Effects of Representation on Solving Complex Spatial-Temporal Problems

Baylor Wetzel
Department of Computer Science and Engineering, University of Minnesota
wetzel@cs.umn.edu

Abstract

Human data are used to study how people solve complex problems that have spatial and temporal components. Major findings include the use of task-focused representations, unexpectedly tight coupling of representation and search, time and space conflation, and use of multiple concurrent representations. The major contributions of this work include a set of abstract representations that strongly support spatial-temporal reasoning.

Introduction

Tower Defense (TD) games are among the most popular type of games. In a TD game the goal is to prevent enemies from reaching the end of a path by selecting and placing a series of defense "towers" at strategic locations. There are many types of towers, varying by cost, strength, speed and range. Some towers temporarily slow enemies, accentuating an already existing temporal aspect to the problem. An example is shown in Figure 1.

The TD problem leverages human strengths in spatial reasoning and transfer learning. Humans re-represent problems as sets of abstractions, biases, goals and strategies. Concepts that are difficult to reason with precisely (e.g., time) are re-represented as concepts that are easier to manipulate (e.g., space). This allows humans to leverage experience to solve new problems. In earlier work we showed that a human takes, on average, one hour and two dozen attempts to solve their first TD map while subsequent maps are often solved in three minutes and a single trial (Wetzel 2011).

We are interested in both how humans are able to solve complex spatial-temporal reasoning problems and how that knowledge can help us design algorithms that, leveraging the strengths of computers, can do as well or better on similar types of problems.

A key contribution of the work done so far is the identification of types of spatial relationships and abstractions used to support strategies for solving complex spatial reasoning problems. Much of the current work on spatial reasoning relies on some form of connection calculus (Randell, Cui, and Cohn 1992) between two physical objects. Such representations can describe the space but do not directly assist reasoning. Human representations of space have been proposed by (Ragni and Brüssow 2011) but focus on low level operations on simple tasks.

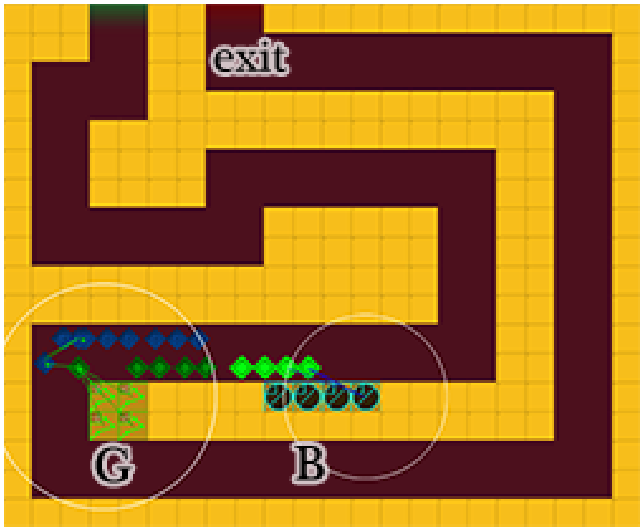

Figure 1: Two rows of objects move along a path (maroon) to the map exit. In the preparation phase, the player places defense towers on the walls (gold). Green towers (G) damage the objects while blue towers (B) temporarily slow them. Range is shown by white circles.

To identify spatial relationships and abstractions we have collected data from several dozen human subjects playing a TD game we created. Experiments have three phases: subjects train until response stabilization, are tested under a think-aloud protocol on 12 maps (five training, seven novel) then explain their reasoning in an after-action review.

Subject solutions (actions and intent) are recorded by two independent coders using a (paper) behavioral model containing several hundred variables. Using the behavioral model, we have analyzed human data for between- and within-subject parameter stability. We have identified key abstractions and catalogued special items such as space-time conflation, recognition-based strategy activation and concurrent abstract/concrete representations.

Contrary to our initial expectations, the analysis done to

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date suggests that the key to spatial-temporal reasoning is not a complex reasoning process but a series of learned goal-selection biases paired to task-focused, context-dependent data representations. Our work shows that spatial representations are abstract (to support transfer learning) but tightly coupled to the reasoning process. We also show that humans use affordances, i.e. qualities of objects that enable or suggest actions.

