Sub-optimalities in Group Foraging and Resource Competition

Michael E. Roberts (MichaelRoberts@DePauw.Edu)
Department of Psychology, DePauw University, 7 E. Larabee Street
Greencastle, IN 46135 USA

Robert L. Goldstone (RGoldsto@Indiana.Edu)
Department of Psychological and Brain Sciences, Indiana University, 1101 E. 10th Street
Bloomington, IN 47405 USA

Abstract

Previous group foraging research has shown that human groups sub-optimally distribute themselves to resources and display undermatching, with a smaller-than-expected proportion of individuals at the more abundant resource pool. In order to further explore these sub-optimalities, we extended a group foraging paradigm to test three variables: the effects of three resource pools, travel cost between pools, and the size of the pools. Although each condition led to undermatching, the conditions showed significant differences in the extent of undermatching, the frequency of switching between resource pools, the wealth inequality among foragers, and the comparative wealth inequality at different resource pools. The results for the three pool conditions suggest that human groups have difficulty in discriminating the relative value of resource pools. The results for the travel cost conditions indicate that human groups distribute themselves to resources more optimally when individuals can easily switch between pools, which is the opposite of the result found with foraging pigeons. Finally, the results for the pool size conditions indicate that larger pool sizes promote greater undermatching, apparently because individuals inefficiently compete over large areas rather than effectively parceling the pools into smaller, distinct regions.

Keywords: Group foraging, collective behavior, adaptive behavior, probability matching, wealth inequality

Introduction

Goldstone and Ashpole (2004) used a networked computer experiment to test how human groups distribute themselves to resources. Participants each sat at their respective computers and saw an 80 x 80 gridworld where resources were steadily dropped in two resource pools. In the visible food/visible agents condition, participants could see both the food and the locations of the other competitors in the world as each person moved their avatar using arrow keys to collect as many resources as possible. In the invisible food/invisible agents condition, participants could not see the food or the other participants, but a piece of food briefly appeared on a participant's screen if he or she happened to step on it. Thus, participants could gradually determine the pool locations and the productivity of each resource pool. Groups participated in six experimental conditions: the two visibility conditions crossed with three distribution conditions (80/20, 65/35, and 50/50 distribution of the resources to the two pools). Both visibility conditions led to significant undermatching for the 80/20 and 65/35

distributions, with significantly fewer than expected foragers at the more plentiful pool.

Goldstone, Ashpole, and Roberts (2005) extended this paradigm to test the alternative visibility conditions: invisible food/visible agents and visible food/invisible agents. Interestingly, the former condition once again produced undermatching, but the latter condition led to overmatching, perhaps because individuals could see food rapidly appear in the more productive pool, and the individuals were not dissuaded by the presence of other, invisible competitors. Roberts and Ashpole (2006) developed an agent-based model, EPICURE, to explain why undermatching and overmatching occur in the respective conditions. Essentially, at each timestep, each agent in the model weights the food density of an area (visible food), the agent density of an area (visible agents), the Euclidean distance to each piece of food (visible food), the value of previous rewards obtained in an area, and whether the area is along the agent's current directional heading. Using these calculations, each agent probabilistically decides where to move. The model accurately fit the human data from Goldstone and Ashpole (2004) and Goldstone et al. (2005), and the further model simulations provided an explanation for undermatching. Undermatching emerges from the interaction between foragers' patrolling behavior and the rate and spatial distribution of incoming food. When the resource pools are Gaussian distributions, some foragers can become disproportionately successful by patrolling the high-density center of a resource pool.

Goldstone and Ashpole (2004) and Goldstone et al. (2005) examined the effects of food and agent visibility on human group distribution, but the foraging literature suggests that several other variables may have significant effects. Sokolowski and Tonneau's (2004) three pool human study extended their previous two pool undermatching results (Sokolowski, Tonneau, and Freixa Baque, 1999) with simple tokens, and a three pool extension of the Goldstone et al. paradigm could test perceptual effects on group discrimination of resources. The Baum and Kraft (1998) pigeon foraging studies found decreased undermatching with increased travel distance between pools, and they also found decreased undermatching by increasing the resource accessibility with troughs rather than bowls. These results led us to test six new experimental conditions using the Goldstone et al. paradigm: three pools with invisible food/invisible agents, three pools with visible

food/visible agents, two pools with low travel distance, two pools with high travel distance, two pools with low variance of food placement within a pool, and two pools with high variance of food placement within a pool. Furthermore, unlike the previous foraging experiments, we also analyze the distribution of wealth among participants in order to determine the factors that lead to "haves" and "have-nots."

