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Journal

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Publication Date
2023

Peer reviewed

The Impact of Risk and Prevalence on Foraging Behavior in Hybrid Visual Search

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Abstract

The hybrid foraging paradigm mimics a wide range of real-world searching scenarios. In the hybrid foraging paradigm, foragers search for multiple targets in multiple patches throughout the foraging session. In this study, we incorporate an element of risk in the standard hybrid foraging paradigm, and investigate the effects of risk and prevalence on foraging behavior. The primary finding reveals that human foragers tend to prefer certainty and avoid risk when performing hybrid foraging tasks. Changing the prevalence of the risky targets modulates the aversion to risk, but overall the effect of risk still outweighs the effect of prevalence. Our findings suggest that risk aversion might lead to sub-optimal foraging strategies.

Keywords: hybrid foraging; risky choice

Introduction

Imagine that you are in the woods and hunting for various types of mushrooms (e.g., shiitake, oyster, portabella, etc.). A common strategy would be to search in one region for the different types of mushrooms, and then, at some point, to move on to a new region in search of more mushrooms. This is an illustration of "hybrid foraging" (Wolfe, Aizenman, Boettcher, & Cain, 2016). In hybrid foraging, people search multiple patches (here, regions of the woods) for multiple possible instances of multiple possible types of targets (those types of mushrooms).

Hybrid foraging combines the characteristics of hybrid search (search the presence or absence of any of several types of target; e.g., Schneider & Shiffrin, 1977; Wolfe, 2012) and foraging (a search for multiple instances of a single target type; e.g., Bond, 1981; Cain, Vul, Clark, & Mitroff, 2012; Stephens & R, 1986; Wolfe, 2013). It is characteristic of a wide range of real-world search scenarios, from looking for keys and cards in pockets to surfing the internet for a literature review (Pirolli, 2007) to life-or-death situations, such as screening medical images for signs of cancer (Wolfe et al., 2016; Trueblood et al., 2021; Wolfe, Wu, Li, & Suresh, 2021; Williams & Drew, 2019). Understanding hybrid foraging helps us understand the key factors that influence behavior in these common but complex real-world search scenarios.

The prevalence of different target types plays a significant role in shaping hybrid foraging behavior (e.g., Wolfe et al., 2016; Wolfe, Cain, & Alaoui-Soce, 2018). A common target is usually preferred over a rare target, if both targets have the same value (e.g., the prevalence effect). To date, the existing literature on hybrid foraging (e.g., Wolfe et al., 2018; Wiegand & Wolfe, 2021) has primarily focused on situations where targets guarantee a fixed amount of reward (i.e., sure targets). This is analogous to each mushroom having the same appeal and quality.

Things might be different if you really wanted shiitakes but only one in ten of that variety were of edible quality. In such a situation, the mushroom hunter must weigh the risk against the prevalence of different kinds of mushrooms to maximize their outcomes. Therefore, risk might also play a significant role in shaping hybrid-foraging behavior. To this end, the aim of this paper is to examine how risk affects foraging behavior and how the effect of risk interacts with the effect of prevalence within the hybrid foraging paradigm.

Risk has been consistently shown to affect the behavior of animals in food foraging (Kacelnik & Bateson, 1996; Bateson, 2002), and in various decision-making paradigms for humans (Weber, Shafir, & Blais, 2004). When foraging for food, animals often encounter choices between options differing in reward variance. For example, bumblebees and monarch butterflies usually have to decide whether they should forage from the flower species providing constant nectar volumes (i.e., sure targets) or the flower species providing varying nectar volumes (i.e., risky targets). Studies (e.g., Waddington, Allen, & Heinrich, 1981; Cartar & Dill, 1990; Rodrigues, Goodner, & Weiss, 2010) find that, in most cases, these nectar-collecting foragers prefer the constant reward over the variable reward, reflecting a risk-averse foraging strategy. On the other hand, animal foraging behavior can change depending on the situation (see review in Bateson, 2002). For instance, Caraco and his colleagues (1981; 1990) showed that juncos when juncos had ample intakes or the ambient temperature was comfortable, they visited the station providing a fixed amount of millet seeds more frequently than the station providing variable seed amounts (i.e., risk-averse). But when their survival was in danger, juncos became risk-seeking and visited the risky station more often than the sure station.

