No matter what you do, travel is travel in visual foraging

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Abstract

In visual foraging, foragers collect multiple items from a series of visual displays (or "patches"). When the goal is to maximize the total or the rate of collection of target items, foragers must decide when to leave a depleted patch given that "traveling" from one patch to another incurs a temporal cost. In three experiments, we investigated whether the interposition of a secondary task during travel between patches in visual foraging altered patch-leaving behavior. Over the course of 10- or 30-minute experiments, participants foraged in simulated "berry patches" and traveled to the next patch at will. While they traveled, they either actively performed a secondary task or simply observed passing visual stimuli. Travel time was varied across conditions. The addition of a secondary task, regardless of its relevance to visual foraging, to traveling, or to both, did not impact patch-leaving times in the primary visual foraging task. In Experiment 1 and more weakly in Experiment 2, the patch-leaving decision was based on how long the travel took as predicted by the Marginal Value Theorem (MVT). In Experiment 3, however, patch-leaving did not depend on travel time. Participants 'overharvested' in a manner that suggests that they may have adopted rules different from those of MVT. Across all three experiments, patch-leaving did not depend on the nature of the travel.

Keywords: visual foraging, travel, patch-leaving, visual search

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Everything has an end, and visual search is no exception. When we search for a target, we typically wish to find it accurately and rapidly (Wolfe, 2023). If we do not find what we are looking for, it is similarly important to know when to conclude that the item is not present (Becker et al., 2022; Chun & Wolfe, 1996; Zenger & Fahle, 1997).

The question of when to quit search changes when it comes to visual foraging tasks that involve searching for multiple targets in the same display. If the observer's task is to collect as many items as possible in a fixed amount of time and, thus, to maximize the rate of return, exhaustive collection of every item in a display is generally not the best solution. As target items are collected from a patch, that patch becomes depleted, and the picking becomes slower. There comes a point where it becomes advantageous to stop collecting targets from the current patch and pay for "travel time," the time required to move to a new patch. Travel time imposes a cost because targets cannot be collected during this time. However, it also provides the opportunity to encounter more targets in the next, fresh patch. Foragers should monitor their performance, including travel time, in an effort to leave each patch at the optimal moment.

The Marginal Value Theorem (MVT, Charnov, 1976) provides one way to calculate the optimal patch-leaving time. MVT is particularly applicable in foraging scenarios involving the collection of numerous items across multiple patches (e.g., grazing or berry picking). Its application is less straightforward of tasks with long and variable intervals between target acquisition (e.g., a lion 'foraging' for antelope). According to MVT, the optimal patch-leaving moment occurs when the instantaneous rate of return from the current patch drops to the overall rate of return from the entire habitat. While MVT is an appealing formulation, it also assumes an idealized, arguably over-simplified view of the foraging task. The real world can be more complex. Collecting a target is not always successful (Oaten, 1977). Foragers may not have a good estimate of the average rate of return, particularly at the onset of their search (Kagel et al., 1986). The environment can change (Fougnie et al., 2015) and an understanding of these changes may develop slowly through evidence accumulation (Davidson & El Hady, 2019; Kilpatrick et al., 2021) and learning (Constantino & Daw, 2015; Harhen & Bornstein, 2023). In other words, the decision to leave a patch is influenced by more than just the current rate. Environmental constraints also play a critical role (Stephens & Krebs, 2019). Therefore, it is not always easy to define what is *optimal* in visual foraging (Pierce & Ollason, 1987).

Despite these limitations, MVT does provide a useful framework for analysis of foraging data, especially if, as in the present work, the analysis is focused on comparison between foraging conditions. We can use MVT metrics to investigate if foraging behavior is influenced by changes in conditions even if we cannot assert with complete confidence that the behavior is or is not optimal.

In the present work, we focused on the nature of "travel" between patches. In the idealized framework of MVT, travel is defined as the period from the end of collecting targets in one patch to the start of collecting in the next. Its salient property is that the forager cannot collect targets while traveling. Consequently, traveling must drive down the average rate of return in the task. The logic of MVT holds that, if travel time is long, then the forager should stay longer in the current patch. Traveling to a new patch is not as rewarding as staying longer in a patch when travel is long.

In the real world, however, travel may not be so simple. For example, suppose a person talks on the phone while traveling or stops for lunch or performs some other activity that fills the travel time with some activity of value, even if that activity is unrelated to the foraging task. Is that time counted as empty time, lowering the average rate of return or is it discounted in some fashion? We don't know. Human foraging research has concentrated on factors such as patch quality (Fougnie et al., 2015; Zhang et al., 2015), target templates (Grössle et al., 2023; Tünnermann et al., 2021), value of foraged items (Wolfe et al., 2018), or forager experience (Ehinger & Wolfe, 2016; Wolfe et al., 2019) (but see Bustamante et al., 2023). The present study concerned the question of what counts as travel in visual foraging.

Three experiments in this study aimed to determine whether inserting a goal-irrelevant task between patches would affect patch-leaving behavior. Will foragers integrate the time spent on a secondary task into the calculation of travel time, thereby including a cost that would lower the average rate of return? Otherwise, will they discount time spent on a secondary task and base their patch-leaving behavior based on some discounted estimate of the travel time cost?

All of the studies reported here are foraging tasks in which participants collect "good berries" from a patch containing overlapping distributions of good and bad berries. Participants were asked to pick as many good berries as possible in a limited amount of time. They could move to the next berry patch at will but would encounter some travel time cost. Between patches, three different types of travel tasks were injected for a limited time period. These tasks included: an obvious travel-related task (Experiment 1), a separate foraging task that was distinct from the primary foraging task (Experiment 2), and a task that was completely unrelated to visual foraging (Experiment 3). All three tasks consumed time. The patch-leaving rules with the three secondary tasks were compared to with simple travel. If this time was discounted, patch should be abandoned earlier than when travel time is simple, empty time.

Experiment 1

In Experiment 1, participants “traveled” from one patch to the next in either an “active” or a “passive” manner. This manipulation was based on the classic observation that passive conditions, where events simply happen to observers, train those observers less effectively than active conditions in which the observer is “in control” (Held & Freedman, 1963; Held & Hein, 1963).

Method

Participants

Power calculations were based on Wolfe (2013). In that study, 10 participants were adequate to produce significant correlations ($r = .77$ and $r = .92$) between the overall rate and instantaneous rate at the time of leaving the patch. Power analysis based on these correlations showed that a sample size of 10 would be adequate to detect a correlation of 0.77 with an expected power of .90 and α error probability of 0.05. We aimed for 15 participants per condition to increase power. In Experiment 1, a total of 60 participants were recruited from Prolific and compensated for their participation. The study consisted of four groups: Active-Short Travel, Active-Long Travel, Control-Short Travel, and Control-Long Travel. Participants submitted online consent form before the experiment started. The procedures were approved by the Institutional Review Board of Brigham and Women’s Hospital.

Stimuli

The experiment was programmed with PsychoPy and PsychoJS library and was conducted online. Online experiments disable precise control over stimulus and monitor size as well as color and luminance. Therefore, sizes are specified in units relative to the screen height.

Participants were restricted by experimental settings not to start the experiment with tablet PCs or mobile phones.