Experiments

Methods

A total of 142 subjects participated in 9 groups of size 10, 15, 16, 16, 16, 16, 17, 18, and 18. Each group was intended to participate in every condition, but data was only collected from 7 groups in the low travel condition and 8 groups in the high variance condition due to networking errors. As in the Goldstone and Ashpole (2004) and Goldstone et al. (2005) experiments, each experiment lasted five minutes, and the order of conditions was randomized. Foragers' locations, foragers' earnings, and food locations were recorded every two seconds. Movement (up, down, left, right) remained the same, and participants obtained a piece of food by stepping on its gridcell. Food was delivered every 4/N seconds, where N is the number of participants. The instructions emphasized that food appeared in patches, but they did not reveal the number of patches.

Unlike the Goldstone et. al. experiments, the size of the gridworld was enlarged to 90 x 90 in order to accommodate the three pool conditions and still maintain space between the pools. However, in keeping with the prior experiments, pool locations were essentially rotations and reflections for the various conditions, which prevented participants from guessing the pool locations or comparative pool distributions at the beginning of an experiment. For the three pool conditions, all pools were approximately 54 steps apart, each pool had a Gaussian distribution with a variance of 5 cells, and pool distributions were 60/30/10. The travel distance and variance conditions all used 75/25 pool distributions. For the travel distance conditions, each pool had a Gaussian distribution with a variance of 4, but the low travel distance condition had pools at approximately 21 steps apart, while the high travel distance condition had pools at approximately 67 steps apart. For the variance conditions, each pool was approximately 56 steps apart, but the low variance condition had Gaussian pools with a variance of 3, while the high variance condition had Gaussian pools with a variance of 9. Thus, the travel conditions and variance conditions were scaled by factors of 3. Populations in the three pool and variance conditions were analyzed by labeling anyone within a 20-step radius of a pool as currently in that pool, while the travel conditions used a 10-step radius for the pool definition because of the mere 21 steps separating the pools. The pool definition may be a bit restricted with respect to the high variance condition; however, the 20-step radius still accounts for more than two standard deviations of the Gaussian-distributed food.
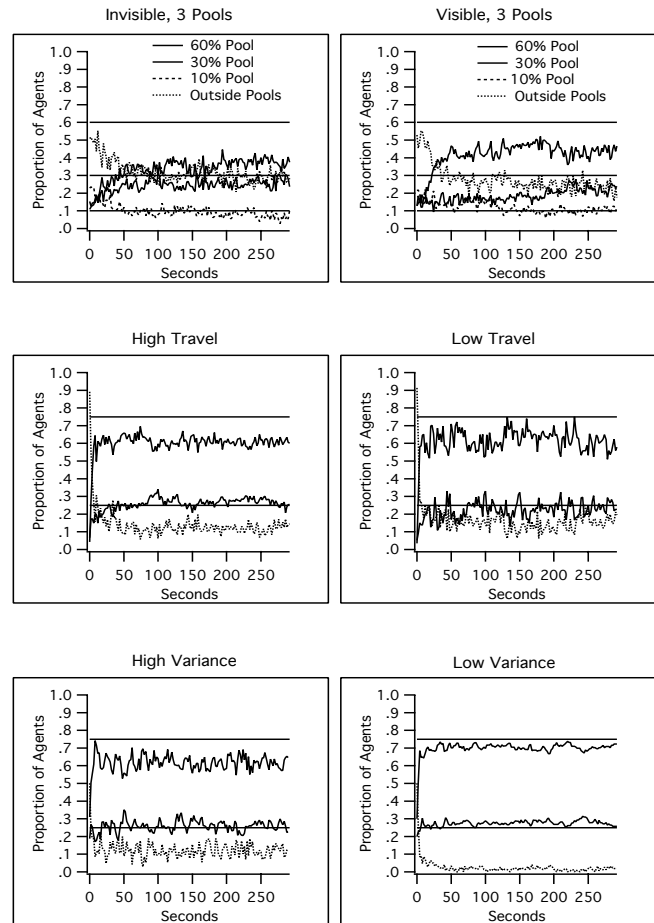

