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Priming and Conservation Between Spatial and Cognitive Search

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Abstract

There is compelling molecular and behavioral evidence that human goal-directed cognition is an evolutionary descendent of animal foraging behavior. A key observation is that similar dopaminergic processes are used to modulate between exploratory and exploitative foraging behaviors and control attention across animal species. Moreover, defects in these processes lead to predictable goal-directed cognitive pathologies in humans, such as attention-deficit/hyperactivity disorder and Parkinson's disease. However, the cognitive relationships between exploration in space and exploration in the mind have not been examined. Using a spatial foraging task with two treatment conditions (clumpy and diffuse), followed by a word search task involving patches of words to be found in letter sets, we show that individuals who experienced clumpy resource distributions in space behave as if resources are more densely clumped in the word search task, relative to those who experienced the diffuse spatial treatment. We show this is not a function of general arousal but is consistent with longer giving-up times in the word search task, which is a qualitative prediction of optimal foraging theory. We also show that behavioral tendencies during search are conserved within individuals: Those who explore more of the physical space leave letter sets sooner. Along with the biological evidence, our results support a general search process underlying cognition, which operates both in external and internal environments.

Keywords: Goal-directed behavior; attention; animal foraging; foraging; dopamine; search; spatial search; word search; priming; individual differences; ADHD; Parkinson's.

Introduction

More than a hundred years ago William James noted “We make search in our memory for a forgotten idea, just as we rummage our house for a lost object” (James, 1890, p654). This relationship is anecdotally supported by the fact that cognitive representations of spatial and semantic knowledge are often characterized as maps or networks (Steyvers & Tenenbaum, 2005; Tolman, 1948). Though these internal representations are specific to particular contexts, the search processes required to navigate them may not be. In all cases, cognitive navigation relies on appropriate modulation of attention between exploration and exploitation in ways fundamentally similar to the behavioral ecology of animal foraging (Kareiva & Odell, 1987; Walsh, 1996).

Significant evidence from various fields suggests that this relationship between spatial foraging and internal cognitive search is not just a consequence of convergent evolution, but one of evolutionary homology (Hills, 2006). Research from neuroscience, genetics, and human pathology provide evidence that molecular and neural mechanisms that developed over evolutionary time for the purpose of modulating between exploration and exploitation in spatial foraging have subsequently been exapted for the purpose of modulating attention. A key observation is that similar dopaminergic processes are used to modulate goal-directed behavior and attention in multiple behavioral modalities across species (Floresco et al., 1996; Watanabe et al., 1997; Wang et al., 2004; Schultz, 2004). Furthermore, numerous pathologies of goal-directed cognition (e.g., attention-deficit/hyperactivity disorder—ADHD, drug addiction, and obsessive-compulsive disorder) involve dopaminergic defects or respond to dopaminergic drugs in ways that are consistent with dopaminergic effects on spatial movement behavior, as in, for example, the nematode and the fruit fly (Berke et al., 2000; Nieoullon, 2002; Schinka et al., 2002; Hills et al., 2004; Kume et al., 2005).

These observations suggest that spatial search in physical space and abstract search in a cognitive space share a common basis in the brain and may therefore share key control features. While prior work has shown that animal foraging theory can be successfully applied to human search behavior (Pirolli & Card, 1999; Wilke, 2006), these efforts have been made based on arguments for optimality or robust decision heuristics. An argument based on a common biological basis for goal-directed cognition, however, would mean that spatial and abstract foraging are not simply similar because of similar selective forces in the environment, but are, in fact, themselves constrained by similar underlying physiologies. Given this, if the search mechanisms for different domains are not independent of one another, then activity in one ‘environment’ may influence activity in another. In such a case, we would expect that differences in individual foraging behavior could be primed across spatial and abstract contexts. That is, prior experience with resource distributions in a spatial environment could prime foraging behavior in an abstract environment. Similarly, we would

expect that an individual's exploratory behavior in a spatial environment could be indicative of that individual's exploratory behavior in an abstract environment.

