Visual Foraging Tasks Provide New Insights into the Orienting of Visual Attention: Methodological Considerations

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Abstract

The topic of visual attention has played an increasingly large role in visual perception research in the past half-century or so. This highlights the need for paradigms that allow a thorough understanding of the function of visual attention and that the experimental tasks that are used are varied and dynamic enough to sample the operational characteristics of visual attention. We discuss newly developed foraging tasks that are more dynamic than many tasks used in the literature, such as the visual search task. Our orienting in the visual environment may not be particularly well encapsulated by the analogy of search for a single item, a search that then ends once the single target is found. Multitarget foraging tasks might cast further light upon the orienting of visual attention, especially in dynamic, multitarget environments. During foraging, observers are asked to select a certain number of target types among distractor items. Here we discuss such foraging tasks, the main considerations for efficient design and effective data analysis. We propose that these tasks will be a highly valuable addition to the toolbox of scientists who investigate the operation of visual attention and visual cognition more generally.

Keywords Visual foraging, Visual attention, Optimal foraging, Patch leaving, Visual search

1 Introduction

The topic of visual attention has played a central role in visual perception research in the past half-century. Selective visual attention has been shown to influence more or less all aspects of the visual process, amplifying the processing of the stimuli that are most relevant to behavior at any given moment [1–4]. Attention has been shown to have an influence at processing stages all the way from low-level processing in the lateral geniculate nucleus [5] to higher-level object representations in the ventral visual stream [6].

This highlights the need for paradigms that allow a thorough understanding of the function of visual attention and that the experimental tasks that are used are varied and dynamic enough to sample the operational characteristics of visual attention sufficiently well. One way of studying visual attention involves how we

locate or select the visual stimuli that are important to us at a given moment. A popular way of modeling this procedure experimentally involves the well-known visual search task [7, 8].

In the version of the visual search task that has become dominant in the field, observers typically search for a single target among distractors [9, 10]. Older experiments often involved multiple target types [11–13], although there was usually only one target to search for in these paradigms in each instance of the task (each trial). These tasks can be of various difficulties that depend both on stimulus factors, such as whether noise is included to decrease visibility in the display [8, 14] and instructional manipulations such as what rules distinguish the target from the distractors: Is the target the single item that has a certain unique color or the single item that has a certain color *and* a certain shape [15]? Observers are typically asked to indicate whether a predesignated target is present or absent in an array of visual search items and their response times (usually with key press) are recorded. When they have responded, the search trial ends and a new trial follows. Results from this task have been extensively used in theories of the operation of visual attention for decades. A common assumption is that the search process occurs in processing stages [16, 17], and this is the main idea in Anne Treisman's highly influential *feature integration theory* of visual attention [18]. Neisser [19] proposed the idea of a preattentive stage, where individual items are not processed. Observers noted that individual nontarget letters in his search task were "only a blur." The crux of the feature integration theory is that an attentive stage follows this preattentive stage where free-floating features are integrated and objects identified, a process that takes time and effort (e.g., [10]).

The single-target visual search task has undeniably yielded important insights regarding the operational characteristics of visual attention, such as its processing capacity [13], its processing speed [16, 19], what captures attention [20], how attention is guided across a visual scene [21], what items can be processed in parallel [15], and how this is influenced by the context that the stimuli appear in [22, 23]. Feature integration theory is at its core a two-stage theory, where a distinction is made between preattentive processing and attentive processing, and this distinction has been dominant in the literature on visual search and visual attention [24], where the assumption is that some items can be found preattentively while others need processing by visual attention and effortful feature integration. Many results have however cast doubt upon such a stringent distinction [23–27] necessitating modifications of the basic tenets of many theories of visual attention.

2 Visual Foraging

A number of authors have speculated that more dynamic tasks might cast further light upon the orienting of visual attention. Our orienting in the visual environment may not be particularly well encapsulated by the analogy of search for a single item, a search that then ends once the single target is found. One method that researchers have increasingly used in recent years to investigate human visual orienting is the so-called *foraging* task. During foraging, observers are asked to select a certain number of target types among distractor items (see example in Fig. 1). The foraging task has its roots in research on how animals feed [29–35].