Figure 1: Non-normalized matching results for the six empirical conditions

Results and Discussion, Three Pools

Figures 1 and 2 present the non-normalized and normalized matching results for the respective conditions. The non-normalized results include the number of foragers who are outside of both pools on a given time step, while the normalized results only compare the proportion of foragers in each pool. Figure 1 shows the familiar undermatching relationship, with fewer than 60% of the foragers in the 60% pool. Tables 1 and 2 present the more detailed statistical analyses. First, AveragePool1 measures the average proportion of participants in the 60% pool for the last four minutes of the experiment. AveragePool1 serves as an average measure of how well groups match to the more abundant pool, and it presents a useful comparison across perceptual conditions. We have excluded the first minute of the experiments due to the large population fluctuations as foragers first explore the environment and discover pools. In parentheses, we have provided the normalized proportions, which exclude foragers outside of the pools. An independent samples t-test found that AveragePool1 was significantly higher in the visible food/visible agents three pools condition than the invisible food/invisible agents condition, $t(16) = -2.59$, $p < .05$, and this result replicates
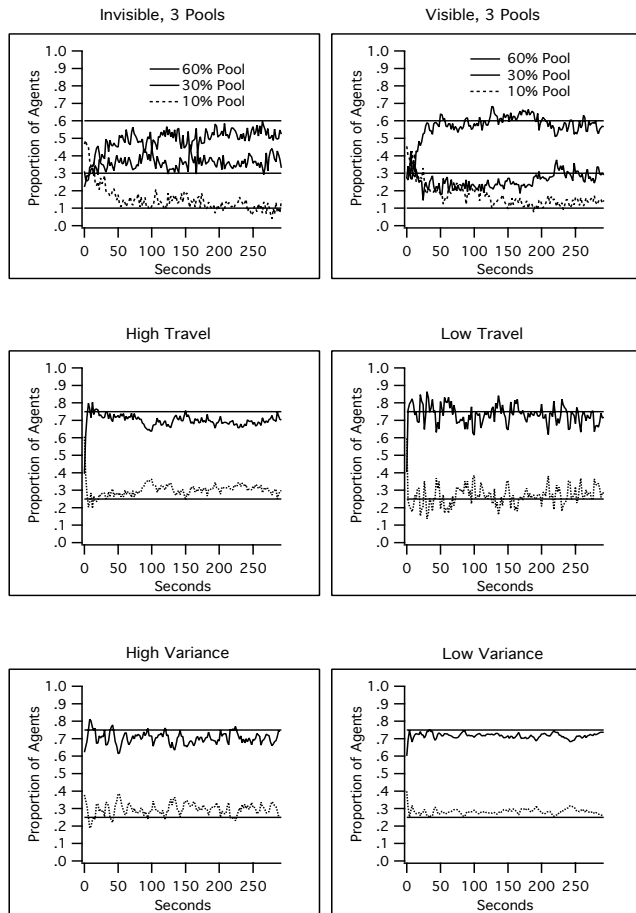
Figure 2: Normalized matching results for the six empirical conditions

the behavior described in the two pool conditions from Goldstone and Ashpole (2004).