Risk-sensitive preferences have also been documented in human decision-making. As captured by Prospect Theory (Kahneman & Tversky, 1979; Tversky & Kahneman, 1992), when choosing between a sure gain, such as a token for $100,

and a risky gain, such as a gamble yielding $200 with 50% probability or $0 reward, people tend to be risk-averse and prefer the sure option over the risky option, although the expected value of both options are equal. On the other hand, when choosing between a sure loss (-$100) and a risky loss (-$200 with 50% probability or $0 loss), people tend to be risk-seeking and prefer the risky option over the sure option. Furthermore, when people learn the option information (e.g., the reward probability and the mean reward value) from experiential sampling, as opposed to description, their risk-sensitive preferences can change such that they tend to be risk-seeking in the context of potential gains and risk-averse in the context of potential losses (e.g., Hertwig, Barron, Weber, & Erev, 2004; Weber et al., 2004; Madan, Ludvig, & Spetch, 2014).

In this paper, we examine the impacts of risk and prevalence on human foraging behavior in a hybrid risky foraging task. In a 15-minute hybrid-foraging task, participants collect reward points by searching for target letters in "patches" (i.e., screens full of letters). They can travel to a new patch at any time during the task. Different target letters are associated with different numbers of reward points with different probabilities, but the expected outcomes from the targets are identical. In addition, the prevalence of different target letters would vary in some conditions.

We quantify the degree of risk across targets using the coefficient of variation (CV). Compared to other risk measurements, such as the outcome variance, the CV has been shown to be a better predictor for risk-sensitive preferences in meta-analyses of both animal foraging behavior (Kacelnik & Bateson, 1996) and human risky choice (Weber et al., 2004). Specifically, the CV measures the outcome variability in relation to the mean value for a risky alternative, as it is a ratio of the standard deviation of outcomes (SD) to the expected value (EV). For instance, if a target yields a 20-point reward with 20% likelihood and 0 points with 80% likelihood, then the $CV = \frac{SD}{EV} = \frac{\sqrt{64}}{4} = 2$. Intuitively, it reflects the degree of risk per unit of return. Within the hybrid foraging paradigm, a high value of CV indicates that acquiring the target involves a large amount of risk (i.e., a risky target), while a zero-valued CV indicates a target providing a sure reward (i.e, a sure target). Following the convention in standard hybrid foraging tasks (Wolfe et al., 2016, 2018), we control the prevalence of targets by manipulating the display proportion of different targets at the onset of patches.

We investigate the effects of risk and prevalence on hybrid-foraging behavior by manipulating these two factors across four conditions. In the equal-prevalence, unequal-risk condition, the variation among targets is solely in CV, and we assess the main effect of risk on foraging behavior in this condition. In the unequal-prevalence, equal-risk condition, we assess the main effect of prevalence on foraging behavior by having all the targets be sure targets (i.e., CV = 0). In the next two conditions, we are interested in the interaction between risk and prevalence. In the common risk condition, the risky target has the highest prevalence; while in the common

sure condition, the sure target has the highest prevalence. Our results suggest a robust preference for the sure target over the risky target, even in the situation where the risky target is much more prevalent. This finding highlights a strong risk-aversion tendency in human hybrid foraging behavior.

Methods

Participants

In order to have 50 participants in each condition, we targeted a sample size of 200 participants. A total of 201 participants (102 women, 99 men, age: M = 40.86 , SD = 12.61), recruited from Amazon Mechanical Turk using the CloudResearch platform, completed the study online. The sample size was determined prior to data collection, and the data was analyzed only after all data had been collected.

All participants who completed the 15-minute experiment were paid a $1 base rate and a performance-based bonus ranging from $0 to $1 to incentivize effort. The amount of the bonus was determined by the average points participants earned per second: $0.20 for 2-3 points per second, $0.50 for 3-4 points per second, $1 for above 4 points per second, and $0 for below 2 points per second.

