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, Kalff, & 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; Fougnie, 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, 2012; Fougnie et al., 2015; Gilchrist et al., 2001).
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 than visual search tasks and thus have 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; Fougnie 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 × 15 cm and an effective resolution of 1024 × 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 ¼ of the set-size, drawn on a black background (see Fig. 1). The diameter of targets and distractors was 20 pixels, approximately 0.37° of visual angle.

The items were randomly distributed across a non-visible 10 × 8 grid offset from the edge of the screen by 150 × 100 pixels. The whole viewing area therefore occupied 15 × 12 cm (approximately 14.3 × 11.4°). The exact position of individual items within the grid was jittered by adding a random horizontal and vertical offset (\(x/2 \cdot y/2\)) 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 × 2 in Experiment 1 and 3 × 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 separate 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) × 4 (set-size 20, 40, 60 and 80) repeated-measures ANOVA on the average run number confirmed significant main effects of both condition, \(F(1,11) = 107.05, p < .001, \eta^2_p = 0.91\), and set-size, \(F(3,33,14.58) = 42.66, p < .001, \eta^2_p = 0.80\). The
interaction was also significant, $F(1.59,17.45) = 34.32$ $p < .001$ $\eta^2_p = 0.80$. 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, $F(3,52) = 60.16$ $p < .001$ $\eta^2_p = 0.790$ but not during conjunction foraging, $F(3,52) = 1.23$ $p = .309$ $\eta^2_p = 0.073$, 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, $F(1,11) = 120.89$ $p < .001$ $\eta^2_p = 0.917$, and set-size $F(2.15,23.65) = 65.55$ $p < .001$ $\eta^2_p = 0.856$ on proportional run number. The interaction, however, was not significant $F(1.95,21.46) = .41$ $p = .663$ $\eta^2_p = 0.036$.

### 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
analyze separately: i) a ‘cruise-phase’ which involves all ITTs 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 (ΔITTs) throughout the trial, shown in Table 3. ΔITT was calculated as the difference between an ITT and the previous ITT so that negative

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.
ΔITTs represent shorter ITTs (downward slope on average as the trial progresses) and positive ΔITTs 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) × 4 (set-size) repeated measures ANOVA was conducted for each of the phases. For the cruise-phase, ΔITTs 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, \( F(1,11) = 17.37 \) \( p = .002 \) \( \eta^2_p = 0.612 \) but not of set-size, \( F(1.29,14.24) = 2.74 \) \( p = .114 \) \( \eta^2_p = 0.199 \), and their interaction was not significant, \( F(1.78,19.56) = 1.05 \) \( p = .362 \) \( \eta^2_p = 0.087 \). The ΔITTs 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 ΔITTs. 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, \( F(1,11) = 132.63 \) \( p < .001 \) \( \eta^2_p = 0.923 \). The effect of set-size was not significant, nor was the interaction significant, set-size: \( F(2.15,23.66) = 0.37 \) \( p = .711 \) \( \eta^2_p = 0.032 \); intersection: \( F(1.99,21.90) = 1.03 \) \( p = .375 \) \( \eta^2_p = 0.085 \). 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, \( F(1,11) = 34.83 \) \( p < .001 \) \( \eta^2_p = 0.760 \), and set-size, \( F(2.32,25.56) = 4.54 \) \( p = .017 \) \( \eta^2_p = 0.292 \). However, as Fig. 3 shows, the set-size pattern needs to be interpreted in light of the significant condition × set-size interaction, \( F(2.66,29.23) = 5.90 \) \( p = .004 \) \( \eta^2_p = 0.349 \). 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).