The experiment was composed of visual foraging and travel tasks (see Figure 1A). The visual foraging task presented observers with a series of simulated berry patches. For Experiment 1, the screen was divided into three columns, and each column was scaled to a third of the width of the participants' screen. Two visual patches for the visual foraging task were present in the first and the third columns, occupying 0.9 of each column width. The left-hand patch was labeled "Pick Here" at the top, while the right-hand patch was labeled "Next Patch".

Each patch was composed of a 10 × 10 grid of colored squares (see Figure 1B). Each square corresponded either to a 'good' target (ripe red berry), a 'bad' target (unripe red berry) or a non-target (green leaf). Within each patch, 30%, 40% or 50% of the squares were red berries, with 50% of these being 'ripe'. Participants were instructed that bright and red squares represent ripe berries, and dimmer, darker squares represented unripe berries. The color of the targets was defined using RGB color space, with the triplet [R, (255-R)/2, (255-R)/2] for berries and [100, G, 100] for leaves (R and G stand for the value of the red and green channels). R for good berries was randomly chosen from a normal distribution with a mean of 200 and a standard deviation of 20, while that for bad berries was chosen from another normal distribution with a mean of 150 and a standard deviation of 20. The value of G for leaves was randomly selected from a uniform distribution ranging from 100 to 200. The performance had to be imperfect due to overlapping distributions of good and bad berries. Ideal performance would result in a *d'* value of 2.5. A participant is likely to begin picking the brightest berries and move to less obviously good berries. As a result, the rate of successful search will decline as berries are depleted and as the likelihood of picking a bad berry increases.

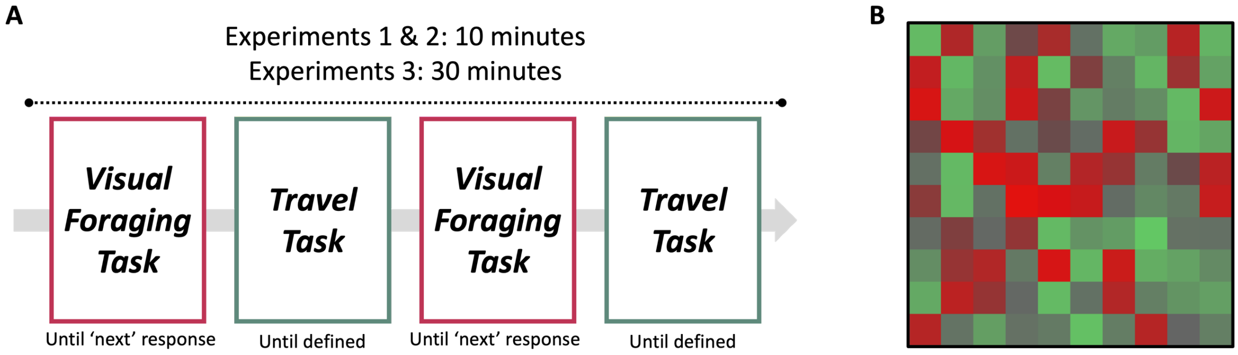

Figure 1: Schematic description of procedures (A) The visual foraging task and the travel task were conducted in alternation until the limited time was exhausted. Each visual foraging period lasted until participants clicked on the 'next' button, while each travel task lasted for a fixed time in each experiment. (B) Sample display of visual foraging patch with 10 × 10 grid. In Experiment 3, patch size was 20 × 20.

The middle column of Figure 2 showed the travel route. It consisted of 6 rows × 20 columns of invisible cells. Each cell subtended 0.05 of the patch size. The route could contain either two or twenty stones. In the Short versions of both Active and Control conditions, just two stones were present. Each stone was randomly positioned in one of the 20 columns and 6 rows. In the Long version, twenty stones were present. One stone was positioned in each of the 20 columns and the row was randomly selected. During the experiment, feedback was provided at the top and bottom of the screen, showing the time elapsed in the experiment, the score achieved, and the rate of targets collected. The experiment lasted 10 minutes.

Procedure

The study was preregistered on the Open Science Framework (OSF) https://osf.io/2vdmu/. During the visual foraging task, participants were instructed to collect as many good targets as possible while avoiding bad targets over 10 minutes. Participants were informed that they did not have to pick every good target in a given patch. Rather, their primary goal was to maximize the overall number of good berries collected in 10 minutes. When a berry, whether good or bad, was clicked, the square turned into a green leaf, accompanied by either a 'good' or 'bad' feedback sound. Upon collecting targets for as long as desired in that patch, participants were allowed to move from the current patch (*n*th patch) to the next patch (*n*+1st patch) by stepping across the stones either actively or passively, depending on their group. The travel time started once the leftmost stone was clicked.

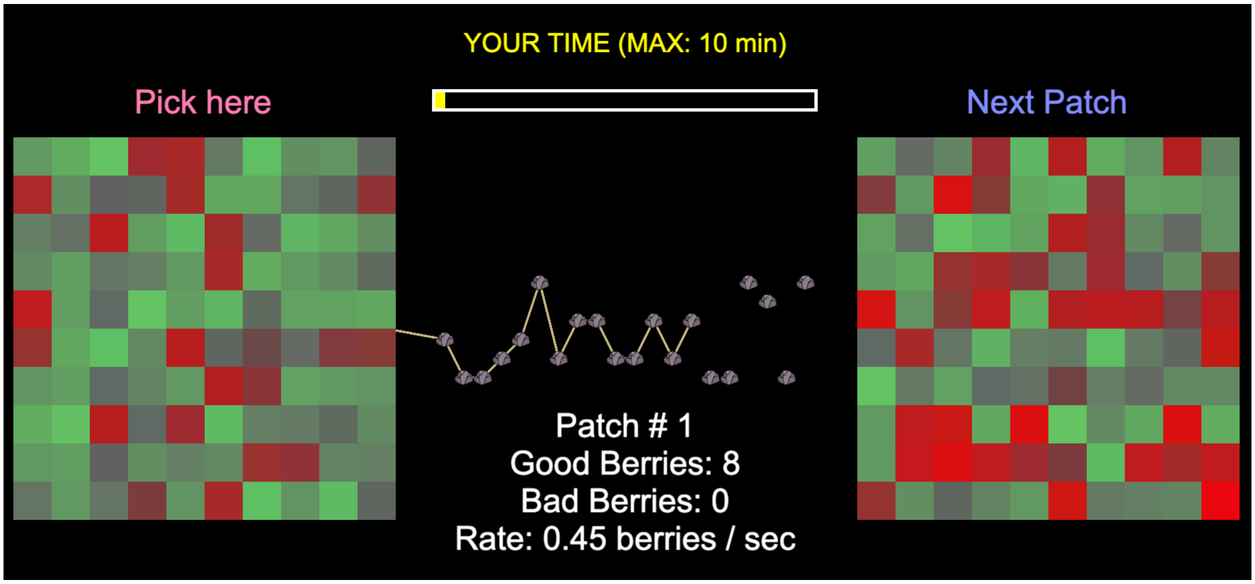

Figure 2

Sample display of stone stepping task from in Experiment 1. This figure is an example of Long Travel condition with the traveler about 2/3rds through the 20 stones on the way to the next patch, as shown by the connecting lines. Short Travel condition had just two stones on the route.