Participants who had low performance (i.e., either their rate of earning points per second was less than 1.5 or they committed more than 20% false positive errors) were excluded from the data analyses. The exclusion criteria were pre-registered at: `https://osf.io/bf9st/?view _only=fa60a1d7492a4f3997678045951 31c9c` . In total, 22.38% of participants (N = 45) were excluded. After the exclusions, we had 38 participants in Condition a, 34 in Condition b, and 42 in Condition c, and 42 in Condition d.

Materials

We programmed the hybrid risky foraging task in JavaScript. At the beginning of a hybrid risky foraging session, eight letters were randomly selected from the English alphabet. Four of the letters were assigned to represent targets (i.e., T1, T2, T3, and T4), and the other four were used as distractors. A click on a letter removed the letter from the screen. Clicking on a distractor resulted in zero reward. Selecting a target letter yielded a certain amount of reward points with a certain probability of occurrence. Specifically, a selection of T1 (i.e., the sure target) would always yield 4 reward points. T2, T3, and T4 were designated as risky targets, with the potential to yield 5, 8, 20 points respectively, upon selection, with a probability of 80%, 50%, 20% respectively. Note that the expected value is the same for all targets. The order of risk (as reflected in the CV values) among targets was T1 < T2 < T3 < T4, with T4 being the most risky target.

The prevalence of a target was defined by the number of instances of that target over the total number of instances of all targets at the onset of patches (t_0): *Prevalence of Ti =* $\frac{Number\ of\ T_i\ at\ t_0}{\sum_{i=1}^{4} Number\ of\ T_i\ at\ t_0} = \frac{N_{i,t_0}}{\sum_{i=1}^{4} N_{i,t_0}}$. In order to prevent participants from adopting a counting strategy, we pseudo-

randomized the initial number of T_i in a patch (i.e., N_{i,t_0}) [1]. On average, a foraging patch had 32 targets. The number of distractors was determined by the number of targets, in order to keep the total number of letters on screen constant at 64.

The association between CV and prevalence determined four between-subject conditions (a, b, c and d). In Condition a (unequal prevalence, equal risk), targets had equal prevalence but varied in risk (i.e., CV). In condition b (common risk), the value of CV was positively correlated with prevalence (i.e., riskier targets were more prevalent). In Condition c (common sure), the value of CV was negatively correlated with prevalence, resulting in the sure target having the highest prevalence. In Condition d (unequal prevalence, all sure targets), targets varied solely in prevalence and the value of CV was held at zero (i.e., sure targets). In the equal-prevalence condition, the average number of a target on display at the onset of patches was 8. In the unequal-prevalence conditions, the average number of a target on display varied between 2, 4, 9, or 17.

To prevent participants from adopting a reading strategy (Wolfe et al., 2016), all of the letters (i.e., items for foraging) were constantly moving on the screen at a rate of 20 pixels per second. The total screen size of a patch was set to be 650 pixels × 650 pixels. Participants could proceed to a new patch at any time during the foraging session by clicking on a button. The location of patches on the screen remained fixed throughout the entire session.

Procedures

After consenting to participation, participants were randomly assigned to one of four between-subject conditions. At the beginning of the experiment, participants were informed that their task was to collect as many points as possible for 15 minutes by foraging for target letters across multiple patches. They were also informed that their performance, measured by the amount of points they earned per second, would determine the amount of their bonus payment. After reading through the payment schedule, participants were informed about the identity of the four target letters and about the reward points, the winning probabilities, and the prevalence of each target type. When participants were ready, they proceeded to a 15-minute hybrid foraging session after completing a short practice session where they were required to collect 100 points. Participants were informed that their performance in the practice session would not affect their bonus amount.

During the hybrid-foraging session, participants selected a letter by moving a blue cursor on top of it and clicking on it. Once a letter was selected, it disappeared from the current patch. If the selected letter yielded a reward, the cursor would turn green for 100 milliseconds with a coin-dropping sound. Distinct coin-dropping sounds were assigned for different numbers of reward points. If a selection resulted in

zero points, the cursor would turn red for 100 milliseconds with a negative feedback sound.