Initial Results

In the tower placement process, human subjects choose a relationship between the object to be placed (target) and a reference object (anchor). Although the target and anchor can be any object or spatial feature (e.g., tower, U-turn), they are more commonly items such as an object's properties (e.g., a tower's range, a tower's range's exit boundary), effects (e.g. the space over or duration which an object is slowed) and spatial affordances (e.g., a spot where the path passes through a specified tower's range three times).

Much of the "reasoning" work we observed is actually handled by the representation. Consider a subject whose play style is to create a single large offensive area and line the path leading to it with slowing towers and light attack towers. For the placement decision of the light attack towers, the target is a chain of locations and the anchor is, first, a spatial gap between a path entrance and a neighborhood and, second, a compromise between usable range and an active effect (i.e., the enemies are slowed). Representing the map as a set of strategically valuable features such as spatial gaps, role-based groups, effect areas, or path splits, makes it easier to represent, transfer and instantiate strategies.

TD has some interesting properties that are not immediately apparent and have not been addressed in other literature. One of these is the relationship between space and time. Dedicated visual processing centers make many spatial tasks easy and effortless for humans. One such task is judging the relative size of two areas. A common TD strategy is *maximum usable range* – place towers where they cover the largest number of path cells. The assumption is that the more area the tower covers, the more damage it can do. This strategy relies on a spatial property while a tower's total damage dealt relies on a temporal property – the total damage is the product of the damage done in one time unit by the time the tower is active. Since the unit damage is constant, the goal should be to find places that maximize the active time. Many subjects reasoned that a larger range meant the tower was active for more time and therefore area was a useful approximation of tower temporal activity. Substituting spatial properties for temporal ones allowed subjects to leverage innate spatial abilities, allowing subjects to quickly generate good solutions to moderately difficult TD problems.

While time and space can be profitably conflated, the risk is missing superior strategies. In Figure 2, the towers on the left cover 30 path cells. Observant players noticed that the first enemy could be attacked over the entire range but, as long as the tower was focused on the first enemy, subsequent enemies could move through the range unharmed. The result is that the amount of time the tower has to attack an enemy shrinks over time.

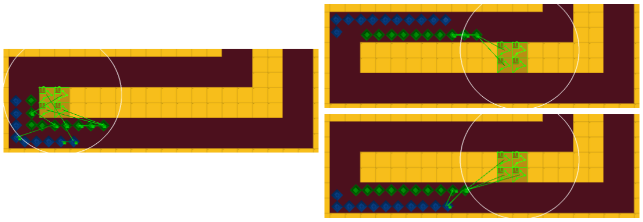

Figure 2: The strategy *Maximum Usable Range* (left) attempts to maximize time by maximizing space. The strategy *Temporal Separation of Attack Windows* (right) sacrifices space to increase time.

Subjects solved this queuing problem with a strategy we called *temporal separation of attack windows*. In Figure 2, the towers on the right have two independent attack windows (top and bottom). The first enemies leave the range early, allowing the towers to focus on later enemies, and do not reenter the range until the towers have finished with the later enemies. Neither group is able to provide a significant buffer for the other. Although the towers on the right cover 13% less area (26 path cells), they fire 30% more often (546 vs. 711 times), resulting in a score 73% higher (11 vs. 19).

Future Work

We have created a random baseline agent, implemented some of the identified spatial-temporal features in agents that use those features to decide where to place the defense towers. We currently are interestied in determining the effectiveness of the strategies and testing the agents' performance on the maps we used with human subjects. To support our implementation we are working on a *Spatial Affordance Query System*, which allows an agent to perform the types of queries identified in our human subject studies against an annotated map that is auto-generated from the map geometry.

In the longer term, we hope to follow up on our initial findings regarding how human subjects revise their strategies in the face of feedback, how they transfer knowledge across maps and on the mechanisms of negative transfer.

References

Ragni, M., and Brüssow, S. 2011. Human spatial relational reasoning: Processing demands, representations, and cognitive model. In *Proc. Nat'l Conf. on Artificial Intelligence (AAAI)*.

Randell, D. A.; Cui, Z.; and Cohn, A. G. 1992. A spatial logic based on regions and connection. In *Proc. Int'l Conf. on Knowledge Representation and Reasoning*.

Wetzel, B. 2011. Transfer learning in spatial reasoning puzzles. In *Int'l Joint Conf. on Artifical Intelligence*, 2864–2865.