For the travel time, we used a stepping-stone task that was placed between successive berry patches as shown in Figure 2. In the Long Travel condition, participants had to step on 20 stones to reach the next patch, while in the Short Travel condition, they only had to step on two stones. There were Active and Passive (Control) conditions, and participants in each travel time condition were randomly assigned to either of conditions. In the Active condition, participants were instructed to click each stone image as if to step from one stone to the next, from left to right, until they clicked on the last one in order to reach the next patch. Each clicked stone was connected to the previous one by a line. The last stone, once clicked, was connected to the *n*+1st patch after 0.8 s. Participants should have completed the task as quickly as possible in order to minimize the ‘dead time’ between patches.

In the Control condition, participants passively observed the stones being traversed. (Note: We call the Passive condition the Control condition because, in standard laboratory foraging experiments, participants merely passively wait out the travel time). As a result, the Control group’s anticipated travel duration was approximately 2.4 s for the Short Travel and 16.8 s for the Long Travel condition, including additional 0.8 s before the travel ended. Upon arrival at the right-hand patch, the left-hand patch was replaced with the *n*+1st patch, and the right-hand patch was replaced with the *n*+2nd patch. Participants began visual foraging at the *n*+1st patch on the left side of the screen. The experiment was finished when 10 minutes were over.

A time bar was displayed at the top of the screen to indicate the time elapsed from the start of the experiment. The time bar was visible during both foraging and travel task. The 10-minute session ended when the time bar reached the right end of the screen.

If the effort of clicking on each stone is considered more of a burden that just watching, participants might be expected to stay longer in patches to cut down on the amount of unrewarded stone clicking (Anderson & Lee, 2023). It is also possible that the Active and Control lead to different estimates of elapsed time. This, too, would alter the MVT prediction of patch-leaving time.

Results

Data cleaning

One participant was excluded from the Active-Short Travel group due to an average RT of 8.05 s. After exclusion, the average RT for each berry was 0.85 s (*SD* = 0.39 s). We then removed RTs longer than 4 s and the first click from each patch. This eliminated 6.25 % of total clicks. The distribution of travel time differs by travel mode. As travel in Active group was self-paced and Control group was computer-defined, the Active group, especially in Long Travel condition, unsurprisingly exhibited greater variability. Travel took longer in Long Travel conditions (Active: *M* = 17.13 s, *SD* = 10.85 s; Control: *M* = 16.77 s, *SD* = 0.01 s) than in Short Travel condition (Active: *M* = 2.55 s, *SD* = 0.37 s; Control: *M* = 2.41 s, *SD* = 0.17 s). Note that average Active and Control travel times were comparable. However, the median travel length of Active group was 11 s, which was 5.8 s shorter than the Control condition.

As would be predicted by MVT, participants collected more targets in each patch with longer travel times. This drives down the average rate in the longer travel time conditions compared to shorter travel time. The average rate of return was calculated by dividing the number of good targets collected from the berry patches by the entire duration of the experiment (10 minute). This time includes travel periods. The average rates for the conditions of Experiment 1 are found in Table 1.

	Control	Active
Short Travel	0.83 (0.24)	0.92 (0.32)
Long Travel	0.47 (0.13)	0.56 (0.24)

Table 1. Mean of average rate of return from Experiment 1. The numbers in parentheses are standard deviations.

An ANOVA on overall rate was submitted with travel time (Long Travel, Short Travel) and travel mode (Active, Control) as fixed effects. The longer travel with many stones resulted in lower overall rate in the Long Travel condition, $F(1, 55) = 34.19$, $p < .001$, $\eta_p^2 = .383$. However, though the overall rate appears somewhat lower in the Control conditions, the overall rate was not significantly affected by the travel mode, $F(1, 55) = 2.20$, $p = .143$, $\eta_p^2 = .039$, nor was there an interaction of travel mode and travel time, $F(1, 55) < .001$, $p = .992$, $\eta_p^2 < .001$. These overall rates can be seen as the horizontal lines in Figure 3A.

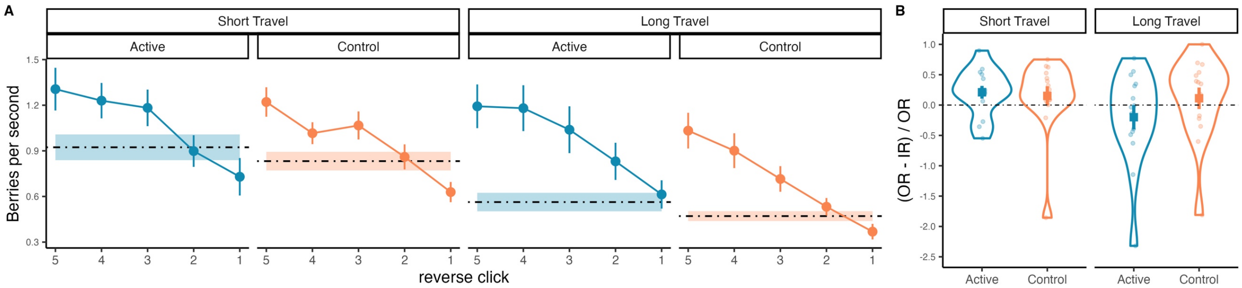

Figure 3. Patch-leaving behavior in Experiment 2*:* (A) Instantaneous rate of return as a function of five reverse clicks. Error bars indicate standard errors. Horizontal lines show overall rate and shaded areas indicate standard errors for each condition. (B) Normalized distance between instantaneous rate (IR) and overall rate (OR) from the last click. Solid square and error bar represent mean and standard error of condition. Semitransparent

dots are individual subjects. Horizontal line at 0 means patch-leaving occurred when instantaneous rate and overall rates were the same.

In order to assess the patch-leaving behavior, all clicks within a patch were aligned in reverse order, starting with the final click in a patch, then averaged across patches. This is done because our interest is in the instantaneous rate at the point when the participant leaves the patch. In Figure 3A, this last click before departing the patch was labeled as Reverse Click #1, the second to last click as Reverse Click #2, and so forth. Foraging performance was evaluated for each click by taking into account the probability that the current click results in a successful target acquisition (positive predictive value; PPV) and the reaction time (RT). As the number of good targets decreased within a patch, participants became slower and less accurate. The instantaneous rate is calculated as the ratio of PPV to RT at each reverse click position. This rate gives the number of good targets collected per second at each reverse click position, showing how foraging efficiency changes over the course of patch exploitation.

Figure 3A displays the instantaneous rates of the last five reverse clicks. As predicted, participants showed declining instantaneous rates as targets were depleted from the patch. MVT predicts patch exit when the instantaneous rate of return falls to the overall rate. Patch-leaving behavior observed in this experiment is in good agreement with the predictions of MVT. Participants left a patch when their instantaneous rates either met or just fell below the overall rate.