Some of the key variables that researchers have investigated with regard to foraging behavior involve things such as the concept of the *search image* (see Table 1). The idea is that during search and foraging, observers use search images whose content reflects the task goals in each case [36–38]. They have a rather clear analogue in the literature on human visual attention, where they are referred to as templates that are assumed to be stored in working memory [2, 39–43]. Working memory is capacity limited, which may be one reason why participants do not always forage optimally. In the words of Tinbergen ([34], pp. 332–333), birds "perform a highly selective sieving operation on the visual stimuli that reach their retina [and] can only use a limited number of different search images at the same time."

Another key concept is that the search image forces particular *run behavior* (Table 1). This refers to in what order participants forage for the different target types in the display. Early findings on run patterns showed that foraging for two different target types is typically nonrandom in animals. Experimental studies of such run-like behavior involve investigations of patterns of free choice [44, 45], serial-detection responses [36, 46] or direct measures of the order in which items are selected [47], and how *crypsis*, which involves how easily targets can be found in the display, affects foraging patterns.

Early foraging studies of humans involved mechanical displays [48–50]. Recent technological progress, such as the availability of touchscreen technology, has enabled easier assessment of human foraging. Note that foraging tasks are by no means confined to touch, however—foraging can also be done by mouse clicks [51] and eye gaze [52] in real-world displays where observers physically interact with the stimuli that they should collect [49, 50] or in virtual reality [52].

The foraging paradigm yields very rich datasets—and perhaps the large amount of multifaceted performance measures and their interaction can be overwhelming. The typical methods of visual search tasks are far more manageable, and perhaps this partly
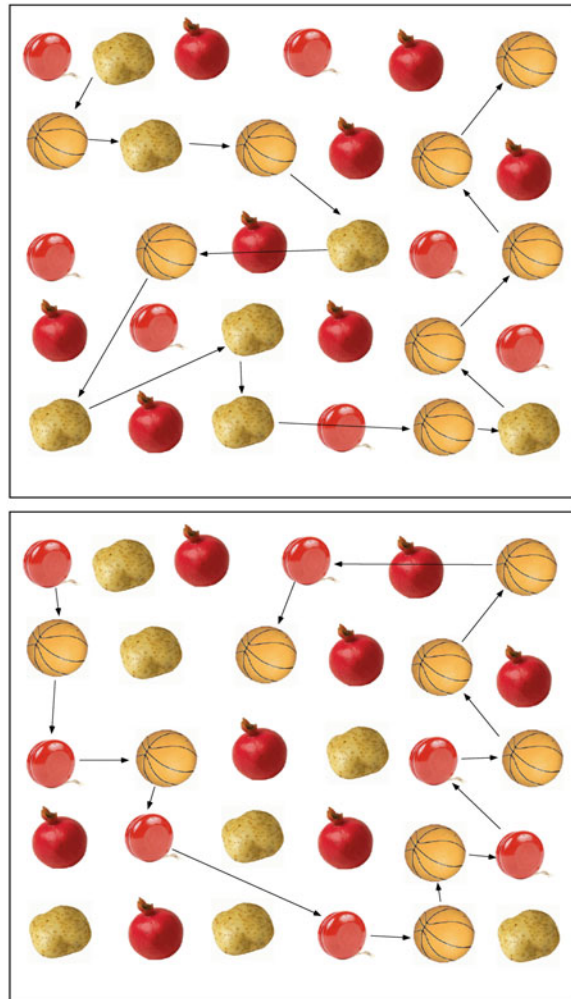
Fig. 1 A foraging task showing how a forager might select targets depending on different instructions or selection rules. In the top panel, the task is to select all the items that have a certain color, while in the lower panel, the observers must forage for all the items connected to sports or games. (The individual images come from Ref. [28])

accounts for the popularity of visual search methodology. For example, slopes that are assumed to assess the involvement of attention allow easy summary interpretations of visual search data, although their blind use as indices of the involvement of visual attention is highly suspect [24].

While it is not our goal here to go over in detail what the findings on human foraging have revealed, foraging results have in many ways deviated from many predictions, such as from theories of visual attention, predictions from priming studies [53], and conceptions of working memory and its capacity. In Kristjánsson