Participants did not need to hold the target letters in memory, as they were constantly displayed at the top of the screen (see Figure 1). The number of points participants earned per second was displayed on the top-left of the screen, and the total number of points participants accumulated within a patch was presented on the top-right of the screen. The 15-minute foraging session was divided into three 5-minute blocks to allow participants to take a short break in between. The remaining time for a block and the total points earned by participants throughout the hybrid-foraging session were displayed on the right side of the screen for participants.
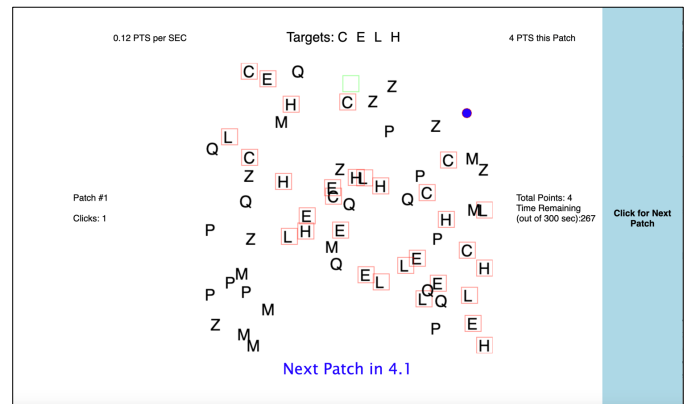

Figure 1: An example screenshot from the hybrid-foraging experiment. The colored boxes around targets and the countdown at the bottom of the screen only appeared during the transition between patches, and were absent during foraging.

Participants could move to a new patch during the hybrid-foraging session by clicking on a blue vertical bar located on the right side of the screen at any time, with a cost of a 5-second transition time between patches. The transition time is analogous to the travel time when a mushroom hunter moves from one region to another in the woods. During the transition time (Figure 1), movements of letters ceased. Green boxes were displayed at the locations of targets that had been selected, while red boxes were displayed at the locations of uncollected targets on screen. Meanwhile, a countdown for the transition time was displayed at the bottom of the screen. After completing the 15-minute hybrid-foraging task, participants were informed about the amount of bonus they earned and were asked to fill out a demographic questionnaire.

Results

Within Patch Foraging Preferences

We evaluated within-patch foraging preferences for targets by assessing the extent to which the selection behavior deviated from random selection. Specifically, we compared the relative proportion of a target being selected (termed the "selection proportion") to the relative proportion of that target

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[1] Let $\overline{N}_{i,t_0}$ denotes the mean value of the initial number of Ti at t_0. The actual number of Ti at t_0 was then set to be $\overline{N}_{i,t_0}$ with 0.6 likelihood, $\overline{N}_{i,t_0} - 1$ with 0.2 likelihood, and $\overline{N}_{i,t_0} + 1$ with 0.2 likelihood.

on display at each click (termed the "display proportion"). We estimated the difference between these two proportions for each target from the first to the 30th click within patches. Fewer than 37% of patches received over 30 clicks.

The display proportion for each type of target (the top row of Figure 2) quantifies the proportion of a specific target on display in relation to the total number of targets on display at the nth patch click. The pattern of display proportions reflects the changes in the prevalence distribution among targets as they are depleted during foraging in the current patch. The selection proportion of each type of target (the second row of Figure 2) are calculated by dividing the number of selections made on a specific target at the nth patch click by the total number of selections made on all targets at the nth patch click. For instance, if a participant made his first clicks on targets in 22 out of 25 patches he viewed, and out of these 22 clicks, he selected T1 13 times, T2 6 times, T3 2 times and T4 1 time, then his selection proportion for T1, T2, T3, and T4 at the first patch click would be $\frac{13}{22}$, $\frac{6}{22}$, $\frac{2}{22}$, and $\frac{1}{22}$, respectively. Thus, the four values at each click will add to 1.

The differences between selection and display proportions (the bottom row in Figure 2) reflect the foraging preferences for each target after accounting for the variation in prevalence among targets. Random selection would be indicated by a zero difference between selection and display proportions. A positive difference indicates over-picking a target; whereas a negative difference reflects under-picking a target compared to what chance would predict. We estimated the proportion differences of each target for each participant, and then performed analyses on those individual-level estimates. The statistical results from robust regressions (Table 1) support the patterns of proportion difference in each condition as discussed below.