The normalized distribution of patch-leaving times from the overall rate was further analyzed (Figure 3B). The difference between instantaneous rate at the last click and the overall rate can be expressed in units of berries per second, if the difference is divided by overall rate, it is possible to have fair comparison of patch-leaving strategy within the MVT framework even when the overall rates vary between conditions. Using this metric, 0 means optimal MVT-style patch-leaving. A value lower than 0 indicates earlier patch-leaving than predicted by MVT. A value greater than 0 means later patch-leaving than MVT's prediction. Using this measure, the patch-leaving rule was not significantly altered by travel time, $F(1, 55) = 1.83$, $p = .181$, $\eta_p^2 = .032$. Importantly, the active/passive manipulation of the travel time task didn't affect patch-leaving rule, $\underline{F}(1, 55) = 0.58$, $p = .451$, $\eta_p^2 = .010$. Participants stopped target collection when their performance was similarly close to the overall rate, irrespective of whether they had to move to the next patch with exertion or ease. The interaction between the travel mode and travel time was not significant, $F(1, 55) = 1.24$, $p = .269$, $\eta_p^2 = .022$.

Since MVT is not universally popular as a way to analyze foraging data (Pierce & Ollason, 1987), patch-leaving can be assessed solely based on the instantaneous rate of return from the last click. This leaves out the MVT assumption of what optimal behavior would look like and simply asks if the manipulation of travel time and travel time task modulates the patch-leaving behavior. Examining the final target collection rate before patch-leaving (Reverse Click #1 in Figure 3A), the main effect of travel time condition was significant, $F(1, 55) = 4.77$, $p = .033$, $\eta_p^2 = .080$. Additionally, participants tended to leave the patch earlier, albeit at a marginally significant level, when actively traveling, $F(1, 55) = 4.03$, $p = .050$, $\eta_p^2 = .068$. This effect can be attributed to the fact that active travel was largely faster than the computerized travel, encouraging participants to leave early. The interaction between the travel mode and travel time was not significant, $F(1, 55) = .70$, $p = .406$, $\eta_p^2 = .013$. Again, we found no evidence that travel mode or travel duration affected patch-leaving times.

Discussion

In Experiment 1, the travel time was filled with what could be deemed to be travel-related task, hopping from stone to stone. This produced patch-leaving behavior that was broadly consistent with MVT. Interestingly, whether participants actively engaged in moving from stone to stone or passively observed the process seemed to have minimal impact on their patch-leaving behavior.

This experiment can be seen as a baseline, classic foraging situation. If you are foraging for berries and need to walk to the next bush, your patch-leaving behavior will be shaped by the travel time in a manner consistent with MVT's predictions. If you are somehow conveyed to the next bush in a passive manner, the results are the same. What would happen if you were performing one foraging task (perhaps, picking berries) in alternation with another (perhaps, pulling weeds)? In Experiment 2, the travel time between "berry patches" was filled with a different foraging task.

Experiment 2: Foraging during the travel period

Method

Participants

As in Experiment 1, the study consisted of four groups, each consisting of 15 participants: Active-Short Travel, Active-Long Travel, Control-Short Travel, and Control-Long Travel. The 60 participants were recruited from Prolific and compensated for their participation. Participants gave online consent prior to participating in the experiment. The procedures were approved by the Institutional Review Board of Brigham and Women's Hospital.

Stimuli

The experiment was conducted online, which, as noted, disables precise control over stimulus and monitor size. Therefore, the stimulus sizes are reported proportionally to the screen size. The primary foraging task was the berry patch task as in Experiment 1. In Experiment 2, the travel task period was filled with a T among L letter foraging task. For the berry patch task, a single patch was presented at the center of the screen. Each patch was a square measuring 0.7 of screen height and composed of 10 × 10 colored squares. The berry patches were otherwise the same as the patches in Experiment 1. The secondary T among L travel-time patch was divided into an 8 × 8 invisible grid, with each cell containing either a T-shaped or L-shaped items. The component lines forming the Ts and Ls overlapped by 10%, making Ts and Ls with + junctions rather than simple Ts and Ls. This makes the search task somewhat more difficult. Ts occupied 32 of the 64 cells. The remaining 32 were filled with Ls. Each item was randomly rotated between 0 and 359 degrees. An example is shown in Figure 4.

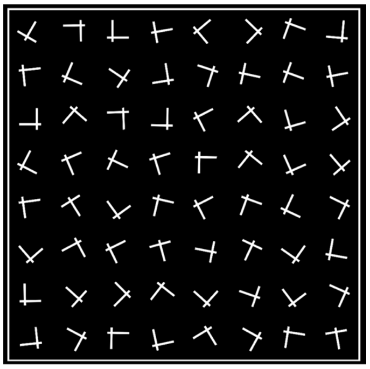

Figure 4. Sample display of the secondary TvsL foraging task that filled the travel time in Experiment 2.

Procedure

Participants were told that their primary task was to collect as many good berries as possible from berry patches while avoiding bad berries in 10 minutes. The “next patch” button was placed on the right side of the patch. When this button was clicked, the secondary task (Figure 4) was introduced to fill the travel time. Participants were instructed either to actively collect Ts among Ls (Active group) or to simply watch Ts travel across the display at a constant speed while Ls remained static (Control group). No feedback, including the number of Ts collected, was provided. The duration of secondary visual foraging task was fixed at either 9 s (Short Travel condition) or 14 s (Long Travel condition). Participants were not free to end this TvsL foraging task. They were asked to forage (or passively watch) until the designated time limit was reached. At that point, the next primary berry patch immediately appeared and began. The travel time was fixed and counterbalanced across participants.

Results

One participant out of 60 was excluded due to 54% false alarm rate in the TvsL foraging task. Among the remaining participants, those in the Active-Short Travel group collected on average 94.07 Ts (*SD* = 29.89) over the course of the experiment, while participants in the Active-Long Travel group collected an average of 144.73 Ts (*SD* = 47.28) in total. In both cases, participants collected Ts at a similar speed. For primary visual foraging, we again excluded RTs greater than 4 s, and we excluded the first click in the berry patch (5.66% clicks).

The average overall rates for each travel time and travel mode can be found in Table 2. It can be seen that the overall rate was slightly lower in the Long Travel condition, aligning with expectations. However, the effect of travel time is small and non-significant as is the interaction between travel mode and travel time, $F(1, 55) = 2.31$, $p = .134$, $\eta_p^2 = .040$; $F(1, 55) = 0.72$, $p = .401$, $\eta_p^2 = .013$, respectively. The overall rate seems to be lower in the Active group than the

Control group, with this difference just reaching statistical significance, *F*(1, 55) = 4.11, *p* = .047, η_p^2 = .070.

	Control	Active
Short Travel	0.68 (0.04)	0.59 (0.04)
Long Travel	0.60 (0.03)	0.57 (0.02)

Table 2. Mean of overall rate of return for Experiment 2. Numbers in parentheses are standard deviations.

