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 the control of attention across animal species. Moreover, defects in these processes lead to predictable goal-directed cognitive pathologies in humans, such as Attention-deficit/hyperactivity disorder, drug addiction, and Parkinson's disease. However, the cognitive relationships between exploration in space and exploration in the mind have not been examined. Using Cox proportional hazards analyses, we show that behavioral tendencies during search are conserved within individuals as they move between literal spatial and abstract cognitive search tasks. Individuals with short giving up times, who explore more of the physical space, also move more rapidly between information in a cognitive search task. These individuals also make more exploratory guesses in the abstract task if they are more exploratory in their spatial foraging behavior. We further show that subjecting individuals to clumpy resource distributions in space leads them to behave as if resources are more densely clumped in the abstract cognitive task. Our findings provide evidence for a task independent mechanism of cognitive exploration, which operates both in external and internal search processes, and for which internal search strategies are primed by experience with external resource distributions.

Keywords: Goal-directed behavior; attention; animal foraging; dopamine; proportional hazards analyses; search; spatial search; word search; ADHD.

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). 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 between 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 one of evolutionary homology (Hills, 2006). In other words, molecular and neural mechanisms that developed over evolutionary time for the purpose of modulating between exploration and exploitation in spatial foraging, have subsequently been put to work 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 et al., 2002). Furthermore, numerous pathologies of goal-directed cognition (e.g., attention-deficit/hyperactivity disorder, drug addiction, and obsessive-compulsive disorder) involve dopaminergic defects or respond to dopaminergic drugs in ways that are consistent with dopaminergic affects on spatial foraging behavior (Berke et al., 2000; Nieoullon, 2002; Schinka et al., 2002). These observations suggest that spatial search in physical space and abstract search in a cognitive space may share key control features.

However, evidence for cognitive modularization (Barkow, 1992; Barrett & Kurzban, 2006; Nieder, Freedman, & Miller, 2002) might suggest that cognitive search processes share similar modularity and, because they are specific to a given modality, unlikely to transfer between tasks. Consistent with this argument, it is difficult to find transfer of problem solving strategies between divergent contexts (Gick & Holyoak, 1980, 1983). However, if general search processes are used to navigate both external and internal topographies, then the way resources are distributed in one setting should affect search behaviors in subsequent settings.

To investigate the relationship between spatial and cognitive navigation, we had human subjects forage in

external and internal search spaces (see Methods). Subjects first foraged for hidden spatial resources in a two-dimensional field and then searched for words in a series of jumbled anagram-like letter sets. Figure 1 shows the resource distributions for the two spatial foraging treatments and also presents some typical subject foraging paths. The letter sets contained multiple words, but subjects could move to a new letter set at any time. We then used these tasks to address two questions concerning the conservation and priming of navigation strategies between spatial and cognitive search domains. Will individuals who explore more in space show similar tendencies to explore in the word search task? And will differences in the way resources are distributed in space prime individuals to stay longer or shorter durations after they move onto the word search task?
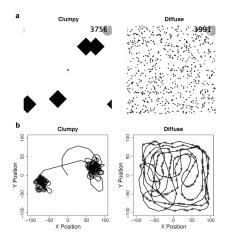

Figure 1: (a) Examples of clumpy and diffuse resource distributions. Black pixels represent resources. (b) Example paths for two subjects in the clumpy and diffuse treatments. Grey circles are positioned over the pixels where subjects found a resource. The clock informs subjects when the search trial will end.

Figure 2 shows that spatial exploratory behavior was a significant predictor of letter set leaving times ($P < 0.01$, $n = 40$). Subjects who explored more spatially switched between letter sets more frequently, increasing their hazard rate for leaving each letter set by approximately 10% for each percentage increase in spatial exploration (see Table 1). We also compared spatial exploration with the number of words submitted, reasoning that if some individuals are prone to greater exploration of spatial distributions, these individuals should also have higher rates of exploratory—and hence possibly incorrect—word submissions. There was a significant correlation between

spatial exploration and incorrect word submission rates, with a 7% increase in hazard rate for incorrect word submission with each percentage increase in spatial exploration ($P < 0.01$, see Table 2). Thus, exploratory tendencies in spatial search processes are conserved in the internal word search task both at the level of letter set switching rate and at the level of individual word submissions.
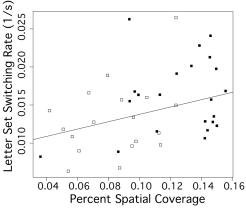

Figure 2: Percent spatial exploration versus letter set switching rate across individual subjects. Filled squares represent subjects in the diffuse spatial treatment; open squares represent subjects in the clumpy treatment. The regression line, controlling for treatment group, indicates a significant conservation of exploratory tendency from the spatial foraging task to the word search task, corresponding to a faster switching rate between letter sets as spatial exploration increases.

Table 1: Individual differences in spatial exploration predicts movement between letter sets.

Covariate	β	$\exp(\beta)$	robust se	P
Percent Coverage	0.10	1.11	0.03	0.003
Treatment	-0.08	0.92	0.23	0.740

Table 2: Individual differences in spatial exploration predicts word submission rates

Covariate	β	$\exp(\beta)$	robust se	P
Percent Coverage	0.068	1.07	0.02	0.003
Treatment	-0.18	0.83	0.14	0.210

Individuals who were first primed for goal-directed exploitation in clumpy spatial resource environments stayed in letter sets longer (mean 91.7 seconds per set) than individuals who experienced diffuse resource distributions (mean 66.9 seconds; Figure 3a). Comparing pre-treatment with post-treatment effects revealed that this was due to clumpy-treatment subjects staying on average 22 seconds longer per letter set after treatment ($P < 0.05$), whereas subjects in the diffuse treatment did not have significantly different pre- and post-treatment letter set departure rates ($P = 0.62$). Correspondingly, subjects in the diffuse treatment had a letter-set leaving hazard rate 78% higher than subjects in the clumpy treatment (Fig. 3b, see Table 3). Total resources found in the spatial foraging task were not a significant predictor of letter-set leaving times ($P = 0.30$). Thus, the attentional priming effect in the letter set task was due to resource distributions and not overall response to rewards in the spatial foraging task.