As a first step towards investigating the relationship between spatial and cognitive navigation, we had participants forage in external and internal search spaces. The external search space was represented by a two-dimensional field on a computer screen, over which participants foraged by controlling the movement of an animated icon. For the internal search, we focused on a specific aspect of mental search—namely search by manipulation in working memory of letter cues in a series of jumbled anagram-like letter sets (e.g., find words that can be created with four or more of the letters in “SULMPA”—Wilke, 2006; Wilke, Hutchinson, & Todd, 2004). Because each letter set can form multiple words, the letter cues provide a means of anchoring and constraining a depleting internal resource space composed of English words. Participants only gain access to this solution space via abstract manipulation of letters in the letter set (they were not allowed to write anything down). When participants decide they have sufficiently foraged in a given letter set, they can move to a new letter set. This allows us to create an abstract space analogous to a patchy spatial foraging environment. We used both of these tasks to address two questions concerning the conservation and priming of navigation strategies between spatial and abstract search domains: 1) Will differences in the way resources are distributed in space prime individuals to stay for longer or shorter durations in each patch in the word search task? 2) Will individuals who explore more in space show similar tendencies to explore more in the word search task?

Methods

Participants

Forty-one English speaking undergraduate university students at Indiana University participated in the experiment. All participants were recruited on a volunteer basis and there was no financial reward for their participation.

Materials and Procedure

Participants were seated in front of a computer and asked to follow written instructions that appeared on the screen. Instructions guided participants through a series of three activities, beginning with a training and pretest session in the word search (anagram) task, followed by a spatial foraging task, and then a post-test session in the word search task. All participants saw the same sequence of tasks and letter sets in the same order, however, participants were randomly assigned by the computer to either of the spatial foraging treatments described below (in a between participants fashion; $n = 19$ clumpy and $n = 22$ diffuse).

External Foraging Task Participants controlled the movement of a foraging icon using the 'I', 'J', 'L', and 'K' keys representing 'Go', 'Left', 'Right', and 'Stop', respectively. Left and right keys initiated turns of 35 degrees per step, and forward ('go') speed was approximately 20 pixels per second.

No participant used the stop key more than 1% of the time. To get familiarized with the controls, participants first had to navigate a two-dimensional maze. Then in the foraging treatment, participants saw a blank screen, 200x200 pixels in size, with their search icon in the center. They were told to move the icon to find as many hidden 'resource' pixels as they could in the allotted time, indicated by a sweeping clock-hand in the upper-right screen corner (clock units are in number of remaining steps, where a step is equal to one pixel of movement). Participants were randomly assigned to one of two resource distributions, 'clumpy' or 'diffuse', consisting of 3124 resource pixels in either 4 patches of 781 pixels each or 624 patches of 5 pixels each, respectively. Figure 1 shows the resource distributions for the two spatial foraging treatments and also presents typical participant foraging paths for each treatment. Resource pixels were not visible to participants until they were encountered, nor was their path visible (except where they had previously moved over resource pixels). Participants experienced five foraging trials, each two minutes long, and each with a different random arrangement of patch locations.

We measured spatial exploratory behavior for each individual by overlaying a 3-pixel grid (half the size of the minimal possible path loop that could be made by movement of the icon) on the spatial arena and determining how many of the grid squares each participant entered. Turning angles were also measured at 0.3s intervals by taking the angle between the last 0.3s line and the penultimate 0.3s line.

Internal Word Search Task In the internal search task, participants were asked to find words (anagrams) made up of at least four letters from each of a sequence of letter sets (e.g., the letter set "SULMPA" can be used to form, among other words, "SLAP" and "PLUM"). Following visual display of each letter set, participants could type in as many words as they wanted, or press a button at any time to move to the next set. Letter sets were constructed using only the twenty most common letters in the English alphabet (i.e., excluding K, V, X, Z, J, and Q), as previous work has shown participants in this task to be sensitive to letter frequency (Wilke, 2006), and we did not want obvious cues to the number of possible words for each letter set. Correct and incorrect entries were signaled to the participant after each word submission. There were on average 14.7 (SD = 5.5) valid words per letter set, judged according to the wordsmith.org anagram dictionary. Participants could leave a letter set at any time but had to wait fifteen seconds after indicating their desire to switch before the next letter set was shown. After leaving a letter set, participants could not visit it again. Participants received instructions and training on one letter set before moving to the pretest session. In the pretest, participants went through four letter sets and were given no directions on how many words to find before moving on to the next letter set. The pretest session ended when participants left the fourth letter set. In the post-test word search phase (following the spatial foraging treatment), participants were told that they needed to find a total of 30 words across any number of letter sets to finish the experiment, that they could spend as much time as

they liked on any given letter set, and that they should allocate their time appropriately so as not to stay too long or too short in any given letter set.