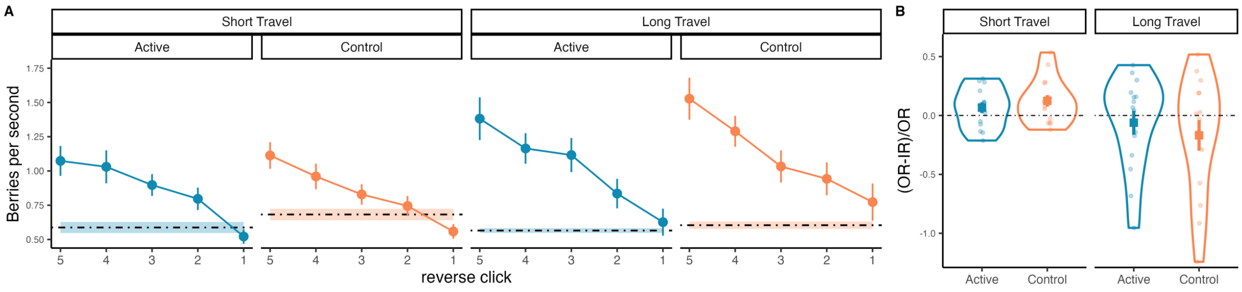

Figure 5. Patch-leaving behavior in Experiment 2. (A) Instantaneous rate of return as a function of five reverse clicks. Error bars indicate standard errors. Horizontal lines and shaded areas show overall rate and standard errors for each condition. (B) Distance between instantaneous rate on the last click (IR) and overall rate (OR), normalized by overall rate. Solid square and error bar represent the mean and standard error of condition. Semi-transparent dots are individual subjects. The horizontal line at 0 indicates MVT-style optimal patch-leaving threshold where instantaneous rate and overall rate are the same.

Figure 5A shows participants' instantaneous return rates from the last five clicks and the overall return rates (horizontal lines). Again, as predicted by MVT, participants stopped foraging when the instantaneous rate reached the overall rate.

Our main interest is not on whether patch-leaving in this experiment aligns with MVT or not. Our aim was to test if the patch-leaving strategy was changed by filling the travel interval with a different foraging task. If the TvsL task, was not counted as "lost" time, participants would calculate a higher overall rate in the Active secondary foraging conditions. This, in turn, should cause them to leave the primary berry patch foraging sooner. The true overall rate would be unchanged so there would be a predicted difference between the instantaneous rate and overall rate in the Active secondary foraging conditions. This moved the normalized distance between overall rate and instantaneous rate to a point lower than 0 (see Figure 5B).

The patch-leaving behaviors in each condition as assessed by computing (OR – IR) / OR are plotted in Figure 5B. Those metrics were submitted to a 2 × 2 ANOVA with travel time and travel mode as main effects. Importantly, travel mode did not significantly affected the patch-leaving rule, $F(1, 55) = .05$, $p = .823$, $\eta_p^2 < .001$. Similarly, the interaction between travel mode and travel time was also not significant, $F(1, 55) = .48$, $p = .491$, $\eta_p^2 = .009$. This suggests evidence that actively engaging in a secondary foraging task did not alter patch-leaving threshold. However, the main effect of travel time was significant, $F(1, 55) = 5.00$, $p = .029$, $\eta_p^2 = .083$. Participants in the Long Travel condition left patch later than those in the Short Travel condition.

As noted above, MVT is not the only way to evaluate foraging data. A more theory neutral approach is examining just the instantaneous rate of return from the last click. This will provide insight into the objective performance at the time of patch-leaving. An ANOVA on the instantaneous rate at Reverse Click 1 with main effects of travel time and travel mode showed no main effect of travel time, *F*(1, 55) = 2.93, *p* = .092, η_p^2 = .051, no travel mode effect, *F*(1, 55) = .97, *p* = .330, η_p^2 = .017, and no interaction, *F*(1, 55) = .35, *p* = .558, η_p^2 = .006. Participants stopped collecting berries when their instantaneous rate was similar in all conditions.

Discussion

Experiment 2 aimed to investigate the impact of an additional foraging task between visual foraging patches on patch-leaving decisions. The additional task could have raised participants' estimates of their overall rate if they either discounted the time spent foraging for Ts and Ls or counted the Ts as a kind of "berry." In either case, participants would have found their instantaneous rate reaching the subjective overall rate sooner, and they should have abandoned search at a higher instantaneous rate. This did not happen. As in Experiment 1, there was a good match between the rate at the final click in the patch and the overall rate. There was no observable effect of the additional foraging task and no difference between the Active and Passive conditions. In addition, the effect of the duration of the travel time was weak and not statistically reliable.

This result has the usual problem of a negative result. Perhaps the task added to the travel interval did not make the right assessments. In Experiment 3, we tried again with a task more dramatically different from the berry picking task.

Experiment 3

Imagine that, between berry patches, you stop picking in order to play a game on your phone. Would that still count as "travel time" in your calculation of your overall rate of return? In Experiment 3, the travel time interval between patches was filled with a task that was irrelevant to either foraging or travel. As in Experiment 2, we asked if this task would remove the travel time from the subjective calculation of overall rate, thus causing participants to leave the berry patches more quickly.

Method

Participants

Using the same assumptions about power as in the previous experiments, we collected data for three groups from a total of 46 participants (Active *N* = 16, Passive *N* = 15, Control *N* = 15). Participants completed two sessions in the lab, each with a different travel time (Short and Long Travel) for either monetary reward or course credit. Participants gave informed consent prior to participating in the experiment.

Stimuli

As this experiment was conducted in lab, stimulus size can be reported in degrees of visual angle. For the visual foraging task, each patch measured 19.24° and consisted of a grid of 20 × 20 colored squares. Targets accounted for 20%, 25% or 30% of the squares. The remaining properties were same as Experiment 1. The 400-cell patch allowed for larger set sizes and, presumably, longer bouts of picking in each patch.

The travel task was a version of a multiple identity tracking (MIT) task and used 25 cartoon animal images sourced from Horowitz et al. (2007). The display, matching the size of visual patch, was divided into a 5 × 5 grid. Four, six, or eight animals were randomly located at the centers of a subset of the 25 cells. The cell at the very center was occupied by the target animal, so that other animal images could not appear there. Each image measured 1.9° both in width and height.

Procedure

Experiment 3 consisted of two 30-minute sessions, each session was composed of alternating episodes of the visual foraging task and the MIT travel task. Each episode of the visual foraging task was self-paced, terminated when the participant chose to leave the patch. Each episode of the travel task took either 9.5 s or 14.5 s, depending on the session. After completing a session with one travel duration, participants took a break before starting the next session with the other travel duration. The session order was counterbalanced across participants.

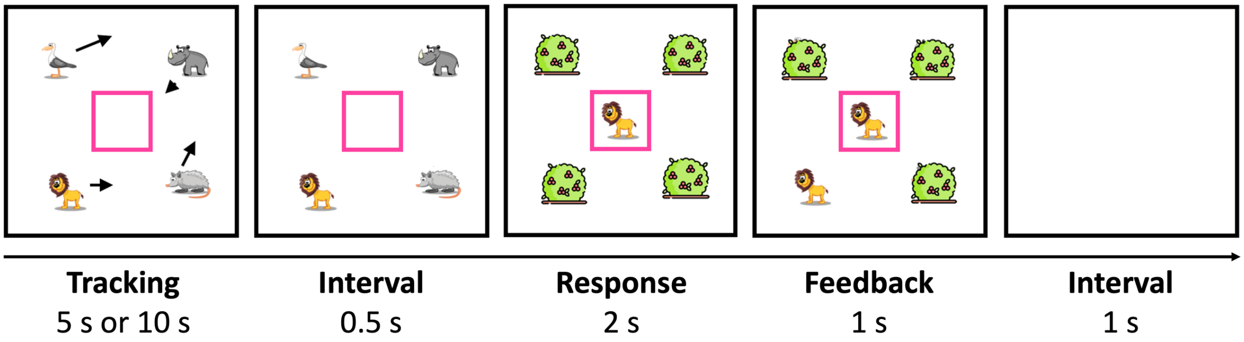

Figure 6: Stimuli and procedure of multiple identity tracking task in Experiment 3. Items were not drawn to scale.