Table 3: Consequences of treatment in either clumpy or diffuse spatial resource distributions

Covariate	β	$\exp(\beta)$	robust se	P
Treatment	0.58	1.78	0.26	0.03
Training	-0.11	0.99	0.00	0.011
Resources Found	0.00	1.00	0.00	0.300

The finding that exploitative behavior is primed between tasks that differ in terms of their spatial or abstract representations implies that cognitive search mechanisms are not task specific. 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 highly dissimilar domains as traditionally conceived. 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), consistent with spreading activation theories of semantic processing (Collins & Loftus, 1975; Neely, 1977), and these also appear to operate via local-to-global modulation. Our results imply that these focus-shifting cognitive processes may be influenced by search in physical space, hinting that exploratory spatial movement may be tightly linked with problem solving, semantic memory, and other cognitive functions. Furthermore, these findings may provide insight into clinical disorders of attentional focus, such as ADHD and schizophrenia, by showing that cognitive tendencies for attentional persistence are revealed in tasks involving spatial exploration and, furthermore, that tasks which focus attention in space may increase the persistence of attention in subsequent nonspatial tasks. If such tasks could be made to have long-lasting effects, for example by exposure during development, then they may provide useful hints towards non-pharmacological treatments for disorders of attention.
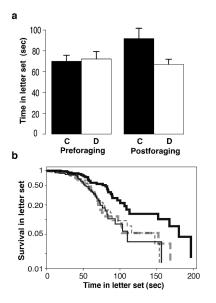

Figure 3: (a) Letter set departure times for the word search task before and after the foraging treatment. Black bars represent clumpy and white bars represent diffuse spatial treatments. Error bars show standard error. (b) The Kaplan-Meier survival curves, where survival is interpreted as the probability that a subject is still in a letter set after a given time (thin lines represent pre-foraging, thick lines represent post-foraging; solid black lines represent clumpy, and dotted grey lines represent diffuse spatial treatments). The log axis reveals a constant letter set departure rate after approximately 50 seconds. Only the clumpy post-foraging group is significantly different from the others.

Methods

Subjects

40 university students participated in the experiment, which consisted of a training session in the word search (anagram) task, followed by a spatial foraging task, and then a test session in the word search task.

Foraging Task

Subjects controlled the movement of the foraging icon using the 'I', 'J', 'L', and 'K' keys representing 'Go', 'Left', 'Right', and 'Stop', respectively. Left and right keys initiated turns of 15 degrees per step, and forward ('go') speed was 22 pixels per second. No subjects used the stop keys more than 1% of the time. To improve familiarity with the controls, before the foraging trials subjects had to navigate a two-dimensional maze. Upon completion of the maze subjects

were moved to a blank screen, 200x200 pixels in size, and 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. Subjects 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. Resource pixels were not visible to subjects until they were encountered. Subjects experienced five foraging trials, each two minutes long, and each with a different random arrangement of patch locations.

Word Search Task

Subjects were asked to find words (anagrams) by rearranging at least four letters from each of a sequence of letter sets (e.g., "SULMPA", containing, among other words, "SLAP" and "PLUM"). Following visual display of each letter set, subjects 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 subjects 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 subject after each word submission. There were on average 14.7 valid words per letter set (judged according to the wordsmith.org anagram dictionary), with a minimum of 7 words. Subjects 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, subjects could not visit it again. In the training phase, subjects went through four letter sets and were given no directions on how many words to find before moving on the next letter set. The training phase ended when subjects left the fourth letter set. In the test phase (following the spatial foraging treatment), subjects 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 a given letter set.

Analyses

Except where stated otherwise, statistical analyses were performed using a recurrent event stratified Cox proportional hazards model, where the hazard, h, representing the proportional likelihood that a subject will leave a letter set or submit a word (where appropriate), is a function of the time in the letter set, t, and the individual covariates, X.

$$h_g(t, X) = h_{0g}(t)e^{\beta_1 X_1 + \ldots + \beta_2 X_2 + \beta_p X_p}$$

We used covariates representing the individual subject's treatment group and their percent coverage of space in the first trial of the spatial foraging task, where subjects knew the least about the hidden resource environment. We stratified the data by letter set, g, and then used Prentice, Williams, and Peterson gap-time format (Kelly & Lim, 2000) to solve for the coefficients, β, and used robust standard error (robust se) estimates to calculate significance (Therneau & Grambsch, 2000). All subjects completed the four letter sets in the word search training phase and (at least) four letter sets in the test phase. Our analyses are restricted to these events.

To test the hypothesis that individuals maintained exploratory tendencies between spatial foraging and abstract cognitive foraging, we measured spatial exploratory behavior for each individual by overlaying a 3-pixel grid (half the size of the minimal foraging path loop) on the spatial arena and determining how many of the grid squares the subject entered. This spatial exploration score was then used in the recurrent event stratified Cox proportional hazards model to predict the effect of spatial exploration on hazard rates in the word search task.

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