2002). Behavioural and ecological consequences of limited attention. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 357(1427), 1539–1547.
- Dukas, R., & Kamil, A. C. (2001). Limited attention: The constraint underlying search image. *Behavioral Ecology*, 12(2), 192–199.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96(3), 433–458.
- Egeth, H. E. (1966). Parallel versus serial processes in multidimensional stimulus discrimination. *Perception & Psychophysics*, 1(4), 245–252.
- Egeth, H. E., Virzi, R. A., & Garbart, H. (1984). Searching for conjunctively defined targets. *Journal of Experimental Psychology: Human Perception and Performance*, 10(1), 32–39.
- Fougnie, D., Cormiea, S. M., Zhang, J., Alvarez, G. A., & Wolfe, J. M. (2015). Winter is coming: How humans forage in a temporally structured environment. *Journal of Vision*, 15(11) 1 1.
- Friedman-Hill, S., & Wolfe, J. M. (1995). Second-order parallel processing: Visual search for the odd item in a subset. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 531–551.
- Gilchrist, I. D., North, A., & Hood, B. (2001). Is visual search really like foraging? *Perception*, 30(12), 1459–1464.
- Hills, T. T., Kalf, C., & Wiener, J. M. (2013). Adaptive Lévy processes and area-restricted search in human foraging. *PLoS One*, 8(4), e60488.
- Huang, L., & Pashler, H. (2007). A Boolean map theory of visual attention. *Psychological Review*, 114(3), 599–631.
- Hulleman, J., & Olivers, C. N. L. (2017). The impending demise of the item in visual search. *Behavioral and Brain Sciences*, 40, 1–69.
- Jóhannesson, Ó. I., Kristjánsson, Á., & Thornton, I. M. (2017). Are foraging patterns in humans related to working memory and inhibitory control? *Japanese Psychological Research*. <https://doi.org/10.1111/jpr.12152>.
- Jóhannesson, Ó. I., Thornton, I. M., Smith, I. J., Chetverikov, A., & Kristjánsson, Á. (2016). Visual foraging with fingers and eye gaze. *i-Perception*, 7(2), 1–18.
- Kaptein, N. A., Theeuwes, J., & van der Heijden, A. H. C. (1995). Search for a conjunctively defined target can be selectively limited to a color-defined subset of elements. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 1053–1069.
- Kristjánsson, Á. (2006). Rapid learning in attention shifts: A review. *Visual Cognition*, 13(3), 324–362.
- Kristjánsson, Á. (2011). The intriguing interactive relationship between visual attention and saccadic eye movements. In S. Everling, I. D. Gilchrist, & S. Liversedge (Eds.). *The oxford handbook on eye movements* (pp. 455–470). Oxford: Oxford University Press.
- Kristjánsson, Á. (2015). Reconsidering visual search. *i-Perception*, 6(6), 1–14.
- Kristjánsson, Á. (2016). The slopes remain the same: Reply to WOLFE (2016). *i-Perception*, 7(6) 2041669516673383.
- Kristjánsson, Á., & Ásgeirsson, Á. G. (2019). Attentional priming: Recent insights and current controversies. *Current Opinion in Psychology*, 29, 71–75.
- Kristjánsson, Á., Jóhannesson, Ó. I., & Thornton, I. M. (2014). Common attentional

- constraints in visual foraging. *PLoS One*, 9(6), e100752.
- Kristjánsson, T., & Kristjánsson, Á. (2018). Foraging through multiple target categories reveals the flexibility of visual working memory. *Acta Psychologica*, 183, 108–115.
- Kristjánsson, T., Thornton, I. M., & Kristjánsson, Á. (2018). Time limits during visual foraging reveal flexible working memory templates. *Journal of Experimental Psychology: Human Perception and Performance*, 44(6), 827–835.
- Kristjánsson, Á., Ólafsdóttir, I. M., & Kristjánsson, T. (2019). *Visual foraging tasks provide new insights into the orienting of visual attention: Methodological considerations*. Springer Neuromethods.