The instructions for the visual foraging task were identical to Experiment 1 with the exception that the duration was 30 minutes, rather than 10 minutes. Participants had to travel between patches in the foraging task. There were three versions of travel. In the Active conditions, participants performed the MIT task (Horowitz et al., 2007). Cartoon animals moved at random around the display at a speed of 3.6° per second, altering their direction upon collision with each other or with the patch boundary. After a tracking time of either 5 or 10 s, depending on the session, all animals “hid” behind bushes (0.5 s) and a target animal appeared at the center of the screen. Participants in the Active group were required to track the movement of animals over the 5 or 10 s and, then, click on the bush hiding the target animal within 2 s. Immediately after the response, participants received either positive or negative feedback, along with visual feedback as to the correct location for 1 s. Negative feedback was given if participants failed to respond within the response window or clicked on the wrong bush. The next berry patch followed after 1 s blank screen interval. Participants in the Passive group saw the same display but observed the correct target bush revealed without needing to respond. They always received the positive auditory feedback. The MIT task took either 9.5 or 14.5 s to complete, including the response, blank interval, and feedback (Figure 6).

Participants in the Control group did not perform the MIT task. Instead, they watched animals traversing the display from the left to right at a constant speed, 1.8° per second for the Short Travel and 1.2° per second for the Long Travel condition. Animals that arrived at the rightmost boundary waited there until the designated travel time was finished. The visual foraging task from a new berry patch began once all the animals arrived at the end after 9.5 or 14.5 s.

Results

The mean accuracy of the MIT task was 64% (*SD* = 14%; set size 4 = 85.28%, set size 6 = 59.57%, set size 8 = 47.63%) for the Short Travel condition and 60% (*SD* = 19%; set size 4 = 80.91%; set size 6 = 59.03%, set size 8 = 46.63%) for the Long Travel condition. Accuracy declined as set size increased, and participants generally performed better than the chance levels (set size 4 = 25%, set size 6 = 17%, set size 8 = 12%). Note that our primary interest lies not in the performance on the MIT task itself, but rather in confirming that participants actively engaged with the task. One participant who performed worse than chance was excluded from the following analysis. For the foraging task, we excluded 2.79% of the RTs. These were either longer than 4 s or were the first click in each patch.

We first compared whether the overall target collection rate was affected by irrelevant task performed during travel. The average rate was lower with longer travel time, *F*(1, 42) = 7.25, *p* = .010, η_p^2 = .147. However, the average rate of return was not affected by the task performed during travel, *F*(2, 42) = .25, *p* = .781, η_p^2 = .012, nor by the interaction of travel mode and travel time, *F*(2, 42) = .06, *p* = .943, η_p^2 = .003. The travel task seems not affect overall performance in the foraging task. The average rate of each travel time and travel mode can be found in Table 3.

	Control	Active	Passive
Short Travel	0.80 (0.13)	0.78 (0.18)	0.79 (0.16)
Long Travel	0.75 (0.14)	0.69 (0.17)	0.71 (0.10)

Table 3: Means of overall rate of return for Experiments 3. Numbers in parenthesis are standard deviations.

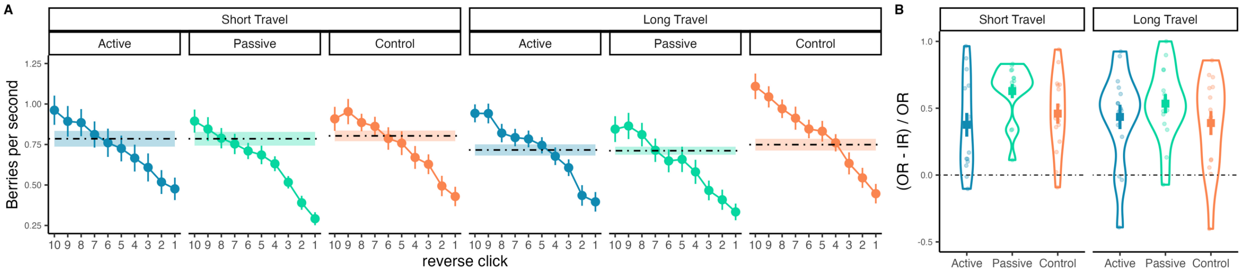

Figure 7: ***Patch-leaving behavior in Experiment 3*** **(A) Instantaneous rate of return as a function of final ten clicks. Error bars represent standard errors. Horizontal lines and shaded areas show the overall rates and their standard errors of each condition. (B) Normalized distance between instantaneous rate (IR) from last click and overall rate (OR).**

Solid square and error bar represent mean and standard error of condition. Semitransparent dots are individual subjects. The horizontal line at 0 is MVT-style optimal patch-leaving threshold where IR and OR are the same.

Figure 7 shows the foraging behavior. In these longer sessions with larger berry patches, participants picked many more berries per patch. Therefore, Figure 7A presents the instantaneous rate for the last ten clicks in each patch. Clearly, these data do not fit the MVT prediction. All groups, including the Control group, continued to collect targets even after their instantaneous rates had dipped well below the overall rate. The normalized distance between instantaneous and overall rates (Figure 7B) hovered near 0.5 in all conditions, suggesting that instantaneous rate dropped to about half of the overall rate before participants left the patch. This is commonly referred to as “overharvesting” in the jargon of the foraging literature (e.g., Carter & Redish, 2016; Constantino & Daw, 2015; Hayden et al., 2011; Kane et al., 2022).

For purposes of this paper, the central question was whether filling the travel time with a different and irrelevant task influenced foraging behavior. Accordingly, repeated-measures ANOVA was tested on the normalized distance to examine whether this overharvesting extent is affected by the travel mode and/or the travel time. There was no significant effect of the travel mode, $F(2, 42) = 1.71$, $p = .194$, $\eta_p^2 = .075$, or of travel time, $F(1, 42) = 1.04$, $p = .313$, $\eta_p^2 = .024$. The interaction was also not significant, $F(2, 42) = 1.91$, $p = .161$, $\eta_p^2 = .083$. It looks like participants tended to overharvest at a similar extent regardless of their engagement with an irrelevant task during travel.

Ignoring the overharvesting issue, the same analysis can be performed on the instantaneous rate of return at Reverse Click #1, the final click in the patch. Here, too, there was no effect of travel mode, $F(2, 42) = 1.88$, $p = .166$, $\eta_p^2 = .083$, the travel time, $F(1, 42) = .06$, $p = .804$, $\eta_p^2 = .001$, or their interaction, $F(2, 42) = 1.80$, $p = .178$, $\eta_p^2 = .079$. Whatever rule governed participants' patch-leaving behavior in this experiment, it responded to neither the duration nor method of travel between patches.

