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Traveling Salesman

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Definition

The traveling salesman problem is the task of determining an optimal path through several points and return to the starting point.

Introduction

"Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city once and returns to the origin city?" The traveling salesman (or salesperson) problem (TSP) is a well-known mathematical problem that was first defined in the 1800s and studied in the 1930s. The task is to connect each of several points (nodes) and return to the origin using the shortest possible path (tour) (see examples in Fig. 1).

Despite the simplicity of the problem's description, solving the TSP is computationally hard. The only known method to solve any TSP between N nodes is to calculate and compare all possible (N-1)! tours, which becomes impractical for large Ns. For example, there are 24 potential tours to join five nodes. This number increases over 300,000 when it is required to join ten nodes, putting solutions for 50 nodes or so out of reach of current computing machineries. For these reasons, the TSP has become a classic algorithmic problem in computational mathematics that belongs to the class of NP-complete problems for which the worst case running time for any algorithm increases super-polynomially with the number of nodes. Many algorithms have been developed to find approximations of the optimal tour with reduced computation time. This approach is used in a broad range of applications in logistics, manufacturing, telecommunication, genetics, and neurosciences, to name just a few (Applegate et al. 2007).

Over the past 50 years, researchers in psychological, cognitive, and behavioral sciences have started to exploit the TSP to study perceptual problem-solving, planning, navigation, and spatial cognition in humans and some other animals. The problem is so complex that animals are not supposed to be capable of solving it. Instead, they may use simple decision rules (heuristics) to find efficient tours in a limited time. The questions addressed, procedures used, and results obtained in these researches have varied considerably across studies.

The experimental approach falls into two broad versions of the TSP: a visual (two-dimensional) TSP and a navigational (three-dimensional) TSP. In both cases the performance of the subject is

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typically compared to the optimal solution (Fig. 1a), chance (Fig. 1b), and simple heuristic models (Fig. 1c).

Visual TSP

In psychology, the TSP has been used to assess cognitive functions and complex problem-solving abilities. The task for the subject is to connect an array of dots on a sheet of paper or a computer screen in just one or a few trials. Variants include closed TSPs, in which the tour must start and end at the same node (Fig. 1a–c), and open TSPs, in which the tour must start and end at two different nodes (Fig. 1c).

In such a task, humans can produce paths that approach optimal in problems with up to 100 nodes, generating a solution quickly and with little apparent effort. Human solutions tend to be very good and frequently outstrip the simpler heuristics' solutions despite great variations in the experimental procedures used (e.g., time to complete the task, possibility to erase path) (MacGregor and Ormerod 1996). Several strategies varying in their levels of complexity (global versus local processing) have been proposed to explain these performances. For example, subjects may simply choose the nearest available unconnected node (nearest neighbor heuristic, Fig. 1c), avoid crossings (crossing-avoidance heuristic), follow borders (convex hull model), or link clusters of nodes (pyramid algorithm). Human performances on visual TSPs do not appear to reflect exclusive use of one of these heuristics, but indicate a probabilistic use of a single or a combination of strategies.

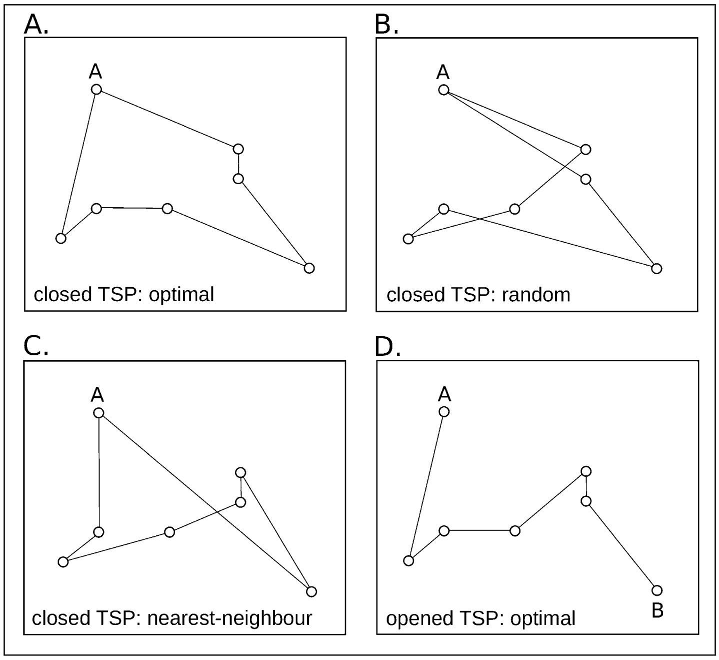
Recently, visual TSPs have been extended to nonhuman animals using smaller arrays of less than ten nodes. For instance, pigeons required to peck nodes on a touchscreen without returning to a previously picked node in order to obtain a food reward perform better than random but significantly worse than the optimal route or a nearest neighbor strategy (Gibson et al. 2007). Hummingbirds also solve simple visual TSPs when collecting sucrose solution on artificial flowers displayed on a vertical board, often choosing the shortest path to visit all flowers once after training (Tello-Ramos et al. 2015).