Table 1
Key concepts involved in studies of visual foraging

Search image	The concept that foragers form an internal image that contains the characteristics of the target (or targets) in each case. The concept is roughly similar to templates in visual working memory
Run behavior	In what order do observers select the different target types in the display? Do they select the same target type repeatedly until they are all gone or select the different target types randomly? A run is defined as the repeated consecutive selection of the same type of prey
Patch leaving	In experiments where observers can move to a new foraging display ("patch") before all the targets in their current one have been collected, patch leaving involves how soon they move to the next target source
Optimal foraging theory and the *marginal value theorem*	According to optimal foraging theory, observers will adjust their foraging so that it matches the marginal value theorem which states that foragers will leave a food source when the collection rate drops below the average collection rate within an environment
Collection rate	A measure of how quickly target items are collected. Usually measured in the number of items per second
Intertarget times	The time that passes between each target selection *within* a foraging trial
Cruise phase	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
Mid- and end peaks	Mid-peaks are seen in difficult foraging tasks (e.g., conjunction foraging) and reflect when observers switch between target categories. End peaks are seen at the end of foraging trials (in tasks where observers must find all targets)
Switch costs	Involve the increase that appears in ITTs when observers switch between target types
Foraging organization	How observers organize their foraging within a trial. Typically measured in three ways: with *best-R (see below)*, *distance traveled*, *and the number of intersections*

et al. [53] where observers foraged for multiple instances of two target types simultaneously, interestingly, some observers could forage simultaneously for two conjunction targets, going against the predictions of theoretical conceptions such as feature integration theory, and the findings of Kristjánsson and Kristjánsson [54] argued against influential slot conceptions of working memory [55, 56]. This highlights how foraging tasks can help to decide between theoretical accounts and the additional information that these foraging paradigms can provide over and above the

reductionist approach used in many studies of visual search and visual working memory.

In what follows, we discuss a number of issues to consider when foraging studies are designed. Our aim is to provide an overview of methods used in foraging research, including statistical treatment of the large datasets that foraging experiments yield.

2.1 Procedures

2.1.1 Exhaustive Foraging Versus Non-exhaustive Foraging and "Patch Leaving"

One distinction made in the foraging literature is between exhaustive foraging and non-exhaustive foraging. Exhaustive foraging means that every target in the foraging patch must be found, while in non-exhaustive foraging, the forager can freely move to a new "patch" (in computerized foraging tasks a new foraging display), whenever he chooses, called *patch leaving* (Table 1). Patch leaving refers, in other words, to when foraging within a certain patch is terminated and the forager moves to the next patch [51]. Several parameters affect when foragers leave a patch and move to the next one. The availability of targets [51], expectation of the number of targets [57], the time it takes to move to a different patch or the effort that it involves [51], the difficulty of the foraging task [58], and the value of the foraged items [59, 60] can all affect patch leaving. When the targets are abundant, foragers will leave a patch earlier than if targets are scarce, which at first glance might seem counterintuitive. Consider, however, that if you are searching for food and there is little food about, it is likely that you will exhaustively search each area before moving to the next. If, however, there is a lot of food around, you are likely to pick the easily accessible food and leave behind food items that are harder to find. This is also related to the effect of expectation; if the collection rate is lower than expected, foragers will leave that patch earlier than if the collection rate matches or exceeds the expected collection rate. The time or cost of moving to a new patch also affects patch leaving and does so in a very intuitive way, when you have to travel a long distance to a new patch; if moving to the new patch takes a long time or if it puts the forager at risk to move, the forager will stay in the current patch for longer. This is logical as long as the collection rate in the current patch is not zero. If you could have collected several targets in the time it takes to move to a new patch, the collection rate at the new patch must be higher than at the current patch to make leaving the current patch beneficial. In addition, the value of the foraged targets affects the patch leaving behavior. Wolfe et al. [59] showed that when targets have different values, foragers will conduct a roughly exhaustive search of the more valuable targets while leaving more of the less valuable targets behind. This effect seems to override or at least strongly skew the effect of availability, although there were also some individual differences.

Non-exhaustive foraging replicates natural food foraging situations, where humans and animals are generally able to leave a foraging patch. There are however situations where finding every single target is required for the task at hand; in those situations, exhaustive foraging tasks better represent those situations. In addition, studying exhaustive foraging allows for better control over the number of targets selected and therefore a more controlled study of variables such as switch costs and the number of runs. Further, according to *optimal foraging theory* and the *marginal value theorem* [61]; (see Table 1), foragers will leave a food source when the collection rate drops below the average collection rate or the expectancy of such an average. Exhaustive foraging allows the study of foraging after the collection rate drops below average, and the forager would have left the patch in a patch leaving paradigm. Both procedures therefore have their obvious value.