Discussion

In Experiment 3, *something* clearly changed foraging behavior, at least in terms of the predictions of MVT. When plotting the distance between instantaneous and overall rates against overall rate across conditions of this experiment, the degree of overharvesting was positively correlated with the average rate of return, $r = 0.41$, $t(88) = 4.23$, $p < .001$. This suggests overharvesting was, if not optimal, at least useful to participants. We will return to this point later. Whatever the cause of the overharvesting might be, it does not seem to be related to the nature of the foraging-irrelevant contents of the travel period. All the conditions appear to be treated approximately equally. Disappointingly, there was no effect of the absolute travel time on the patch-leaving. One can see in Table 3 that longer travel time did produce a lower overall rate of return, as would be expected. But this did not seem to influence the patch-leaving time. Instead, in all cases, including the Control condition, participants tended to leave a patch when the instantaneous rate was about half of overall rate. Despite the violation of MVT, patch-leaving was not affected by having the travel time filled with an irrelevant task. Consistent with Experiments 1 and 2, The nature of activity during travel does not seem to influence patch-leaving times.

General discussion

This study was conducted to understand if secondary tasks, interposed between visual foraging episodes, change the perception of the travel time between foraging 'patches' in a manner that has an impact on patch-leaving behavior. Three different types of travel tasks were used: an approximation of 'real' travel (Experiment 1), a different foraging task (Experiment 2), or a task unrelated to foraging (Experiment 3). In each experiment, there were passive and/or control conditions where participants "traveled" for the same amount of time but did not actively perform a task during travel. In each of the experiments, what was done during travel did not matter for patch-leaving. Patch-leaving decisions appear to have been based on a simple assessment of the amount of time between patches or, perhaps, to ignore the travel time altogether in Experiment 3. Three different secondary tasks, of different relevance to the primary foraging task, seem to have been simply counted as travel.

In this study, participants multi-tasked between visual foraging and secondary tasks. Task-switching is known to have negative consequences on both accuracy and reaction time (Monsell, 2003), and it is unknown how long the task-set reconfiguration (Monsell et al., 2003; Rogers & Monsell, 1995) from the travel task took or task-set inertia lasted in these studies (Allport & Wylie, 1999; Cohen et al., 1990). Nevertheless, it seems evident that task switching from travel to visual foraging tasks did not affect foraging behavior. Specifically, the overall rate or patch-leaving strategy was not affected by active or passive engagement in the travel task. This aligns with previous finding that brief or longer interruption between foraging does not disrupt patch-leaving strategy (Hong & Wolfe, 2024). Foraging appears to be resistant to task-switching, though further research would be needed to confirm this.

Bustamante et al. (2023) recently argued that the cost associated with cognitively or physically demanding travel can significantly influence decisions on when to leave a patch. The arguments are convincing, considering that any predator will avoid traveling if it has to pass through a maze or fight against a physically stronger enemy. It is sometimes more rational to sacrifice one's yield and save energy. Notably, our approach aligns with Bustamante and the colleagues' conceptual framework while producing somewhat contradictory results. The discrepancy might be reconciled by noting that travel cost in Bustamante et al. was marginal, even with a very large sample size (*N* = 537). Given our more modest sample size, it may be that we were underpowered to see a small effect. That said, the studies do seem adequately powered to see standard foraging effects. For instance, we have more than enough power to see MVT consistent behavior in Experiments 1 and 2 and overharvesting in Experiment 3.

It is interesting that Experiment 3 produced such clear evidence for overharvesting. Something about the structure of that experiment caused the participants to behave quite differently from the participants in Experiments 1 and 2. The most obvious differences are the switch from a 10 × 10 "berry patch" to a 20 × 20 patch and the switch to a 30-minute task duration from a 10-minute task duration. This switch to a larger patch size means that the participants can forage at a high rate for a longer time in a patch. This might make a difference. Perhaps this makes them more tolerant of the decline in foraging rate as the patch is depleted. The topic could be interesting to pursue in future work.

For the present, the important point is that participants did not follow the predictions of MVT even in the Control condition of Experiment 3. As noted at the outset, MVT has been a very useful way to think about foraging behavior but it is not the only set of rules that could be used. For instance, a forager could decide "I will pick about 50% of the berries in the patch and then move on." Or, under the conditions of the present task, a participant might move after getting feedback from *N* bad berries or *N* bad berries out of *M* clicks. These strategies might not be strictly MVT-optimal but they would be computationally simple and, in the current experiments, they would not produce bad results. These might be seen as versions of "model-based reinforcement learning" strategies (Alejandro & Holroyd, 2024). These example rules do not concern themselves with the travel time. If our participants were adopting such a rule, it would not be surprising to find, as we do, that the contents of the travel do not matter. Note, however, that the contents of the travel do not matter in Experiment 1, either, even though there is a significant travel time effect in that experiment and even though the results are largely in line with MVT. The same is true in Experiment 2 though the travel time effect is marginal.

We conclude, within the range of travel times and tasks that we used here, what happens during travel is not important. Participants ignore those contents or, perhaps, ignore the role of travel altogether in some situations. This study is limited by the choice of tasks and the parameters of those tasks. Surely, the contents of the interval between foraging epochs must make a difference if the time scale is larger. We are likely to pick apples differently if we are picking from a tree in our own yard versus in an orchard that is a 45 minute drive away. These time scales are hard to study in the lab. Moreover, our berry patches are very regular. Behavior would change, again, if patches were more variable (Bergmann et al., 2020), if other foragers were present in the same patch (Kacelnik et al., 1992), or if predators were threatening to forage the forager (Thornton et al., 2021). Foraging is a rich domain for further investigation. For the present, we can assert that very different nature of the contents of the travel period between patches in our foraging paradigm did not significantly impact our participants' foraging behavior.

Data and code

Data are available at: https://osf.io/2vdmu/

CRediT authorship contribution statement

Injae Hong: conceptualization, methodology, in writing – original draft, writing - review, & editing, visualization, validation. **Grace Yan:** conceptualization, formal analysis. **Jeremy M. Wolfe:** conceptualization, funding acquisition, methodology, writing - review & editing, validation, supervision

Declaration of Competing interests

The authors declare that they have no competing interests.

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References

Alejandro, R. J., & Holroyd, C. B. (2024). Hierarchical control over foraging behavior by anterior cingulate cortex. *Neuroscience & Biobehavioral Reviews*, *160*, 105623. https://doi.org/10.1016/j.neubiorev.2024.105623

Allport, A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In *Attention, space, and action: Studies in cognitive neuroscience.* (pp. 273–296). Oxford University Press.