A major advantage of the moment-to-moment data collection in the Goldstone et al. paradigm is the ability to track each individual's performance in addition to the coarser measures of number of people in each pool. The second column in Table 1 gives the average probability of a forager switching pools per second and per experimental condition. For this measure, we label a switch as anytime that a forager moved out of the radius of one pool and into the radius of the other pool, although the forager could spend intervening time outside of both pools. However, in contrast with the two pool results, the three pool conditions showed no significant differences in pool switching behavior. In fact, the means of both conditions had much larger magnitudes than the corresponding two pool conditions from the Goldstone and Ashpole (2004) data (for the invisible food/invisible agents two pool condition, mean = .0183; for the visible food/visible agents two pool condition, mean = .0276), but it is impossible to conclude whether this reflects greater exploration and adjustment due to the presence of a third pool, or whether the interleaved experimental conditions (such as low travel distance and

high pool variance) affected switching behavior in all conditions. In either case, it is worth noting that the large difference between the non-normalized and normalized AveragePool1 values is due to the large number of people outside the pools, presumably as they intentionally switch pools or explore the environment. By examining the data in a software viewer that replays the experiments, we have observed that both conditions have a substantial number of foragers who seem to treat the entire world as a relatively undifferentiated patch, and they scan back and forth over the world in hopes of collecting food. Moreover, that strategy is not particularly unreasonable if the foragers have little information to distinguish pools, because the presence of three pools means that almost every location in the world has a non-zero probability of getting food.

The last columns of Table 1 provide the mean earnings for a forager in the time step before instances where the forager decided not to switch (column 4), versus the time step before instances where the forager decided to switch (column 5). This measure uses a stricter definition of switching and attempts to test whether individuals' switching behavior is influenced by their recent success, rather than solely being influenced by current perceptual information. For this calculation, we examine whether a forager switched between timestep-1 (the previous time step) and the current time step. Then we assign the forager's earnings between timestep-2 and timestep-1 to the appropriate column's total, and subsequently average these totals for each forager, across foragers in a group, and across groups in an experimental condition. It is worth noting that this calculation uses a conservative definition of switching, in which a forager must directly switch between pools (without spending an intervening timestep outside the pools), and it is only calculated over the last four minutes of an experiment in order to assume that foragers know the pool locations and intentionally choose to switch. Although foragers may explore a great deal early in the experiment, the last columns of Table 1 indicate that switching is clearly influenced by a forager's recent success in a pool, rather than a random or time-limited switching rule ($p < .001$ for both conditions). This is consistent with a win-stay/lose-shift strategy, but simply applying that strategy does not directly predict the observed differences in undermatching between the three pool conditions.

The moment-to-moment data collection also provides a more detailed examination of the wealth distribution among foragers and between the two respective resource pools. Table 2 shows the Gini coefficients for the six experimental conditions. Gini coefficients range from 0 to 1, and a higher coefficient indicates greater wealth disparities, i.e. some foragers are disproportionately more successful than others. The GiniAll measure calculates a Gini coefficient using the amount of food that each forager collected over the course of a five minute experiment, and the coefficient is averaged over groups for each perceptual condition. The two conditions are not significantly different in terms of the overall Gini coefficient. Table 2 also provides separate Gini

Table 1:

Condition	Average Pool1	Switches Per Sec.	Earnings Non-switch	Earnings Switch
Invis, 3 pools	.358 (.512)	.045	.635	.369
Vis, 3 pools	.442 (.588)	.043	.617	.330
High Travel	.609 (.694)	.0057	.499	NA
Low Travel	.619 (.727)	.046	.564	.392
High Variance	.620 (.704)	.018	.496	.392
Low Variance	.705 (.717)	.0062	.468	.337

coefficient results for the 80% and 20% pools in each perceptual condition. In order to calculate these coefficients, we calculated a rate of food collection for each forager in each pool. For example, an agent might collect 18 pieces of food in a total of 60 seconds in the 60% pool (i.e. .3 pieces of food per second) and 4 pieces of food in a total of 20 seconds in the 30% pool (i.e. .2 pieces of food per second), and 1 piece of food in a total of 20 seconds in the 10% pool (i.e. .05 pieces of food per second). For each time step, a forager was labeled as belonging to the 60% pool, 30% pool, 10% pool, or neither pool. If the forager remained in the same pool on the next time step, then the newly collected food was assigned to that pool. If the forager changed pools across time steps, then half of the food earnings were assigned to each pool. Finally, if the agent moved from a pool to neither pool (or vice versa), then all earnings were assigned to the pool, because no food was present outside of pools. Thus, a food collection rate was calculated for each forager in each pool, and the Gini coefficient compared the collection rates among foragers in each pool.