Next, we first present the results from Condition a (equal prevalence) and d (unequal prevalence) to demonstrate the main effects of risk and prevalence on foraging preferences, and then present the results from Conditions b (common risk) and c (common sure) to illustrate the interaction between the effects of risk and prevalence on foraging preferences in the hybrid foraging task.

Unequal Risk, Equal Prevalence (Condition a) In the condition where all of the targets had the same expected value and were distributed evenly at the start of a new patch (i.e., the prevalence of targets was equal), the difference between selection and display proportions varied by the riskiness of the targets (see the first column of Figure 2). The difference between selection and display proportions for T1 was above zero and exceeded that of the other targets in the early stage of patch foraging, reflecting a strong preference for the sure target at the start of a new patch. As T1 became increasingly harder to locate with its decreasing instances, participants began to select the next low-risk target (T2). But T1 was still over-picked compared to chance, as indicated by the proportion difference being positive. In contrast, the proportion differences of risky targets, T3 and T4, were be-
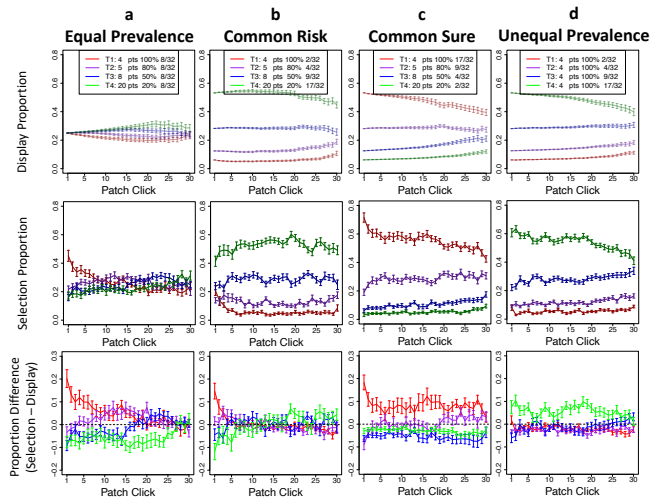

Figure 2: Changes in target display and target selection within patches in each condition. Top Row: proportions of each type of target on display at the 1st to the 30th patch click. Second Row: proportions of each type of target being selected at the 1st to the 30th patch click. Bottom Row: differences between selection and display proportions estimated at each patch click. Error bars denote the standard error of the mean.

low zero in the early course of patch foraging, suggesting that participants selected risky targets less often than predicted by chance. Moreover, with the depletion of targets over time, the most risky target (T4) remained under-picked, reflecting that participants were averse to risk when they foraged for multiple equal valued targets. Eventually, selections among targets converged to random selection towards the end of patch foraging (see the bottom row in Figure 2).

Equal Risk, Unequal Prevalence (Condition d) Condition d was a baseline hybrid foraging condition where all the targets yielded an identical and sure number of reward points. The sole variation among targets was in terms of prevalence. The observed proportion differences (the last column in Figure 2) reflected that participants consistently selected the most prevalent target (T4) more frequently than what random selection would predict, while they under-picked less prevalent targets (T1 and T2) throughout the course of patch foraging. These patterns indicated that participants preferred the common targets over the rare targets, which is consistent with the prediction of the standard prevalence effect as demonstrated in previous hybrid foraging tasks (e.g., Wolfe et al., 2018).

Common Risk, Unequal Prevalence (Condition b) In Condition b, risk was positively correlated with prevalence. That is, the target with a higher degree of risk was more prevalent at the start of foraging patches. Nevertheless, the advantage in prevalence for risky targets did not diminish the participants' aversion to risk. Similar to what was observed in Condition a (equal prevalence but unequal degree of risk), the selection of targets was associated with the degree of risk

in the early stage of patch foraging (second column in Figure 2). Participants over-picked the sure target (T1) the most and under-picked the risky target (T4) the most, despite the risky target being more prevalent and easier to locate at the onset of foraging patches.