Anderson, B. A., & Lee, D. S. (2023). Visual search as effortful work. *Journal of Experimental Psychology: General*, *152*(6), 1580–1597. https://doi.org/10.1037/xge0001334

Becker, M. W., Rodriguez, A., & Pontious, D. (2022). Quitting thresholds in visual search are impacted by target present detection times but not their variability. *Attention, Perception, & Psychophysics*, *84*(8), 2461–2471. https://doi.org/10.3758/s13414-022-02591-3

Bergmann, N., Tünnermann, J., & Schubö, A. (2020). Which search are you on? Adapting to color while searching for shape. *Attention, Perception, & Psychophysics*, *82*(2), 457–477. https://doi.org/10.3758/s13414-019-01858-6

Bustamante, L. A., Oshinowo, T., Lee, J. R., Tong, E., Burton, A. R., Shenhav, A., Cohen, J. D., & Daw, N. D. (2023). Effort Foraging Task reveals positive correlation between individual differences in the cost of cognitive and physical effort in humans. *Proceedings of the National Academy of Sciences*, *120*(50), e2221510120. https://doi.org/10.1073/pnas.2221510120

Carter, E. C., & Redish, A. D. (2016). Rats value time differently on equivalent foraging and delay-discounting tasks. *Journal of Experimental Psychology: General*, *145*(9), 1093–1101. https://doi.org/10.1037/xge0000196

Charnov, E. L. (1976). Optimal foraging: The marginal value theorem. *Theoretical Population Biology*, *9*(2), 129–136. https://doi.org/10.1016/0040-5809(76)90040-X

Chun, M. M., & Wolfe, J. M. (1996). Just Say No: How are visual searches terminated when there is no target present? *Cognitive Psychology*, *30*(1), 39–78. https://doi.org/10.1006/cogp.1996.0002

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*(3), 332–361. https://doi.org/10.1037/0033-295X.97.3.332

Constantino, S. M., & Daw, N. D. (2015). Learning the opportunity cost of time in a patch-foraging task. *Cognitive, Affective and Behavioral Neuroscience*, *15*(4), 837–853. https://doi.org/10.3758/s13415-015-0350-y

Davidson, J. D., & El Hady, A. (2019). Foraging as an evidence accumulation process. *PLoS Computational Biology*, *15*(7), e1007060. https://doi.org/10.1371/journal.pcbi.1007060

Ehinger, K. A., & Wolfe, J. M. (2016). When is it time to move to the next map? Optimal foraging in guided visual search. *Attention, Perception, & Psychophysics*, *78*(7), 2135–2151. https://doi.org/10.3758/s13414-016-1128-1

Fougnie, D., Cormiea, S. M., Zhang, J., Alvarez, G. A., & Wolfe, J. M. (2015). Winter is coming: How humans forage in a temporally structured environment. *Journal of Vision*, *15*(11), 1. https://doi.org/10.1167/15.11.1

Grössle, I. M., Schubö, A., & Tünnermann, J. (2023). Testing a relational account of search templates in visual foraging. *Scientific Reports*, *13*(1), 12541. https://doi.org/10.1038/s41598-023-38362-9

Harhen, N. C., & Bornstein, A. M. (2023). Overharvesting in human patch foraging reflects rational structure learning and adaptive planning. *Proceedings of the National Academy of Sciences*, *120*(13), e2216524120. https://doi.org/10.1073/pnas.2216524120

Hayden, B. Y., Pearson, J. M., & Platt, M. L. (2011). Neuronal basis of sequential foraging decisions in a patchy environment. *Nature Neuroscience*, *14*(7), 933–939. https://doi.org/10.1038/nn.2856

Held, R., & Freedman, S. J. (1963). Plasticity in Human Sensorimotor Control. *Science*, *142*(3591), 455–462. https://doi.org/10.1126/science.142.3591.455

Held, R., & Hein, A. (1963). Movement-produced stimulation in the development of visually guided behavior. *Journal of Comparative and Physiological Psychology*, *56*(5), 872–876. https://doi.org/10.1037/h0040546

Hong, I., & Wolfe, J. M. (2024). Research on re-searching: interrupted foraging is not disrupted foraging. *Cognitive Research: Principles and Implications*, *9*(1), 30. https://doi.org/10.1186/s41235-024-00556-8

Horowitz, T. S., Klieger, S. B., Fencsik, D. E., Yang, K. K., Alvarez, G. A., & Wolfe, J. M. (2007). Tracking unique objects. *Perception & Psychophysics*, *69*(2), 172–184. https://doi.org/10.3758/BF03193740

Kacelnik, A., Krebs, J. R., & Bernstein, C. (1992). The ideal free distribution and predator-prey populations. *Trends in Ecology & Evolution*, *7*(2), 50–55. https://doi.org/10.1016/0169-5347(92)90106-L

Kagel, J. H., Green, L., & Caraco, T. (1986). When foragers discount the future: constraint or adaptation? *Animal Behaviour*, *34*(1), 271–283. https://doi.org/10.1016/0003-3472(86)90032-1

Kane, G. A., James, M. H., Shenhav, A., Daw, N. D., Cohen, J. D., & Aston-Jones, G. (2022). Rat Anterior Cingulate Cortex Continuously Signals Decision Variables in a Patch Foraging Task. *Journal of Neuroscience*, *42*(29), 5730–5744. https://doi.org/10.1523/JNEUROSCI.1940-21.2022

Kilpatrick, Z. P., Davidson, J. D., & El Hady, A. (2021). Uncertainty drives deviations in normative foraging decision strategies. *Journal of The Royal Society Interface*, *18*(180), 20210337. https://doi.org/10.1098/rsif.2021.0337

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition*, *31*(3), 327–342. https://doi.org/10.3758/BF03194391

Oaten, A. (1977). Optimal foraging in patches: A case for stochasticity. *Theoretical Population Biology*, *12*(3), 263–285. https://doi.org/10.1016/0040-5809(77)90046-6

Pierce, G. J., & Ollason, J. G. (1987). Eight Reasons Why Optimal Foraging Theory Is a Complete Waste of Time. *Oikos*, *49*(1), 111–117. https://doi.org/10.2307/3565560

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*(2), 207–231. https://doi.org/10.1037/0096-3445.124.2.207

Stephens, D. W., & Krebs, J. R. (2019). *Foraging Theory*. Princeton University Press. https://doi.org/10.2307/j.ctvs32s6b

Thornton, I. M., Tagu, J., Zdravković, S., & Kristjánsson, Á. (2021). The Predation Game: Does dividing attention affect patterns of human foraging? *Cognitive Research: Principles and Implications*, *6*(1), 35. https://doi.org/10.1186/s41235-021-00299-w

Tünnermann, J., Chelazzi, L., & Schubö, A. (2021). How feature context alters attentional template switching. *Journal of Experimental Psychology: Human Perception and Performance*, *47*(11), 1431–1444. https://doi.org/10.1037/xhp0000951

Wolfe, J. M. (2023). Visual Search. In *Oxford Research Encyclopedia of Psychology*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190236557.013.846

Wolfe, J. M., Cain, M. S., & Aizenman, A. M. (2019). Guidance and selection history in hybrid foraging visual search. *Attention, Perception, & Psychophysics*, *81*(3), 637–653. https://doi.org/10.3758/s13414-018-01649-5

Wolfe, J. M., Cain, M. S., & Alaoui-Soce, A. (2018). Hybrid value foraging: How the value of targets shapes human foraging behavior. *Attention, Perception, & Psychophysics*, *80*(3), 609–621. https://doi.org/10.3758/s13414-017-1471-x

Zenger, B., & Fahle, M. (1997). Missed targets are more frequent than false alarms: A model for error rates in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(6), 1783–1791. https://doi.org/10.1037/0096-1523.23.6.1783

Zhang, J., Gong, X., Fougnie, D., & Wolfe, J. M. (2015). Using the past to anticipate the future in human foraging behavior. *Vision Research*, *111*(Part A), 66–74. https://doi.org/10.1016/j.visres.2015.04.003