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Representation of space: image-like or sensorimotor?

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Abstract—We investigate the relation between the physical world and its mental representation in the 'cognitive map', and test if this representation is image-like and complies with the laws of Euclidean geometry. We have developed a new experimental technique using 'impossible' virtual environments (VE) to directly influence the representational development. Subjects explore a number of VEs — some 'normal', others with severe violations of Euclidean metrics or planar topology. We check if these manipulated properties cause problems in navigation performance. A consistent VE should be easily represented mentally in a map-like fashion, while a VE with severe violations should prove difficult. Surprisingly, we found no substantial influence of the impossible VEs on navigation performance, and forced-choice tests showed little evidence that subjects were aware of manipulations. This suggests that the representation does not resemble a two-dimensional image-like map. Alternatives to consider are sensorimotor and graph-like representations.

Keywords: Spatial representation; cognitive map; navigation; virtual reality; sensorimotor.

1. INTRODUCTION

The relation between the physical world and its perceptual representation has been disputed for a long time. One line of thought argues that the structure of the representation is analogous to the structure of the represented world. This seems most evident in the case of 'mental images' which may be characterized as 'pictorial representations', or more formally, as 'interpreted symbol filled arrays' (for review, see Tye, 1991). We investigate this question for the similar concept of the cognitive map, which is the presumed representation of large-scale spatial environments (e.g., Gallistel, 1990; O'Keefe and Nadel, 1978; Tolman, 1948). Although very popular, the notion has been repeatedly criticized since it seems difficult to provide an undisputed definition of the properties and structure of the cognitive map (e.g., see

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Bennett, 1996). To understand the range of possibilities for such a definition it is helpful to distinguish two extremes.

On one hand, the representation could resemble a real map, in the sense of being inherently two-dimensional, similar to an image, allocentric, and allowing direct mental access to arbitrary locations within the map. This mental representation is sometimes denoted as a 'Euclidean (metric) sense-preserving cognitive map' (Gallistel and Cramer, 1996). It enables path-planning, detours, shortcuts, etc., and can thus be used like an actual map. The representation is often referred to as 'survey knowledge'; other attributes are 'configurational', or 'gestalt-like'. (Note that this concept does not require the mental map to exactly reproduce the measurable properties of physical space; e.g., distances may be shortened or lengthened compared to physical space, they may be asymmetric, and directions may be shifted.)

On the other hand, the representation might be structured like a list, or may just be a set (cf. 'bag of words' concepts, Kosala and Blockeel, 2000). The elements are spatial items, e.g., places, which can be augmented by information about landmarks and/or views. Hence, this type of representation is sometimes characterized as 'landmark knowledge'. It can also contain connectivity information, and the latter type of list can then be seen as a graph (in the formal mathematical sense, not in the sense of the 'pictorial shape' of a drawing of a mathematical graph). If ordinal information is emphasized, this is referred to as 'route knowledge' or 'topological' if the emphasis is on the connectivity of locations rather than their metric relations. The set can also be incomplete; for example, it can contain only places which are located along a specific route an observer has already traveled, or it may contain subsets representing different routes, but these subsets are not related to each other within the representation.

Which concept is the most adequate approach for understanding the mental representation of space is still under debate. In a prominent developmental framework, the landmark–route–survey (LRS) model (Siegel and White, 1975), the different concepts of the representation are seen as successive stages in the natural development of spatial knowledge with increasing experience. The representation is assumed to develop in a succession of distinct stages, from a set-like representation (initially a crude landmark representation) over procedural route knowledge to the final map-like survey representation. However the LRS model, though widely accepted, has also been criticized. First, the development in form of discrete steps has been questioned, in favor of a gradual process, in which an initially coarse representation becomes increasingly detailed with experience (e.g., Evans, 1980; Montello, 1998). Second, the developmental order has been questioned since route knowledge can be acquired prior to landmark knowledge (Gärling *et al.*, 1981) or even without landmarks at all (Allen, 1988), and the metric knowledge assumed to be present in the final stage may actually be represented from the beginning of the process (Yeap and Jefferies, 2000), since subjects have accurately memorized metric information about relative positions of objects with little experience and