As targets were depleted, the difference between selection and display proportions for T4 increased from a negative to a marginally positive value. Meanwhile, the selection of T1, T2, and T3 converged to a random selection pattern as more time was spent in a patch. This suggests that in the later stage of patch foraging, the advantage in prevalence of the risky target eventually led participants to select the risky targets more frequently, but not to an extent that was greater than what would be predicted by chance.

In short, the observed patterns in Condition b reflect an interaction between the effects of risk and prevalence on foraging preferences. High prevalence of the risky targets led to less pronounced risk aversion. In Condition b, the difference between selection and display proportions for T4 was less negative than was seen in Condition a (equal prevalence, unequal risk), $t(2150) = 8.54$, $p < 0.001$. On the other hand, the effect of prevalence was outweighed by the effect of risk. In Condition b, the common targets were selected less often than in Condition d (same prevalence distribution but all sure targets), because the common targets in Condition b were highly risky and participants tended to avoid risk in foraging.

Common Sure, Unequal Prevalence (Condition c) A clear preference for certainty and an aversion to risk were also observed in Condition c where risk was inversely associated with prevalence. Risky targets were less prevalent at the start of patches in Condition c and were not popular choices. Within patches, the difference between selection and display proportions for the sure target (T1) was consistently above zero (the third column in Figure 2), indicating that participants persistently over-picked the sure target throughout the patch. The next low-risk target (T2) was under-picked in the early stage of patch foraging, but then it was selected more often than predicted by chance as sure targets were depleted. Contrarily, risky targets (T3 and T4) were under-picked throughout the patch foraging epoch.

Furthermore, an interactive effect of risk and prevalence was also observed in this condition. In Condition c (common sure), the proportion difference of T1 deviated more positively from zero than in Condition a (equal prevalence, unequal risk), reflecting that participants chose the sure target more often when it was easier to locate. This finding suggests that the preference for certainty (the effect of risk) was amplified by prevalence (the prevalence effect) in Condition c. Additionally, we observed that the difference in selection and display proportions for the risky target T3 was more negative in Condition c than in Condition d (unequal prevalence, all sure targets), although the prevalence and the expected value of T3 were identical in these two conditions. This suggests that aversion to risk was intensified by the rarity in prevalence in Condition c.

Table 1: Estimated coefficients from the robust regression model: Proportion Difference $= 1 +$ Target Type $*$ Patch Click for each condition.

Condition	Term	β	SE	t	p	95% CI
a Equal Prevalence	Intercept	0.103	0.008	13.021	< 0.001	[0.088, 0.119]
	T2	-0.093	0.011	-8.258	< 0.001	[-0.113, -0.072]
	T3	-0.176	0.011	-15.636	< 0.001	[-0.199, -0.153]
	T4	-0.195	0.011	-17.372	< 0.001	[-0.216, -0.174]
	Patch Click	-0.004	0.000	-8.813	< 0.001	[-0.005, -0.003]
	T2 : Patch Click	0.004	0.001	6.853	< 0.001	[0.003, 0.006]
	T3 : Patch Click	0.008	0.001	11.812	< 0.001	[0.006, 0.009]
	T4 : Patch Click	0.006	0.001	9.908	< 0.001	[0.005, 0.007]
b Common Risk	Intercept	0.027	0.007	3.929	< 0.001	[0.014, 0.040]
	T2	-0.020	0.010	-2.065	0.039	[-0.038, 0.000]
	T3	-0.046	0.010	-4.856	< 0.001	[-0.065, -0.026]
	T4	-0.062	0.010	-6.482	< 0.001	[-0.080, -0.042]
	Patch Click	-0.002	0.000	-4.995	< 0.001	[-0.003, -0.001]
	T2 : Patch Click	0.001	0.001	1.502	0.133	[0.000, 0.002]
	T3 : Patch Click	0.003	0.001	5.413	< 0.001	[0.002, 0.004]
	T4 : Patch Click	0.005	0.001	8.953	< 0.001	[0.004, 0.006]
c Common Sure	Intercept	0.097	0.0059	16.580	< 0.001	[0.085, 0.108]
	T2	-0.133	0.0083	-15.999	< 0.001	[-0.149, -0.116]
	T3	-0.152	0.0083	-18.343	< 0.001	[-0.169, -0.135]
	T4	-0.120	0.0083	-14.418	< 0.001	[-0.135, -0.102]
	Patch Click	-0.002	0.0003	-4.604	< 0.001	[-0.002, -0.001]
	T2 : Patch Click	0.004	0.0005	7.945	< 0.001	[0.003, 0.005]
	T3 : Patch Click	0.002	0.0005	3.698	< 0.001	[0.001, 0.003]
	T4 : Patch Click	0.001	0.0005	2.252	0.024	[0.000, 0.002]
d Unequal Prevalence	Intercept	-0.0128	0.0052	-2.436	0.015	[-0.023, -0.003]
	T2	-0.0198	0.0074	-2.677	0.007	[-0.035, -0.006]
	T3	-0.0238	0.0074	-3.216	0.001	[-0.038, -0.009]
	T4	0.0774	0.0074	10.444	< 0.001	[0.063, 0.091]
	Patch Click	-0.0006	0.0003	-2.092	0.036	[-0.001, 0.000]
	T2 : Patch Click	0.0009	0.0004	2.102	0.036	[0.000, 0.002]
	T3 : Patch Click	0.0022	0.0004	5.160	< 0.001	[0.001, 0.003]
	T4 : Patch Click	0.0001	0.0004	0.308	0.758	[-0.001, 0.001]