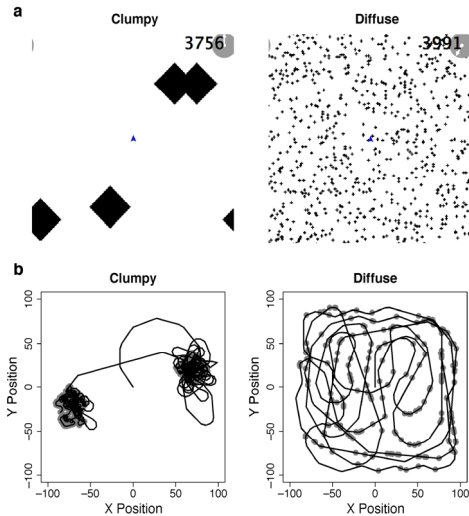


Figure 1: (a) Examples of clumpy and diffuse resource distributions. Black pixels represent resources. (b) Example paths for two participants in the clumpy and diffuse treatments. Grey circles are positioned over the pixels where participants found a resource.

Results

The conventional patch model of optimal foraging formalizes the optimal allocation of time to stay in individual resource patches (Stephens & Krebs, 1986). When resource patches are depleted sooner and travel times between patches are shorter (e.g., our diffuse spatial treatment), then foragers should leave patches sooner than when patches are dense and further apart. In our foraging task, this means individuals in the clumpy task need to turn more frequently when on resources because found resources indicate more resources nearby, whereas individuals in the diffuse condition should do the opposite, turn less, to avoid revisiting areas where they have already depleted the available resources. A genetic algorithm showing this result for resource distributions similar to those used here was described by Hills (2006). Consistent with this, Figure 2 shows that participants' turning angle immediately after encountering resources was significantly lower for those in the diffuse treatment than for those in the clumpy treatment ($t(39) = 2.72, p < 0.01$). Thus, participants were sensitive to the spatial correlations in the two environments, and any differences we find in behavior between the treatments are potentially a consequence of this sensitivity (though we also test other hypotheses below).

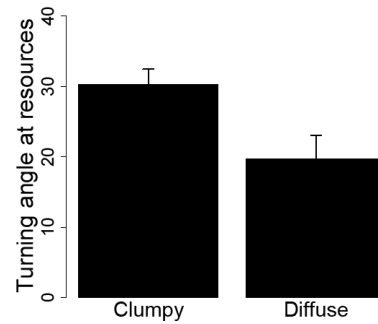


Figure 2: Mean turning angle when participants were on resources. Error bars show standard errors of the mean.

Priming of Abstract Exploratory Behavior by Experience in Spatial Resource Distributions

To test the potential priming effects of spatially correlated resources on patch-leaving times in a subsequent abstract search task, we compared the mean time each participant spent in a letter set 'patch' before and after the foraging treatment. As expected, in the pretest phase the mean letter set times were not significantly different between the two spatial environment conditions ($p = 0.66$) and shared a mean of 85.7 seconds. However, in the post-test after the spatial foraging task, the two treatment groups were significantly different in the corresponding changes in their mean letter set times (Figure 3). Individuals who were first primed for goal-directed exploitation in the clumpy spatial resource environment stayed in letter sets approximately 17.1 seconds *longer* than they did in the pretest, while individuals who experienced diffuse resource distributions stayed approximately 16.3 seconds *shorter* than they did in the pretest ($t(39) = 2.65, p = 0.011$). This is consistent with the biological and behavioral evidence described above, supporting a common 'foraging' cognition across external and internal domains. However, other possible explanations exist, which we now test.

It is possible that our attentional priming effects are a consequence of the total resources received during foraging and are therefore due to a greater anticipation of reward in general. To test this hypothesis, we used a linear regression of spatial resources found on the mean difference in letter set times. The number of resources found was not a significant predictor of mean changes in letter set time ($p = 0.26$). However, to be thorough, we also included resources found as a covariate in an ANOVA containing treatment condition. Again, treatment condition was a significant predictor, $F(1, 37) = 6.4, p = 0.017$, but both the main effect of resources found and the resources found by distribution treatment interaction were not significant ($p = 0.23$ and $p = 0.42$, respectively).

Another alternative explanation is that individuals in the clumpy (or diffuse) trials were in a higher state of arousal because they may have pressed the keyboard response keys more frequently. A test of key presses between the two

groups, however, shows that the two groups did not significantly differ in the number of total key presses during the foraging sessions ($t(39) = 1.26, p = 0.21$). Furthermore, if one group were in a higher state of arousal, we should expect the overall word submission rates in the anagram task to be different between the two treatment groups. However, treatment groups did not significantly differ in mean time to submit correct or incorrect words ($t(39) = 1.61, p = 0.12$ and $t(39) = 1.27, p = 0.21$, respectively). This suggests that arousal state, as measured by key presses and word submission rates, is not the cause of the greater times spent exploring each letter set following clumpy spatial foraging.