- Kristjánsson, A., Wang, D., & Nakayama, K. (2002). The role of priming in conjunctive visual search. *Cognition*, 85(1), 37–52.
- Krummenacher, J., Grubert, A., & Müller, H. J. (2010). Inter-trial and redundant-signals effects in visual search and discrimination tasks: Separable pre-attentive and post-selective effects. *Vision Research*, 50(14), 1382–1395.
- Lamy, D. F., & Kristjánsson, Á. (2013). Is goal-directed attentional guidance just intertrial priming? A review. *Journal of Vision*, 13(3) 14–14.
- Neisser, U. (1963). Decision-time without reaction-time: Experiments in visual scanning. *The American Journal of Psychology*, 76(3), 376–385.
- Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson, Á. (2019). Visual foraging and executive functions: A developmental perspective. *Acta Psychologica*, 193, 203–213.
- Ólafsdóttir, I. M., Kristjánsson, T., Gestsdóttir, S., Jóhannesson, Ó. I., & Kristjánsson, Á. (2016). Understanding visual attention in childhood: Insights from a new visual foraging task. *Cognitive Research: Principles and Implications*, 1(1), 1–18.
- Olivers, C. N., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, 15(7), 327–334.
- Palmer, J. (1994). Set-size effects in visual search: The effect of attention is independent of the stimulus for simple tasks. *Vision Research*, 34(13), 1703–1721.
- Scharf, I., Lubin, Y., & Ovadia, O. (2011). Foraging decisions and behavioural flexibility in trap-building predators: A review. *Biological Reviews*, 86(3), 626–639.
- Shurygina, O., Kristjánsson, Á., Tudge, L., & Chetverikov, A. (2019). Expectations and perceptual priming in a visual search task: Evidence from eye movements and behavior. *Journal of Experimental Psychology: Human Perception and Performance*, 45(4), 489–499.
- Sternberg, S. (1967). Two operations in character recognition: Some evidence from reaction-time measurements. *Perception & Psychophysics*, 2(2), 45–53.
- Theeuwes, J., Reimann, B., & Mortier, K. (2006). Visual search for featural singletons: No top-down modulation, only bottom-up priming. *Visual Cognition*, 14(4–8), 466–489.
- Thornton, T. L., & Gildea, D. L. (2007). Parallel and serial processes in visual search. *Psychological Review*, 114(1), 71–103.
- Thornton, I. M., & Horowitz, T. S. (2004). The multi-item localization (MILO) task: Measuring the spatiotemporal context of vision for action. *Attention, Perception, & Psychophysics*, 66(1), 38–50.
- Tinbergen, L. (1960). The natural control of insects in pinewoods I. Factors influencing the intensity of predation by songbirds. *Archives Neerlandaises de Zoologie*, 13, 265–336.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance*, 16(3), 459–478.
- Vreven, D., & Blough, P. M. (1998). Searching for one or many targets: Effects of extended experience on the runs advantage. *Journal of Experimental Psychology: Animal Behavior Processes*, 24(1), 98–105.
- Wang, Z., & Klein, R. M. (2010). Searching for inhibition of return in visual search: A review. *Vision Research*, 50(2), 220–228.
- Ward, R., & McClelland, J. L. (1989). Conjunctive search for one and two identical targets. *Journal of Experimental Psychology: Human Perception and Performance*, 15(4), 664–672.
- Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception and Psychophysics*, 1, 315–318.
- Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic Bulletin & Review*, 1(2), 202–238.
- Wolfe, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, 9(1), 33–39.
- Wolfe, J. M. (2013). When is it time to move to the next raspberry bush? Foraging rules in human visual search. *Journal of Vision*, 13(3), 1–17.
- Wolfe, J. M. (2016). Visual search revived: The slopes are not that slippery: a reply to Kristjánsson (2015). *i-Perception*, 7(3) 2041669516643244.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 15(3), 419–433.