2.1.2   Do the Foraging Targets Disappear or Persist Once They Have Been Tapped?

In most foraging studies, the targets disappear once they have been tapped. This seems to be a natural procedure as it mimics real-life foraging where food items disappear upon being collected and/or eaten. But studies where targets do not disappear upon being tapped, but persist on the screen, can nevertheless be useful for testing memory for visited locations, both in normal populations and patient populations that may be expected to have problems with spatial memory. Those may include those suffering from hemispatial neglect [62, 63], simultagnosia [64], or impaired spatial working memory [65] and can also address questions such as regarding spatial learning throughout the foraging process.

Observers rarely re-fixate distractors in single-target visual search [66, 67] and seem to have good memory for checked items and locations, but as soon as the targets become two or more, and persist on the screen after they are selected, refixations on both distractors and the previously found targets become significantly more common [66, 68]. Moreover, when targets disappear or if they change into salient, easily distinguishable items when they are found, accuracy is significantly higher than if the targets remain on the screen or change into distractor items once they are found [68].

The presence of already selected targets may misdirect attention. The features of these tapped, but remaining targets, match those of unfound target items, and they may therefore still attract attention, interfering with subsequent foraging [68]. Another explanation of why search accuracy is worse when targets remain on the screen is that found targets may take up working memory resources, thus interfering with further foraging [66, 68]. We should note, however, that Thornton and Horowitz [69] had items either vanish or remain once they had been located. This manipulation had surprisingly little effect on search performance, suggesting that old target items could be efficiently ignored. However, in Horowitz and Thornton [70], where the items moved

around, memory for previous targets was more or less gone, suggesting that locations, not objects, had been memorized in their previous study.

Patients with right hemisphere brain damage often fail to attend to objects, sounds, and events on their left, a condition called hemispatial neglect [71–73]. Neglect patients also show abnormal visual search behavior, where they repeatedly examine items in their right visual hemifield while ignoring items in their left hemifield [63, 71–74]. On bedside paper and pen cancellation tests, which require foraging for multiple items, these patients usually start searching from the right and fail to find targets on the left side of the paper test. Many patients also repeatedly re-fixate locations on their right while ignoring targets on their left [63, 65, 75].

Using a touchscreen foraging task, Parton et al. [63] studied the foraging behavior of two groups of stroke patients with right hemisphere brain damage, with and without hemispatial neglect, in four different conditions: cancellation test, where found targets were marked; invisible cancellation test, where found targets persisted on the screen and no visible marks were left; eraser task, where the targets disappeared upon being found; and finally a bold task, where target outlines became thicker upon being touched, which increased the salience of found targets. If the perceptual salience of found targets is the main reason for revisits, then they should be most common in the cancellation and bold tasks and least common in the eraser task. If, on the other hand, a deficit of spatial working memory is to blame for the results, the revisits should occur predominantly in the invisible cancellation test [63]. For both patient groups, revisits were most frequent in the invisible cancellation test, indicating that their memory for previously searched locations was impaired but that the influence of the perceptual salience of previously found targets was minimal. Mannan et al. [62] used a foraging task with persistent targets along with eye tracking to assess whether neglect patients misjudged whether they were finding a target for the first time or not. The patients were instructed to press a response button only when they fixated a target for the first time. Patients with frontal lobe or intraparietal sulcus lesions repeatedly judged that they were selecting previously found targets for the first time, but patients with occipito-temporal lesions did not. These results indicate that repeated refixations occur because patients do not remember where they have found targets before, suggesting that a spatial working memory deficit accompanies neglect. Using a foraging task where targets persist on the screen after being found thus helped map out the deficits that explain the pathological refixation on targets in the right hemifield of hemispatial neglect patients.