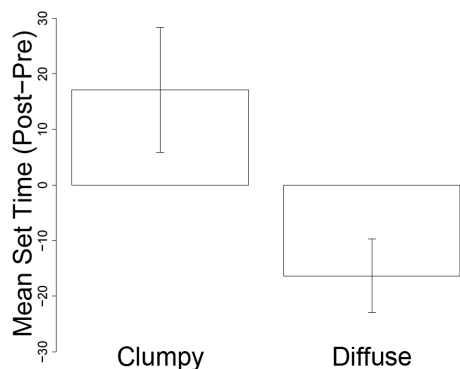


Figure 3: Mean difference in letter set times in seconds (post-test – pretest). Error bars show standard errors of the mean.

Another way to measure patch exploitation is in terms of giving-up time (GUT), which is the time between when the last resource item is encountered and when the forager actually leaves the patch. Using optimal foraging theory, McNair (1982) showed that organisms should use longer or shorter optimal giving-up times when patches are better (clumpier) or worse (more diffuse), respectively. In the word search task, GUTs are analogous with the latencies to switch (the time between the last word submitted and the switch to a new letter set). If participants who foraged in the spatially clumpy treatment—where longer GUTs would be adaptive—are acting as if letter sets in the post-test are also clumpier, then their latencies to switch in the post-test should be longer than participants who experienced diffuse spatial resources.

Figure 4 shows that the latencies to switch in the word search post-test are indeed significantly longer for individuals in the spatial clumpy treatment than those in the diffuse treatment ($t(39) = 2.238, p = 0.031$). This further supports our hypothesis that individuals in the word search task are influenced by their expectations regarding the distribution of resources in patches and that those expectations can be formed with prior experience in spatial distributions.

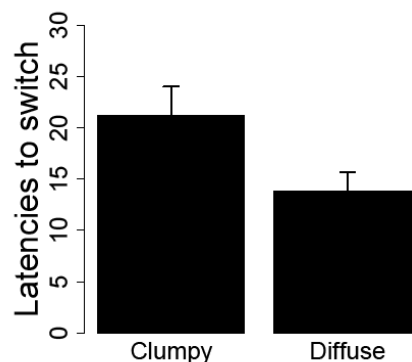


Figure 4: Latencies to switch (in seconds) to the next letter set following the last word submitted. Error bars show standard errors of the mean.

Individual Sensitivity to Spatial Priming

Regression analyses of the individual sensitivities to our spatial foraging treatments reveal that individuals in the diffuse foraging treatments were far more likely to reduce their mean letter set time if their mean set time in the training session was long than if it was short (regression coefficient = $-0.68, p < 0.001, R\text{-squared} = 0.55$). However, the clumpy treatment group did not show a similar sensitivity ($p = 0.12$). This may suggest that external cues to reduce perseveration are more effective than cues to increase perseveration, but more work is needed to validate and understand this difference.

Conservation Between Spatial and Abstract Foraging

Our second focus regards the individual consistency in exploration between spatial and abstract environments. The biological and behavioral basis for general search processes would suggest that if individuals are prone to perseverative search strategies—exploiting found resources—in one environment, they should apply similar strategies in new environments. This prediction of individual search differences conserved across environments, however, must be modulo the individual’s sensitivity to feedback from interactions with new environmental conditions; this sensitivity may vary across types of environments and may be independent of the underlying search processes. Nonetheless, evidence for conserved individual search differences, based for instance on different individual sensitivities to dopamine levels, would be consistent with our argument that the underlying biological basis of goal-directed behavior leads to common search tendencies across task domains.

In the spatial foraging task we measured exploration as the proportion of the total surface area explored. Our hypothesis here is that individuals who explore more in the spatial foraging task (within a treatment condition) should leave patches earlier and submit words at a faster rate. One caveat is

that the proportion of the area explored by participants was significantly influenced by the treatment ($t(39) = -4.70, p < 0.001$), with individuals in the clumpy treatment exploring less than individuals in the diffuse treatment. To control for this effect, but still maintain our statistical power, we included in an ANOVA on mean letter set time, the proportion of spatial coverage, the treatment condition, and the interaction between the two. This effectively controls for the variance in exploration due to the treatment condition and reveals that exploratory behavior was a significant predictor of letter set leaving times ($F(1,37) = 10.25, p = 0.003$). Participants who explore more in space spend less time in letter sets (individual regressions are shown in Figure 5).