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

<table>
<thead>
<tr>
<th>Set-size</th>
<th>Mean RN</th>
<th>Median RN</th>
<th>SD</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature 20</td>
<td>5.46</td>
<td>5</td>
<td>1.44</td>
<td>0.007</td>
</tr>
<tr>
<td>40</td>
<td>8.88</td>
<td>9</td>
<td>2.55</td>
<td>−0.434</td>
</tr>
<tr>
<td>60</td>
<td>12.43</td>
<td>13</td>
<td>3.43</td>
<td>−0.483</td>
</tr>
<tr>
<td>80</td>
<td>15.53</td>
<td>16</td>
<td>4.98</td>
<td>−1.148</td>
</tr>
<tr>
<td>Conjunction 20</td>
<td>3.1</td>
<td>1</td>
<td>1.52</td>
<td>1.239</td>
</tr>
<tr>
<td>40</td>
<td>3.87</td>
<td>2</td>
<td>2.62</td>
<td>1.244</td>
</tr>
<tr>
<td>60</td>
<td>4.11</td>
<td>2</td>
<td>3.45</td>
<td>1.643</td>
</tr>
<tr>
<td>80</td>
<td>5.11</td>
<td>2</td>
<td>4.77</td>
<td>1.534</td>
</tr>
<tr>
<td>Foraging 20</td>
<td>3.1</td>
<td>1</td>
<td>1.52</td>
<td>1.239</td>
</tr>
<tr>
<td>40</td>
<td>3.87</td>
<td>2</td>
<td>2.62</td>
<td>1.244</td>
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<tr>
<td>60</td>
<td>4.11</td>
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<tr>
<td>80</td>
<td>5.11</td>
<td>2</td>
<td>4.77</td>
<td>1.534</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Set-size</th>
<th>Cruise Intercept</th>
<th>ΔITT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature 20</td>
<td>340.09</td>
<td>6.85</td>
</tr>
<tr>
<td>40</td>
<td>309.59</td>
<td>4.06</td>
</tr>
<tr>
<td>60</td>
<td>309.23</td>
<td>2.48</td>
</tr>
<tr>
<td>80</td>
<td>317.82</td>
<td>1.87</td>
</tr>
<tr>
<td>Conjunction 20</td>
<td>405.47</td>
<td>15.79</td>
</tr>
<tr>
<td>40</td>
<td>372.38</td>
<td>6.87</td>
</tr>
<tr>
<td>60</td>
<td>345.77</td>
<td>9.71</td>
</tr>
<tr>
<td>80</td>
<td>330.95</td>
<td>7.49</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Position</th>
<th>Set-size</th>
<th>Mean (ms)</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature foraging</td>
<td>Mid-peaks 20</td>
<td>381.74</td>
<td>57.51</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>378.30</td>
<td>118.23</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>337.33</td>
<td>30.05</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>354.43</td>
<td>77.75</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>487.85</td>
<td>77.13</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>445.26</td>
<td>78.27</td>
</tr>
<tr>
<td>End-peaks 20</td>
<td>499.01</td>
<td>72.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>449.01</td>
<td>130.12</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>538.75</td>
<td>96.47</td>
</tr>
<tr>
<td>Conjunction foraging</td>
<td>Mid-peaks 60</td>
<td>558.17</td>
<td>111.08</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>538.75</td>
<td>96.47</td>
</tr>
<tr>
<td>End-peaks 60</td>
<td>982.94</td>
<td>451.97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>1168.49</td>
<td>461.41</td>
</tr>
</tbody>
</table>
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 × 4 (switch (yes, no) × 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, ηp² = 0.494; repeat/switch: F(1, 12) = 80.29, p < .001, ηp² = 0.870; interaction: F(2.08, 24.99) = .91, p = .421, ηp² = 0.070 during feature foraging. Set-size: F(1.80, 19.79) = 0.79, p = .457, ηp² = 0.067; repeat/switch: F(1, 12) = 158.14, p < .001, ηp² = 0.935; interaction: F(1.62, 17.83) = 12.51, p = .001, ηp² = 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 (ΔITTs) was not significantly affected by set-size, although there was a clear trend towards lower ΔITTs 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

<table>
<thead>
<tr>
<th>Proportion</th>
<th>Mean run number</th>
<th>Median run number</th>
<th>SD</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature</td>
<td>25</td>
<td>8.83</td>
<td>9</td>
<td>2.40 −0.540</td>
</tr>
<tr>
<td>Foraging</td>
<td>50</td>
<td>14.75</td>
<td>15</td>
<td>4.48 −0.451</td>
</tr>
<tr>
<td>75</td>
<td>22.52</td>
<td>23</td>
<td>5.73</td>
<td>−0.920</td>
</tr>
<tr>
<td>Conjunction</td>
<td>25</td>
<td>3.55</td>
<td>2</td>
<td>2.33 1.589</td>
</tr>
<tr>
<td>Foraging</td>
<td>50</td>
<td>3.57</td>
<td>2</td>
<td>3.09 2.431</td>
</tr>
<tr>
<td>75</td>
<td>4.65</td>
<td>2</td>
<td>4.80</td>
<td>1.891</td>
</tr>
</tbody>
</table>

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) × 3 (proportions) repeated measures ANOVA on the average run numbers confirmed significant main effects of both condition, F(1,13) = 186.10, p < .001 η² = .94, and proportion, F(1.73,22.53) = 182.84 p < .001 η² = .934 and a significant interaction, F(1.67,21.74) = 198.49 p < .001 η² = .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 η² = .879 and proportional run number F(2, 39) = 9.87 p < .001 η² = .336, but not for conjunction foraging F(2, 39) = 0.72 p = .494 η² = 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 ITTs 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) × 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 η² = .687, and a main effect of proportion F(1,10,14.34) = 17.65 p = .001 η² = 0.576 on ΔITTs. The interaction between condition and proportion was also significant F(1.14,14.85) = 12.40 p = .002 η² = 0.488. Unlike absolute set-size in Experiment 1, where the effect of set-size on ΔITTs was not quite significant, manipulating relative set-size (target proportion) significantly affected ΔITTs, 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 η² = 0.798, and proportion, F(1,44,18.69) = 30.85 p < .001 η² = 0.704. As in Experiment 1, there was a significant interaction F(1.43,18.59) = 19.45 p < .001 η² = 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 η² = 0.887 and target proportion, F(1.67,21.65) = 19.10 p < .001 η² = 0.595, and a significant condition × proportion interaction. F(1.57,20.45) = 6.36 p = .011 η² = 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)) × 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 η² = 0.586 and proportion F(1.36,17.72) = 28.73 p < .001 η² = 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 η² = 0.088. During conjunction foraging both the main effects and the interaction between them were significant (Switch: F(1,13) = 101.44 p < .001 η² = 0.886; proportion: F(1.51,19.61) = 62.76 p < .001 η² = 0.828; interaction: F(1.62,21.00) = 19.51 p < .001 η² = 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 ΔITTs 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
Experiments 1 and 2 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.
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; Kristjánsson & Kristjánsson, 2015; Kristjánsson & Ásgeirsson, 2019). Understanding how set-size affects visual foraging is 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 (ITT’s) 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...
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; Shurygin, 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 & Faisal, 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 weights 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 intrartial patterns, that carry specific markers that can be important for further understanding of visual attention. Size-set 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?z=ee84ead3-010b-4092-b600-f7308cb82278.

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