2.2 Measures of Foraging Performance

2.2.1 Run Patterns

With multiple target types, it is possible to assess the strategies that observers use to finish the foraging task. Do observers finish all targets of one type before switching to the next, or do they tend to switch between target types within a trial? Measuring this aspect of performance can, among other things, provide information about how many target templates observers can simultaneously keep in mind and how hard it is for them to switch between different target types. Studies on animal foraging have shown that animals often forage for prey in nonrandom "runs" [30, 35, 44]. A run is defined as the repeated consecutive selection of the same type of prey. The typical finding is that the harder the prey is to find, the longer the runs become, while when the prey is easy to detect, switching between target types becomes more frequent, with the animal foraging in many short runs [35, 76]. Studies on the foraging patterns of humans have also revealed that attentional load alters foraging behavior [53, 77]. When targets are defined by a single feature (e.g., color), switching between target categories is frequent and random, but when targets are defined by a conjunction of features (e.g., color and shape), observers tend to exhaustively forage for one target type before switching to the next one (Fig. 2), completing most trials in only two runs [53, 78–80]. Those foraging patterns can be affected, however, by altering task parameters. Switches between target
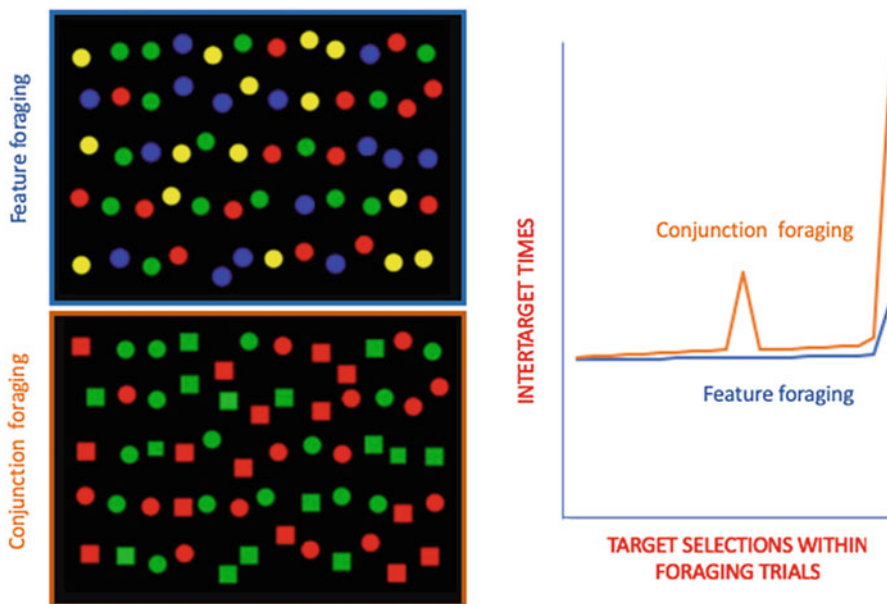

Fig. 2 Feature versus conjunction foraging. The graph shows typical intertrial patterns for the two types of foraging—relatively similar "cruise phases" apart from the mid-peaks for conjunction foraging and the end peaks seen in both conditions. Note that the end peaks are much higher for conjunction foraging

categories during conjunction foraging can be increased by imposing time limits [81], having participants forage using eye gaze and fixation rather than tapping targets [82], and only rewarding switches between target categories [83], indicating that foraging patterns do not only reflect capacity restraints but also a strategy to optimize hit rate with as little mental effort as possible.

2.2.2 Intertarget Times and Collection Rate

Another way to analyze foraging data is to assess how quickly people can forage for a given number of targets. One obvious measure is the total time taken to forage for all targets within a certain time. Another, arguably more interesting measure involves the intertarget times (ITTs, see Fig. 2) that involve the time between each tap on a target. Another way to define foraging speed is with collection rate, which is a measure of how many items are collected per second or in other words 1 divided by the ITTs [59, 84]. So, if the ITTs are 0.25 s, then the collection rate is $1/0.25 = 4$ items per second. Measuring foraging times allows insights into how different foraging conditions affect foraging performance, and whether ITTs are steady throughout a trial, or if they change or fluctuate within trials.

As foraging tasks become more difficult, ITTs become higher, and collection rates therefore drop. ITTs are, for example, higher when the targets are defined by a more complex rule (i.e., by a conjunction of features rather than a single feature [54]), when the number of targets or target types is increased [54], and when the targets are moving [84]. In a series of studies where the researchers used feature versus conjunction foraging to manipulate task complexity (see also discussion above), there was a dramatic difference in total completion times of feature and conjunction-based trials, where observers had to forage for 40 targets of two types among 40 distractors (feature foraging, e.g., green and red targets among blue and yellow distractors; conjunction foraging, e.g., red disks and green squares among red squares and green disks) [53, 77, 82]. But interestingly, the ITTs per tap throughout the majority of the foraging trials were rather similar across conditions. The largest performance differences between ITTs during feature and conjunction foraging involved the mid- and end peaks. The mid-peaks only appeared during conjunction foraging and represented the switch costs that occur when observers switch from one target type to the next. The end peaks appeared in both tasks but were significantly larger during conjunction foraging [78–80]. What is more, there was only a slight upward slope of ITTs throughout the "cruise phase," or, in other words, the taps that did not belong to the mid- or end peaks, meaning that ITTs did not become significantly higher as a function of fewer targets on the screen but remained relatively stable, excluding the mid- and end peaks [78]. Note that, again, this highlights the added information available with foraging tasks over simpler ones, such as visual search tasks.