The visible three pools condition shows a significant difference in inequality between the 60% and 30% pools in a paired samples t-test, $t(8) = -6.51$, $p < .001$, while the invisible condition only shows a marginally significant difference, $t(8) = -2.18$, $p = .061$. These differences in inequality between pools may be partially explained as a statistical artifact caused by fewer foragers in the 30% pool, but it is not a necessary outcome. The Gini coefficient scales with the number of people, but the Gaussian food distributions may mean that one or two foragers in the middle of the 30% pool can patrol the pool's Gaussian center and be much more successful than a few foragers on the perimeter. In the 60% pool, food arrives more frequently so a larger number of participants may share the food in the center and the perimeter. More generally, pools with the worst matching generally have one or two foragers who are doing disproportionately well by patrolling the Gaussian center of the pool, especially when you compare

their performance to foragers who occasionally switch to the pool from outside pools. This story resembles the controversial Kuznets curve hypothesis (Jha, 1996) in which undeveloped countries have relatively low inequality because everyone is a part of the same economy (e.g. agrarian), developing countries have high inequality because some members have access to improved technology, and developed countries have low inequality because everyone has the same technology and general opportunities. At any rate, the matching results and pool inequality results suggest that foragers in the invisible condition appear to have difficulty distinguishing between the 60% and 30% pools, while foragers in the visible condition appear to have difficulty distinguishing between the 30% and 10% pools.

Finally, the last column in Table 2, GiniTime reports regression analyses for the Gini coefficients across time in each condition. This analysis calculates the Gini coefficient for each minute of a five minute experiment (i.e. what is the wealth distribution of food collected by foragers during a given minute, disregarding foragers' total food collected during previous minutes), then applies a regression analysis to see how the degree of inequality changes over the course of the experiment. Both of the three pool conditions exhibit decreases in wealth inequality over time, and the observations of frequent pool switching may be the key to this result. If the presence of three pools induces more exploration early in the experiment, then there will also be more wealth inequality as a few foragers patrol the Gaussian pool centers and other foragers switch pools. As foragers increasingly exploit their knowledge, then wealth inequality should decrease over time.

Results and Discussion, Travel Distance

An independent samples t-test comparing AveragePool1 for the high and low travel conditions revealed marginally significantly better matching for the low travel condition, $t(14) = -2.073$, $p = .057$. This result strikingly disagrees with the Baum and Kraft (1998) pigeon foraging study, which found significantly better matching in the high travel condition and hypothesized that increased movement costs led pigeons to switch only when individual success would be substantially improved. Nonetheless, our matching results may cohere with participants' pool switching behavior, where participants switched significantly more frequently in the low travel condition, $t(14) = -7.17$, $p < .001$. Whereas Baum and Kraft contend that each switch must be more meaningful in the high travel distance condition, it is also possible that frequent switching in the low travel condition allows more dynamic – and therefore more optimal – matching to the resources. After all, the high travel conditions lead to inefficient instances in which foragers begin to switch pools, but "ground conditions" at one pool or the other suddenly change, causing the forager to return to his or her original pool. For a similar reason, we were unable to analyze the causation between recent earnings and pool switching for the high travel conditions because group members did not switch quickly enough to

Table 2: Gini wealth inequality analyses

Condition	GiniAll	GiniPool1	GiniPool2	GiniPool3	GiniTime
Invis, 3 pools	.261	.318	.387	.565	ß = -.405, *p* = .006
Vis, 3 pools	.248	.281	.478	.539	ß = -.456, *p* = .002
High Travel	.240	.246	.388		ß = .086, *p* = .574
Low Travel	.224	.204	.262		ß = .174, *p* = .316
High Variance	.214	.232	.313		ß = .079, *p* = .627
Low Variance	.239	.257	.331		ß = .112, *p* = .466

meet our conservative switching definition (foragers must switch from one pool to the other pool in consecutive time steps, without any time outside of the pools). We suspect that Baum and Kraft's food rate was sufficiently low – even the fast presentation conditions only delivered a pellet when the previous pellet was eaten, so no food accumulated – that the results may not be directly comparable. In fact, the food rate in our experiment (4/N) may still be too slow for humans to accurately estimate the pool differences, or, as discussed in the undermatching explanation provided by Roberts and Ashpole (2006), humans may too heavily weight others' presence as a deterrent.