Using a similar analysis, controlling for treatment and the interaction with treatment, we find a similar effect for mean time to submit both correct and incorrect words ($F(1,37) = 5.40, p = 0.026$ and $F(1,37) = 4.68, p = 0.037$, respectively). In both cases, more exploration means a faster submission rate (data not shown).

While we cannot claim that exploration in a spatial environment is a strong predictor of departure times or word submission rate in the word search task, nonetheless, the behaviors are correlated, despite the fact that the two environments are quite different.

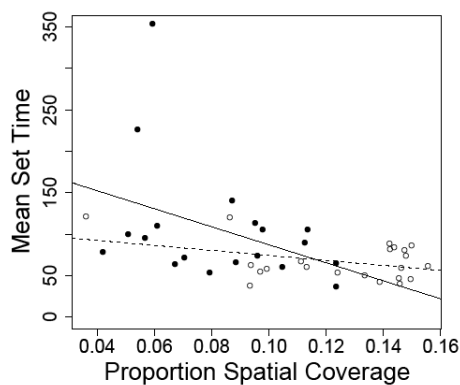


Figure 5: Proportion spatial coverage versus mean letter set time (seconds). Filled circles represent participants in the clumpy spatial treatment; open circles represent participants in the diffuse treatment. The regression lines are for each treatment group independently (solid = clumpy, dotted = diffuse).

Discussion

The present study examined the search strategies of individuals as they moved from a concrete spatial foraging task to an abstract word search task. The main findings were that spatial foraging tasks are capable of priming abstract word search tasks and that individuals conserved their search strategies as they moved between the two tasks.

These results strongly suggest that there are general search processes underlying cognition that are used to search both in space and in abstract cognition. This fits well with the evidence supporting a common basis in the brain for abstract

and spatial goal-directed cognition (Hills, 2006). Moving to a new task leaves intact local-to-global strategies for exploration or persistence fostered by an earlier task even if the two tasks involve domains that are traditionally conceived to be highly dissimilar. The present study, however, only explores these effects in a specific pair of task domains, and represents a starting point for future research on the interactions between resource distributions and cognitive search processes.

Recent neural studies have shown modulation from global brain activation during learning to more localized activation following learning (Jog, Kubota, Connolly, Hillegaart, & Graybiel, 1999; Qin et al., 2003). This is consistent with spreading activation theories of semantic processing (Collins & Loftus, 1975; Neely, 1977), which also appear to operate via local-to-global modulation. Our results may imply that these focus-shifting cognitive processes are potentially influenced by prior experience in physical space. If our interpretations of the biological evidence are correct—and the research described here supports that interpretation—then exploratory spatial movement may be tightly linked with problem solving, memory retrieval, the general control of attention, and other cognitive functions. The general search processes of exploration and exploitation capture commonalities that underlie cognition across these domains.

The verification and limitations of these processes require substantial future research. In the present study, the word search task is still more stimulus driven than other conceivable tasks (e.g., “name all the cities you can think of in a given state”, where states represent depleting patches that cannot be revisited). We chose the word search task specifically because it allows for fairly direct control of the possible solution set and because it is unlikely to be influenced by previous experience with any given letter set. To generalize these results, we must investigate other search domains.

In general and across species, increasing extracellular dopamine increases behaviors associated with exploitation of resources, while reductions in extracellular dopamine leads to more exploratory (or inattentive) behavior (reviewed in Hills, 2006). Though our present study does not directly measure dopamine, our research may provide insight into clinical disorders of attentional focus, such as ADHD and schizophrenia, by showing how cognitive tendencies for attentional persistence may be revealed in tasks involving spatial exploration. Furthermore, tasks that modulate attention in space may alter the persistence of attention in subsequent nonspatial tasks. If such spatial tasks could be made to have long-lasting effects, for example by giving individuals exposure to them during development, then they may provide useful hints towards non-pharmacological treatments for disorders of attention.

Generalized search processes of the sort we have described here have clear adaptive importance, helping organisms accrue necessary resources in an efficient manner. Moreover, most search tasks, including those we have studied in this paper, are conceptually synonymous with attentional processes, which themselves must explore and exploit

external cues to guide behavior. The biological evidence regarding search processes could be taken to support a historical constraint on cognition; in part, cognition is the way it is because of where it came from, evolutionarily speaking. The fact that we can find priming between search in two very different types of environments, external and internal, provides a valuable window onto the cognitive mechanisms that may underlie both types of search.

Acknowledgments

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