Navigational TSP

In ethology, behavioral ecology, and cognitive ecology, the TSP has been used to investigate spatial cognition and navigation behavior. The task for the animal is to find the shortest path to visit multiple baited locations in the lab or in the field. This route optimization problem characterizes the everyday spatial behavior of many central-place foraging animals that exploit food patches from a reference place (nest or shelter). Finding an efficient route between several feeding sites is critical for animals to reduce travel costs and exposure to predators.

The first reported navigational TSP experiment was conducted with chimpanzees that could acquire experience with the spatial distribution of food sites before being tested (Menzel 1973). One experimenter carried a young chimpanzee around a large outdoor enclosure on his back, while a second experimenter hid 18 food items. The chimpanzee was allowed to watch where the food was being hidden and was able to go out and search for the hidden food after being returned to the start location. The routes taken by the experienced chimpanzee were more efficient than the route originally taken by the experimenter, suggesting that while being carried around, the chimpanzee formed a spatial memory of food locations and was able to determine an efficient route between them, following a nearest neighbor strategy. Using a similar procedure, it was found that vervet monkeys have more sophisticated strategies of planning ahead a small number of steps and choosing the path with the shortest length (Cramer and Gallistel 1997).

A second approach to navigational TSP is to test naïve animals that must solve the task as they first discover the problem. In these conditions humans and rats tend to choose routes that are



Traveling Salesman, Fig. 1 Hypothetical examples of solutions to traveling salesman problems (*TSPs*) in a randomly generated array of seven nodes. (**a**) Shortest possible tour, (**b**) random tour, and (**c**) tour resulting from the nearest neighbor strategy in a closed TSP starting and ending at *A*. (**d**) Shortest possible tour in an open TSP starting at *A* and ending at *B*

more efficient than expected by chance (Blaser and Ginchansky 2012). Their performance is generally consistent with the use of nearest neighbor strategy, although both produce longer travel distances than would be expected given the sole use of this strategy.

A third approach to navigational TSP is to examine the role of learning and memory in route optimization by testing animals that can solve the task over multiple trials. In this context, rats (Bures et al. 1992), pigeons (Baron et al. 2015), and bees (Lihoreau et al. 2012) can all develop efficient paths to navigate between multiple locations. For instance, bumblebees allowed to forage for several hours in an array of artificial flowers typically find the shortest possible routes to visit all flowers once and return to the nest. This optimization behavior is reached through trials and errors based on the acquisition of long-term visuospatial memories (Lihoreau et al. 2012). Although the exact strategy used by bees, birds, and rodents to find optimal routes is not known, these results clearly indicate that finding efficient solutions to TSPs does not necessarily require large brains and high computational power.

Conclusion

The TSP has become an established experimental paradigm in which tasks and memory demands can be easily manipulated to study complex problem-solving by human and nonhuman animals. Interest into the cognitive processes underlying efficient path selection has intensified recently because of the surprising finding that many animals perform well in TSPs. Yet their strategies seem to differ a lot depending on the specificity of the task to solve. Visual and navigational TSPs likely require processing different types of information and different cognitive capacities. For instance, in navigational TSP, goals are generally not marked (which involves increased working memory demands and working with reduced number of nodes) and not visible all at once (which may prevent using global strategies to solve the task). Studies using both approaches in humans and pigeons have started to explore these differences (MacGregor and Ormerod 1996; Gibson et al. 2007; Blaser and Ginchansky 2012). Comparative analyses using standard protocols in a wider range of species with different brain sizes and architectures will help clarify the evolution of fundamental perceptual and cognitive abilities required in these tasks.

Cross-References

- ▶ Arthropod Cognition
- ▶ Cattarhine Navigation
- ▶ Central-Place Foraging
- ▶ Cognitive Map
- ▶ Comparative Cognition
- ▶ Decision-making
- ▶ Foraging
- ▶ Foraging by Honeybees
- ▶ Hominoidea Navigation
- ▶ Hymenoptera Cognition
- ▶ Hymenoptera Navigation
- ▶ Insect Cognition
- ▶ Insect Navigation
- ▶ Learning
- ▶ Long-Term Memory
- ▶ Navigation
- ▶ Navigation by Honeybees
- ▶ Optimal Foraging Theory
- ▶ Pigeon
- ▶ Planning
- ▶ Primate Cognition
- ▶ Problem-Solving
- ▶ Rodentia Navigation
- ▶ Spatial Memory
- ▶ Spatial Orientation
- ▶ Spatial Relations
- ▶ Touchscreen
- ▶ Vision
- ▶ Visuospatial Memory
- ▶ Working Memory

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