It seems surprising that the wealth inequality is not significantly different for the high and low travel conditions. Admittedly, our notion of beneficial switching in the low travel condition would be better supported if the low travel condition led to less inequality. Perhaps it is still noteworthy that the high travel condition leads to higher inequality for the 25% pool than the low travel condition, though both conditions indicate higher inequality for the 25% pool compared to the 75% pool (significant for high travel, t(8) = -4.34, *p* < .01; marginal for low travel, perhaps due to less group data, t(6) = -2.22, *p* = .069). Given that the pool variance is equivalent for the high and low travel conditions, the greater inequality for the high travel condition suggests that some foragers disproportionately benefited from the lack of competitive switching. However, it could be that some individuals are being penalized for indecision as they waste time in between the pools. Finally, neither condition showed a change in wealth inequality over time, which suggests that group members are not changing their strategies over time. Unlike the three pool conditions, the travel condition data do not show separate stages of exploration and exploitation.

Results and Discussion, Variance

An independent samples t-test comparing AveragePool1 for the high and low variance conditions showed significantly better matching for the low variance condition, t(15) = -5.38, *p* < .001. This appears to contradict another result from the Baum and Kraft (1998) pigeon foraging study, which found significantly better matching in an elongated trough feeding condition compared to a bowl feeding condition. Baum and Kraft concluded that the trough

condition exhibited less competition, allowing multiple pigeons to feed without fighting for space. Importantly, the current variance experiment may not be a direct analog to the Baum and Kraft study. In the present study, the worse matching in the high variance condition can be largely attributed to the significantly higher frequency of pool switching, t(15) = 6.46, *p* < .001. Matching to the 75% pool is greatly reduced by the proportion of foragers outside the pools as they switch, and in fact, the normalized matching values in Column 2 of Table 2 are nearly indistinguishable for the two conditions. Therefore, the crucial difference between these variance conditions may be that high variance entices foragers to switch. For example, if you are a forager near the perimeter of the 75% pool, you may be easily seduced by a piece of food that appears nearby on the perimeter of the 25% pool. It seems possible that an experimental condition with pools of uniform variance would yield similar results to Baum and Kraft, but simply increasing the Gaussian variance may have confounded factors by increasing the pool size while maintaining a relatively easily patrolled center. Some foragers may specialize in patrolling the center while others collect food on the periphery and frequently switch pools.

The high and low variance conditions do not show a significant difference in overall wealth disparity, which is somewhat surprising given that foragers are apparently using very different strategies. Both conditions show the familiar result of greater inequality at the less abundant, 25% pool (marginal for high variance, t(7) = -2.31, *p* = .057; significant for low variance, t(8) = -2.42, *p* = .042), and neither pool shows a decrease in wealth inequality over time. Furthermore, neither condition exhibits a causal connection between earnings and switching, although both conditions trend in the same direction, with more earnings preceding the decision not to switch. Thus, the high variance appears to entice foragers to switch pools, but foragers still consider their success in the current pool. Interestingly, the high variance condition has approximately twice as much food available on a given time step (mean of 5.93 for the 75% pool, 2.26 for the 25% pool, compared to 3.11 and 1.28 for the low variance condition). In other words, the high variance condition makes the group relatively inefficient despite foragers' frequent switching and attempts to maximize personal gain. Obviously, foragers must travel more distance, on average, to collect

food in the high variance condition, but one could imagine that a highly efficient group that weighted pre-emption even more strongly (i.e. they avoid competitive areas with high densities of other foragers) would still be equally efficient in the two conditions by dividing the pools into territorial regions.