Patch-leaving Rules: Comparisons of the Marginal and Average Rates of Return

Besides deciding what to select within a patch, another essential decision for a forager is to decide when to stop the current patch foraging and move onto a new patch. In general, existing observations of human patch-leaving behavior in hybrid foraging tasks (see Wolfe, Cain, & Aizenman, 2019, for review) align well with the predictions of the Marginal Value Theorem (MVT Charnov, 1976), at least on average. MVT proposes that it is optimal to move to a new patch when the marginal gain from foraging in the current patch drops below the average gain established throughout the foraging session. An example of this would be a mushroom hunter leaving a region when their rate of mushroom acquisition falls below the average acquisition rate established throughout the forest.

We asked if the patch-leaving behavior in our hybrid risky foraging task followed the optimal strategy as predicted by MVT by comparing the instantaneous rate of return when participants left a patch to their average rate of return estimated across the full foraging session. The instantaneous rate of return was estimated by dividing the numbers of reward points obtained from a target by the amount of time spent acquiring that target. For instance, if a participant took 2 seconds to select a target and the selection yielded 4 points, then the instantaneous rate of return was $\frac{4}{2}$ points/sec from this selection. The average rate was calculated by dividing the total points by the total duration of the foraging session, including both the time spent on foraging within patches and the time spent on traveling between patches.

For the following analyses, we excluded extremely fast inter-click times (i.e., inter-click time < 300 milliseconds; 4.5% of the data), and assumed that participants terminated foraging within a patch immediately after making their last

click in that patch. To allow for comparisons across conditions (see Wolfe et al., 2018)), we normalized return rates by dividing the rate by the expected number of reward points for a click which was 4 points in all conditions.

Across all conditions, we first observed that the instantaneous rates decreased to the average rates at the time when participants decided to leave a patch (top row of Figure 3). This indicates that when it was no longer profitable for participants to continue foraging in a patch, they chose to move on to a new patch, which is consistent with the predictions of MVT. The results of paired t-tests confirmed the observed patterns at the mean-level, suggesting that towards the end of foraging in patches, the instantaneous rates of return did not differ significantly from the average rates of return in each condition (Condition a: $t(37) = -0.803$, $p = 0.427$; Condition b: $t(33) = 0.583$, $p = 0.564$, Condition c: $t(41) = -1.54$, $p = 0.132$; Condition d: $t(41) = 1.24$, $p = 0.223$).
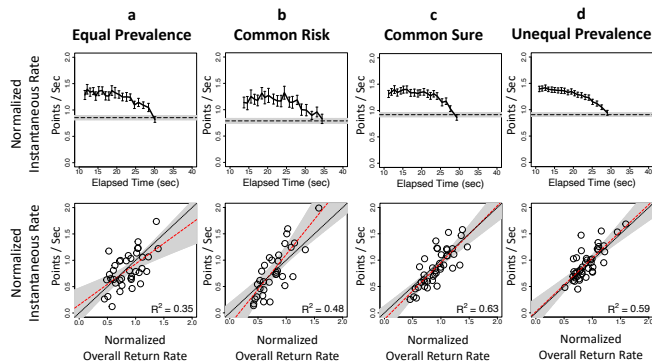