2.2.3 Switch Costs and Mid-peaks

Switch costs involve the increase in ITTs that occurs when observers switch between target types, instead of continuing a run by selecting a target of the same type as the previously selected one. Switch costs are calculated by deducting the mean ITTs of taps in a run from the mean ITTs when observers switch between target types.

In easy foraging tasks, where there are only two target types, defined by a single feature, and all targets are static on the screen, the switch costs are negligible. As the tasks become more complex, the switch costs grow larger; they are, for example, much larger during conjunction than feature foraging [53] and grow as the number of target types goes up [54, 84]. In accordance with this, when there are more than two target types, observers tend to alternate between two target types instead of switching randomly between targets of all types in the display, and this switching results in lower switch costs than switching between more target types [83]. Notably, however, a number of observers actually were able to rapidly switch between target types even during difficult foraging tasks and were tentatively called "super-foragers" [53, 77, 85] as the results seemed to suggest that their capacity to hold complex target types in memory was higher than for the other participants. But Kristjánsson et al. [81] then found that by introducing time limits during foraging; contrasting conditions where observers had 5, 10, or 15 s to forage; and comparing this with foraging with unlimited time, many more observers could switch rapidly between target types. Kristjánsson et al. [81] suggested that this demonstrated the flexibility of working memory—that observers could perform at high capacity for short bursts that require high levels of concentration and that they choose not to do this during foraging with no time limits because of the effort involved. The switch costs then result in so-called mid-peaks in ITTs during foraging trials for the more difficult tasks, reflecting the point where observers switch between target categories, after having finished all targets from the other target category (see Fig. 2).

2.2.4 End Peaks

No matter how simple or easy a foraging task is, observers seem to have difficulty finding the last target item in the display and are usually much slower at this than for other items in the display. This results in a distinct rise in ITTs for the last target item, a performance pattern that has been named "end peaks" (Kristjánsson et al., under review; see Fig. 2). The same applies to end peaks as to switch costs and ITTs in general: As the task becomes more complex, the end peaks become larger. Moreover, interestingly, Kristjánsson et al. [78] found that set size has a different effect on end peaks during feature and conjunction foraging tasks. During feature foraging, end peaks remain the same size regardless of set size, but during conjunction foraging, the end peaks become larger as set size increases. So, when the size of the end peaks of

trials with different set sizes is plotted, set size slopes found in single-target visual search are replicated. What is interesting about these results is that it is only this last selection out of multiple target selections during the foraging task that reflects results from single-target visual search tasks. This highlights the need for varied approaches to studying the complex construct of visual attention, and also the additional information that foraging paradigms provide, since this result suggests that the last target selections in the foraging display simply reduce to one trial in a single-target visual search task.

2.2.5 Measures of Foraging Organization

Another way of assessing foraging performance is to analyze how observers organize their foraging throughout the trial. Do they, for example, start on one side and systematically go through the display in columns or rows, or is their foraging more random than this (see Fig. 3)? As discussed by Woods et al. [86], there are at least three ways to measure foraging organization.

Best-r can be used to test the organization or systematicity of the foraging path that observers take. In a static foraging display, human foragers will typically forage in a systematic way, starting, for example, in the top left quadrant and searching through rows or columns through the foraging display [87–89]. The *best-r* is found by calculating the Pearson correlation coefficient (r) from a linear regression of the x- and y-values independently by the location of each target relative to the order in which they were selected. The higher r-value (either from the x- or y-axis) is then used to assess how systematic or orthogonal the foraging path is. For example, starting in the top left quadrant of the foraging display and selecting targets by columns progressively rightward would result in a higher r-value on the x-axis than the y-axis regression, because the foraging path would be consistently horizontal (left-to-right). A highly organized foraging path would generally result in a high best-r. So, if the r for the regression of the y-axis and selection order was .1, while it was .9 for the same regression relative to the x-axis, we would assume that the search was highly organized by columns. Note, however, that there *are* some systematic paths possible that would result in a low best-r. Best-r is calculated for each trial for each participant, and averages for each participant in each condition can then be used in ANOVAs or *t*-tests or other statistical treatments.

