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A neuromorphic model of spatial lookahead planning

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ABSTRACT

In order to create spatial plans in a complex and changing world, organisms need to rapidly adapt to novel configurations of obstacles that impede simple routes to goal acquisition. Some animals can mentally create successful multistep spatial plans in new visuo-spatial layouts that preclude direct, one-segment routes to goal acquisition. *Lookahead* multistep plans can, moreover, be fully developed before an animal executes any step in the plan. What neural computations suffice to yield preparatory multistep lookahead plans during spatial cognition of an obstructed two-dimensional scene? To address this question, we introduce a novel neuromorphic system for spatial lookahead planning in which a feasible sequence of actions is prepared before movement begins. The proposed system combines neurobiologically plausible mechanisms of recurrent shunting competitive networks, visuo-spatial diffusion, and inhibition-of-return. These processes iteratively prepare a multistep trajectory to the desired goal state in the presence of obstacles. The planned trajectory can be stored using a primacy gradient in a sequential working memory and enacted by a competitive queuing process. The proposed planning system is compared with prior planning models. Simulation results demonstrate system robustness to environmental variations. Notably, the model copes with many configurations of obstacles that lead other visuo-spatial planning models into selecting undesirable or infeasible routes. Our proposal is inspired by mechanisms of spatial attention and planning in primates. Accordingly, our simulation results are compared with neurophysiological and behavioral findings from relevant studies of spatial lookahead behavior.

1. Introduction

The ability to create preparatory spatial plans in complex novel environments where perceptually indirect actions are necessary to obtain a goal is a critical competence for successful interaction with real-world environments. Spatial planning has been hypothesized to co-develop with spatial skills, in both phylogeny and ontogeny, and to support a broad range of human intellectual pursuits (Diamond, 1985; Matthews, 1996). There is a broad range of higher-level flexible spatial planning behaviors in humans and other primates (Buttelmann, Carpenter, Call, & Tomasello, 2008; Carder, Handley, & Perfect, 2004; Miller & Cohen, 2001; Ward & Allport, 1997). Many anatomically and functionally disparate spatial skills share the common conceptual objective of generating and executing a spatial trajectory to transfer one or more objects from their initial state to a desired goal configuration. We introduce a neuromorphic model for generation of such multistep, goal-directed lookahead trajectories in novel 2D visuo-spatial environments.

Neurodegenerative diseases (Cohen & Freedman, 2005; Ersche, Clark, London, Robbins, & Sahakian, 2006; Sahakian et al., 1995) or damage can result in dysexecutive syndrome, a spectrum of deficits characterized by behavioral impulsivity and myopia, in which behavior generation is dominated by immediate stimuli and characterized by response perseveration in situations where task demands change (Carder et al., 2004; Ciaramelli, 2007; Dias, Robbins, & Roberts, 1996; Walker, Mikheenko, Argyle, Robbins, & Roberts, 2006) or when perceptually indirect actions need to be taken to achieve a goal (Carder et al., 2004; Carder, Handley, & Perfect, 2008; Colvin, Dunbar, & Grafman, 2001). These data indicate that specific neural mechanisms are responsible for the generation of flexible goal-directed behaviors in novel visuo-spatial environments, such as those shown in Fig. 1.

Sustained, spatially tuned activations during planning intervals are recordable in posterior parietal cortex (PPC) neurons (e.g., Andersen, Snyder, Bradley, & Xing, 1997; Chafee & Goldman-Rakic, 2000). Moreover, the PPC has long been associated with attentional control and spatial awareness, including an actor's ability to relate visible spatial locations to self and self-initiated actions to the local spatial layout. Unilateral PPC lesions reliably produce hemifield neglect syndromes (e.g., Committeri et al., 2007; He et al., 2007), in which the actor loses the ability to process or attend to locations and to plan actions in an entire spatial hemifield.

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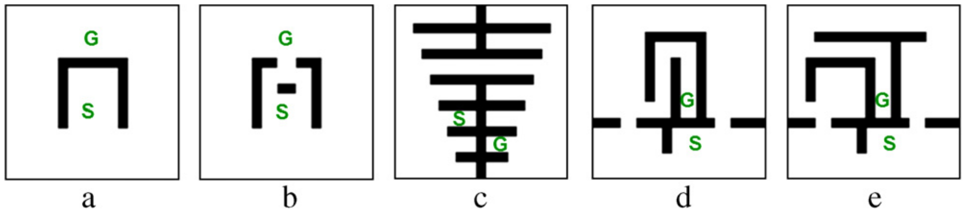

Fig. 1. Five examples of 2D spatial planning tasks that require indirect solutions and therefore nontrivial planning methods. *S* indicates the position of the start state, *G* the position of the goal. White is free space through which the trajectory may be generated. Black marks positions covered by obstacles.

In addition to its general role in supporting working memory operations on, and representations of, task-relevant information (Funahashi, Chafee, & Goldman-Rakic, 1993; Levy & Goldman-Rakic, 1999; Smith et al., 1995), dorsolateral prefrontal cortex (dlPFC) has also been specifically implicated in the preparation and selection of multistep action plans across a range of spatial and nonspatial tasks (Funahashi, 2001; Tanji & Hoshi, 2008). Electrophysiological and functional imaging studies have found high recruitment, and substantial task-dependent selectivity, of dlPFC activity in tasks that require spatial lookahead planning (Averbeck, Chafee, Crowe, & Georgopoulos, 2003; Boussaoud & Wise, 1993; Miller & Cohen, 2001; Miller, Erickson, & Desimone, 1996; Mushiake, Saito, Sakamoto, Itoyama, & Tanji, 2006; Mushiake, Saito, Sakamoto, Sato, & Tanji, 2001; Saito, Mushiake, Sakamoto, Itoyama, & Tanji, 2005).