Figure 3: Return rates estimated from each condition. Top row: the instantaneous rate of return as a function of foraging time in patches. The error bases notate the standard errors of the instantaneous rate. The dashed lines notate the corresponding average rates of return. The gray shaded ban notates the ± standard errors of the average rate. Bottom row: the instantaneous return rates at final clicks plotted against the average return rates. The red line represents the best fit linear relationship between the variables. The diagonal lines illustrate the case when the instantaneous return rate is exactly equal to the average return rate. Points falling on the diagonal indicate behavior consistent with MVT.

The bottom row of Figure 3 presents the instantaneous return rates at the final click compared to average return rates at the individual-level. Consistent with the mean-level observations, the best-fit linear relationships show that the instantaneous rate of return was approximately equal to the average rate of return on the final click, which is consistent with the optimal strategy (i.e., the 1 : 1 diagonal line) in each condition. The best-fit line in Condition a was slightly below the diagonal line, suggesting that many participants in this condition left patches when their marginal return from a selection dropped just below their average rate of return. The best-fit lines in Conditions c (common sure) and d (unequal preva-

lence, equal-valued sure targets) were very close to the diagonal line, suggesting that many participants in these conditions were optimal about patch leaving.

The pattern of the return rates in Condition b (common risk) also suggested that a subset of participants in this condition left patches when it was still profitable to continue foraging. However, this was not because participants in Condition b reduced their efforts in patch foraging. The amount of time spent in each patch in Condition b ($M = 34.453$ seconds) was longer than the amount of time spent in patches in the baseline foraging condition that excluded the effect of risk (Condition d, $M = 29.026$ seconds), $t(74) = 2.27$, $p = 0.026$. Nevertheless, a longer period of patch foraging did not result in a better overall return — the average rate of return in Condition b ($M = 3.15$ points/second) was lower than in Condition d ($M = 3.62$ points/second), $t(74) = -2.07$, $p = 0.042$. This seemingly counter-intuitive observation was likely caused by risk aversion that resulted in participants not optimizing their foraging time in Condition b. Despite the fact that in Condition b, a risky target had the same expected value as a sure target but was much easier to locate, participants still preferred to forage for the sure target over the risky one. Although participants in Conditions a (equal prevalence) and c (common sure) also exhibited a preference for certainty and an aversion to risk, it did not have a significant impact on the optimal foraging strategy as in Condition b. Because in those conditions, locating a sure target did not require additional expenditure of foraging time compared to locating a risky target.

Discussion

The hybrid risky foraging paradigm mimics a wide range of real-world scenarios such as food hunting, grocery shopping, and medical screening. The current study extends the existing literature on both decision making and visual search by examining the influence of risk and prevalence of targets on hybrid foraging behavior. Our results reveal that although both the risk and prevalence of targets influence foraging behavior, risk-sensitive preferences play the dominant role. These findings suggest that risk aversion might lead to sub-optimal foraging strategies.

We utilized simple visual representations (i.e., alphabetic letters) for options to minimize potential visual confounds. Future studies may employ naturalistic stimuli with more complicated visual components (e.g., shape, color) to represent options. Also, due to the dynamic nature of hybrid foraging search (i.e., targets are constantly moving and depleted with selection), future studies may implement studies on touch-based tablets to minimize the delay between visual display and responses (e.g., Kristjánsson, Jóhannesson, & Thornton, 2014). In addition, the current study is limited to the context of potential gains. Future investigation is necessary to examine whether the current findings can be generalized to tasks that also engage potential loss.

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