Total distance traveled is another measure of foraging organization. The most organized foragers should travel the shortest distance on average, going systematically through the display, while more disorganized foragers might be more prone to select targets further away from one another, or forgetting targets in one part of the display, forcing them to go back to collect them and adding unnecessary travel distance. It is also possible to calculate
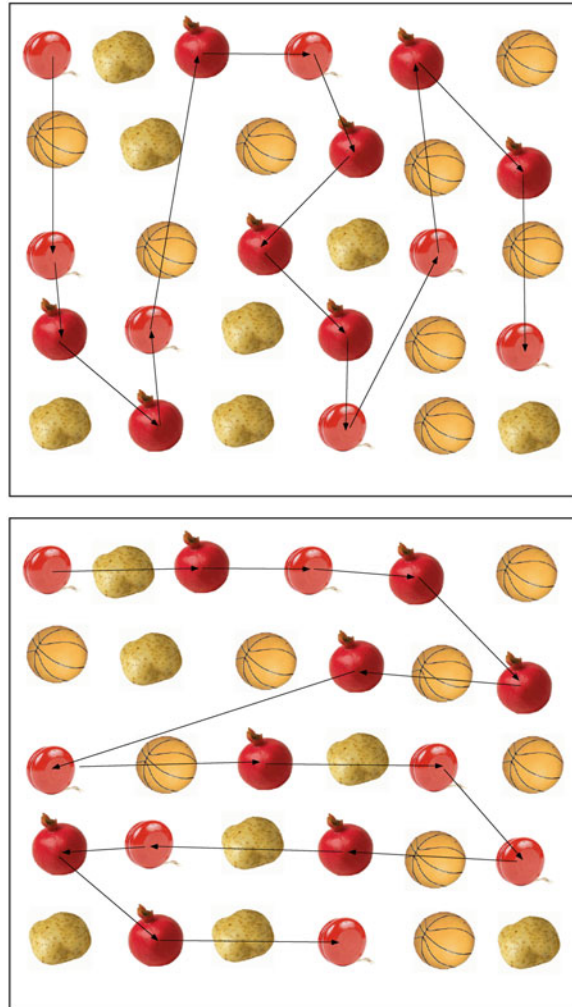
Fig. 3 Different ways of organizing foraging within a given trial, where the targets, in both cases, are the red items

the mean distance between targets [86] with similar results since these measures should be highly correlated.

The number of intersections in the search path is a measure of how often observers revisit parts of the display that they have previously foraged through. If foraging is well organized, there should be no reason to revisit previously searched regions, resulting in few, if any, intersections [86]. The number of intersections should decrease as the foraging becomes more organized. If there is a chance that observers will not collect the same amount of target items (such as in patch leaving tasks or tasks with different set sizes), the total amount of intersections should be divided by the number of items collected, to avoid confounding the assessment with the fact that as more targets are collected, the number of intersections increases on

average [86]. Jóhannesson et al. [82] assessed foraging organization during both foraging with fingers and with eye gaze where observers selected the targets by fixating on them. Firstly, they found that foraging was highly organized during feature foraging. This indicates that participants use consistent horizontal or vertical sweeps through the display when attentional load is low. But during conjunction foraging, performance was not as organized, which may indicate that they were less aware of the locations of other targets in the display.

2.2.6   Patch Leaving

Not all foraging tasks involve that observers must exhaustively forage for all target items in the display. Tasks where participants can choose to leave the current display (or "patch") and move to a new one to forage in, even if all targets have not yet been acquired, allow assessment of when participants choose to leave the current patch. Such studies mimic real-life foraging, where animals seldom exhaustively pick all food items from a patch (e.g., all berries from a single bush) before searching for a better one. As the food items become scarce within a given source, animals tend to move to the next available food source [32, 51].

The marginal value theorem (MVT) is a model of patch leaving behavior that has been used extensively in research on foraging [61]. According to MVT, animals will leave a patch when the instantaneous rate of return drops below the average rate of return for the whole environment [61]. In simple foraging tasks, where all items have the same value, the instantaneous rate of return is essentially the collection rate. If the targets are of different types and have different values, the value of each item collected must be considered [59]. The average collection rate is determined by finding the mean collection rate of the whole area (or the whole set of trials within a block). The average collection rate becomes lower as the time and effort involved in traveling between patches increase [51]. This can be modeled in computerized tasks, for example, by manipulating the amount of time that passes before the next patch appears [51, 59, 84].