Agent-based Model

EPICURE's non-normalized matching predictions for the three pool, travel cost, and variance conditions are strikingly different than the observed empirical results, although it is important to note that these simulations used the same parameter values as the previous model fits from Roberts and Goldstone (2006), so better results might be obtained with the same model. For instance, the three pool conditions look very similar for both visibility conditions in the model, and the results lack the observed similarities between the 60% and 30% pools for the invisible food condition, and between the 30% and 10% pools for the visible food condition. For the travel condition results, the model overestimates the proportion of foragers in the 25% pool in the low travel condition and underestimates the proportion outside of pools in that condition. The model gives the best matching results for the variance conditions, and although it greatly overestimates the proportion of people outside the pools in the low variance condition, at least the qualitative relationship between the high variance and low variance condition seems correct.

EPICURE performs better in its switching predictions for these conditions. Foragers in the high variance condition switch pools significantly more frequently than foragers in the low variance condition ($p < .001$), and foragers in the high travel cost condition switch pools significantly less frequently than foragers in the low travel cost condition ($p < .001$). In the high variance condition, foragers appear to switch pools after being lured from the other pool's periphery. The high travel cost condition makes it difficult for foragers to sustain their switching choice long enough to reach the other pool, because each time step brings the possibility of new distractions. Thus, EPICURE is actually more supportive of the Baum and Kraft (1998) pigeon foraging results insofar as a pool must be consistently superior in order to lead a forager to fully switch, so EPICURE predicts improved matching when travel distance increases.

Conclusions

Our three pool results show resource undermatching, just as Sokolowski and Tonneau (2004) found undermatching using tokens in a non-spatial three pool experiment. Sokolowski and Tonneau discuss a difference-equalization rule and suggest that undermatching arises as foragers distribute themselves so that each pool has the same number of losers. For our three pool conditions, this appears to roughly be the case. However, we also noted that the high variance food condition has nearly twice as much available food in the 75% pool as in the 25% pool. Other conditions

have shown comparable differences between pools, so an available-food hypothesis does not seem to be a robust explanation of the matching results. An intriguing detail of the three pool conditions is that groups in the invisible food condition apparently treated the 60% and 30% pools very similarly, while groups in the visible food condition treated the 30% and 10% pools very similarly. These findings suggest additional experiments to test groups' discrimination capabilities under different perceptual conditions.

The travel distance conditions and variance conditions both led to the opposite of the results obtained by Baum and Kraft (1998) with pigeons, but as noted, our variance conditions may not be directly comparable to their bowl/trough manipulation. Despite the conflicting results, each of our findings appears to be internally consistent across statistical analyses. Therefore, it seems plausible that humans simply weight factors (e.g. local density of other foragers, local food density, etc.) differently than Baum and Kraft's pigeons, and a more general EPICURE model will be necessary in order to explain the different foraging results in detail.

Acknowledgments

References

Baum, W.M., & Kraft, J.R. (1998). Group choice: Competition, travel, and the ideal free distribution. *Journal of the Experimental Analysis of Behavior*, *69*, 227-245.

Goldstone, R.L., & Ashpole, B.C. (2004). Human foraging behavior in a virtual environment. *Psychonomic Bulletin & Review, 11,* 508-514.

Goldstone, R.L., Ashpole, B.C., & Roberts, M.E. (2005). Knowledge of resources and competitors in human foraging. *Psychonomic Bulletin & Review, 12,* 81-87.

Jha, S.K. (1996). The Kuznets curve: A reassessment. *World Development*, 24, 773-780.

Roberts, M. E., & Goldstone, R. L. (2006). EPICURE: Spatial and Knowledge Limitations in Group Foraging. *Adaptive Behavior*, 14, 291-313

Sokolowski, M.B.C., Tonneau, F., & Freixa-Baque, E. (1999). The ideal free distribution in humans: An experimental test. *Psychnonomic Bulletin & Review, 6*, 157-161.

Sokolowski, M.B.C., & Tonneau, F. (2004). Human-group behavior: The ideal free distribution in a three-patch situation. *Behavioural Processes, 65*, 269-272.