These neurobiological and behavioral data indicate that flexible lookahead spatial planning in higher primates utilizes a constellation of explicit processes that are distinct from lower-level conditioned behaviors. To qualitatively model such behavior, we introduce a novel neurodynamic model of spatial lookahead planning that integrates neural modeling concepts of attentional diffusion, transient inhibition-of-return, and competitive selection to enable mental construction of a feasible spatial trajectory from an initial state to a given goal state in the presence of complex, novel configurations of free space and obstacles. An earlier version of this model has been briefly presented in Ivey, Bullock, and Grossberg (2008). Consideration of interactions of the proposed model with cooperative neural processes, such as working memory storage of feasible trajectories and sequential execution, is deferred until the Discussion.

We constrain our attention to the class of planning models that can be formulated as continuous-time dynamical systems, due both to their desirable properties of analyzability and implementation in analog circuitry, and to their potential as candidate models of planning in brains. Our focus on neurodynamical systems contrasts with non-neurodynamic planning algorithms from the control theory and artificial intelligence literature (e.g., Dijkstra, 1959; Koenig & Likhachev, 2002; Stentz, 1995).

2. Model description

Prior dynamical system models of planning have typically dealt with uncluttered environments or relied on repeated learning over multiple attempts. Models that compute difference vectors from start to goal (e.g., Bullock, Grossberg, & Guenther, 1993) are well supported by neurobiological data from simple tasks (e.g., Bullock, Cisek, & Grossberg, 1998), but by themselves do not cope with the indirection required for route planning around obstacles. Conditioned chaining models (e.g. Butz, Sigaud, & Gerard, 2003; Capdepuy, Polani, & Nehaniv, 2007; Fu & Anderson, 2006; Sutton & Barto, 1998; Tolman, 1959) can succeed along familiar (prelearned) paths, but fail in novel or altered layouts, and may require many learning trials to reach acceptable performance (Roitblat, 1994). Attractor/repeller models (Browning, Grossberg, & Mingolla, 2009; Eichhorn, 2005; Elder, Grossberg, & Mingolla, 2009; Fajen & Warren, 2003) are robust for choosing paths around point or convex obstacles, but are insufficient with concave obstacles. These models do not claim lookahead planning as a competence, but are nevertheless possible candidate models and discussed here to note that they are not sufficient to address the present task.

The current model can be regarded as a cognitive preprocessor for the stages assumed in some of these simpler models. It uses goal-sourced attentional diffusion and gradient climbing, illustrated in Fig. 2, as key operations in prospective route planning. The attentional diffusion process is embodied by a 2D topographic map of the environment with excitatory input at the goal. Through diffusion dynamics, the activity spreads throughout the topographic map. The activity is blocked and redirected by environmental obstacles. Note that nearly all motile organisms, including primitive bacteria (Macnab & Koshland, 1972), can detect *external* gradients in the world formed by diffusion processes (e.g., odor gradients), and can climb up or down them as needed to achieve goals. Cognitive gradient climbing (CGC) models propose that at least some primates have discovered how to represent spatial gradients internally, and to exploit such internal representations for mental planning in novel layouts that include concave obstacles.

The adjective "cognitive" is chosen here, similar in spirit to its usage in Tolman's *cognitive maps* (Tolman, 1948), to distinguish between the two broad classes of gradient climbing by life forms. The strategy of seeking high densities of an externally sensed gradient, such as a chemical concentration gradient, requires no internal genesis or representation of the gradient since it already exists in the world. The strategy also requires no preparatory gradient climbing operation since such evaluation of the gradient occurs in-the-loop with physical movement in the world. In contrast, the CGC model explored here proposes that some animals have evolved the capacity to generate a mental representation of a gradient that does not inherently exist in the world, and to iterate a mental process that climbs that mentally generated gradient. In psychology, the external class of models would be called "behavioristic", the latter class "cognitive". Indeed, it was precisely the postulation by Lashley (1951), Tolman (1948) and others regarding the existence and manipulation of internal representations, notably spatial maps, that led to the reemergence of a cognitive psychology after the failure of Watsonian behaviorism. Note that a key aspect of external gradient climbing is that it is a memoryless process. In contrast, when a mental operation fundamentally manipulates internal states, as does the current model, it is properly called cognitive. The current model proposes a process whereby a sequence of forthcoming actions is prepared through internal mechanisms, a hallmark of the cognitive, as opposed to the behaviorist, tradition. Although the non-CGC models noted above are insufficient to account for key aspects of primate intelligence exhibited in complex novel environments, we propose that CGC co-exists with phylogenetically older planning mechanisms that suffice when task demands are simpler.

The current CGC model of spatial lookahead planning is built from neurobiologically plausible mechanisms whereby an entire plan of sequential actions may be mentally constructed and prepared for enactment before any action is taken in a complex novel