Some studies indicate that during simple foraging tasks, human foraging is well predicted by MVT, but when the tasks become more complicated, such as when there is large variation in patch quality [51], when the targets have different values [59], or when the targets cannot be seen (e.g., when observers went fishing in a virtual pond where the availability of fish in the pond was not visible [90]), foraging behavior starts to deviate from the predictions of the model, and observers' behavior tends to become increasingly varied. Recently, Kristjánsson et al. [90] tested patch leaving in humans performing an iPad foraging task. They found that observers foraged for much longer within each patch than predicted by MVT. A clear conclusion from this is that many more variables than

the average acquisition rate within a patch determine patch leaving in particular or foraging performance more generally.

2.2.7 Summary: Modulation of Foraging Strategies

It seems that all the measures discussed above can be modulated by task demands, such as stimulus factors, temporal constraints, or manipulations of motivation (such as with reward). Human foraging performance seems to be affected by various factors, and how observers orient in these multitarget environments can be assessed in many ways. This multidimensional aspect of foraging performance involves a methodological and statistical challenge (a point that we partly address in Sect. 3), while at the same time, this multidimensionality is also an asset for uncovering the operating characteristics of visual attention, enabling unique insights about how observers orient their attention in multidimensional visual environments.

3 Statistical Treatment of Data from Multitarget Foraging Experiments

We should start by noting that foraging paradigms are highly powerful statistically, since they allow rapid acquisition of a large amount of measurements and multidimensional performance measures as discussed in Sect. 2. Measures such as foraging patterns and intertarget times as a function of group and condition can be addressed with standard statistical methods such as ANOVA, regression, or linear mixed models to name a few potential approaches. The last approach in particular may be very promising in assessing both group characteristics and aspects of individual performance. There are however several less traditional methods that are utilized in foraging studies and some further considerations to highlight.

Studying the foraging process generally involves both within-subject and between-subject comparisons. When those within-subject comparisons are performed, it is important to keep in mind that the measures, even between conditions, are highly interdependent, and therefore, if using ANOVA, repeated measures ANOVAs are generally preferable.

A widely used procedure involves the so-called runs test that involves assessing whether observers choose different target types randomly or have a bias toward choosing one target type or the other [91, 92]. The runs test is widely used in the animal literature to test whether animals (from bees to cattle) behave randomly during their selections or not [94]. The basic idea involves determining whether a sequence of x events deviates from a random series of the same number (x) of events. To determine if run behavior is random, a one-sample runs test can be used (a two-sample runs test is called a Wald-Wolfowitz test [93]). Since it is a one-sample test, it needs to be carried out on the data of each participant separately.

Note that since this gives an estimate of whether the run behavior is random for each trial for every participant, it is vital to use post hoc corrections of *p*-values for multiple tests, such as the Bonferroni correction (although other less conservative options should sometimes be considered; [94]). This measure yields a proportion of trials for each participant, in each condition, where run behavior is random. These proportions can then be compared by *t*-tests or ANOVAs depending on the number of conditions. The one-sample runs test has been criticized for its lack of power and often inappropriate use. However, it remains a good choice in ecological studies and studies that fit the initial purpose of the test.

4 Conclusions

The above discussion shows the multifaceted performance measures that are available in foraging studies. Their sheer magnitude may seem daunting, but the tendency in visual attention research has for the last decades or so gone in the other direction. The visual search task (most often involving single targets) has become the standard for assessing whether attention is involved in particular tasks and slopes of set versus response times have actually taken on the status of a diagnostic tool for the question of whether visual attention is involved in a task, and only two main parameters are often assessed (slope and intercept).

We think that this is a mistake [24]. While the visual search task will most certainly continue to be a part of the toolbox of scientists investigating vision and visual attention, more dynamic tasks that more closely resemble real-life visual orienting are also needed. We believe that the visual foraging task is a good candidate for this. In our laboratory we have started to investigate visual foraging in virtual reality environments in an attempt to increase even more the ecological validity of our paradigms. We hope that the discussion here has convinced the reader that foraging tasks will play an important role in the study of human and animal orienting in the visual environment in future research and that the multidimensionality of the approach should be considered a feature rather than a bug.

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