How Vertical Spaces Are Perceived and Represented

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Introduction

The purpose of this symposium is to highlight how the vertical dimension is perceived and represented differently from the horizontal dimensions, and the role of this dimension in spatial learning. This is a new and important issue because literature on spatial cognition has hitherto neglected the study of the vertical dimension, under the assumption that space can identically be investigated in the horizontal plane. This notion, while untested, ignores a crucial, unique property of the vertical dimension – that of being parallel to the force of gravity, which poses constraints on affordances and energetic potential. Additionally, the ability to move freely in three dimensions imposes computational complexities not present in two. New research impetus is trying to clarify the role of the vertical dimension in space. The present symposium will try to tie together different perspectives (psychophysics, cognition, neurophysiology), using different animal models (human and non-human), and different experimental methods (real and virtual environments), in order to provide a synthetic view on this issue, and to establish future goals of common interest. We focus here on two aspects of three-dimensional space: surface properties (e.g., hills and valleys) and volumetric properties.

Surface Properties

A major constraint to terrestrial movement is represented by the inclination of the terrain. While a moderate hill can be a challenge to walk, a steep one can be dangerous and energetically depleting. Therefore, it is ecologically adaptive for our perceptual system to be extremely sensitive in estimating geographical slants. Recent research by Durgin's lab has indeed shown that the coding of slant, and other angular variables, is exaggerated by the introduction of perceptual biases, such that the range of inclinations relevant to locomotion is more densely coded (Durgin & Li, 2011). This angular scale expansion enables us to more precisely represent small differences in inclinations, and thus may improve the precision of action control. Furthermore, the theory quantitatively predicts the well-reported overestimation of hill slant, suggesting that this phenomenon may not be directly due to a role of effort or physical potential, but to a more general angular coding scheme that is useful for action control as well as route planning and spatial orientation.

Beyond perceptual encoding of slope for action, recent research has demonstrated large individual differences in the ability to rely on slope cues for cognitive spatial tasks, including navigation (Weisberg & Newcombe, 2011). Given that slope is a stable and salient part of the lay of the land, a fundamental question explored in a line of research by Weisberg is whether people are able to take slope into account when building a mental map of the environment – and what makes slope difficult to use for some people. Using a navigation task in a virtual environment, it was found that individual's navigation ability is a crucial factor in determining whether terrain slope facilitated a more accurate representation: in a complex environment, only good navigators were able to take advantage of the information. This result is very important because it can explain previously reported sex-specific difficulties with slope in light of individual differences in broad spatial abilities.

Given the theoretical distinctiveness of the vertical component of space, due to its link with the gravity axis, an important question to investigate is the salience of vertical information in spatial learning tasks. Studies on non-human animal models have indicated that vertical information dominates over horizontal information. Recently, a line of research by Nardi has investigated if the same occurs in humans. Reorientation was tested in a real-world environment with two different strategies available: one based on directional cues (the slope gradient of the tilted floor) and one based on positional cues (landmarks). Interestingly, slope information did not dominate the reorientation process, as people were equally likely to rely upon either cue. Furthermore, men and women did not significantly differ in their reliance on slope or landmarks, suggesting that in a real environment there is not a sexually dimorphic preference for spatial strategies. However, men exhibited greater overall confidence in solving the task. These findings suggest that the female disadvantage with slope cues, shown in Nardi, Newcombe, and Shipley (2011), could be due – at least partially – to a general difficulty in reorienting, namely lower spatial confidence.

Volumetric Properties

Our evolutionary ancestors, being aquatic, moved freely in all three dimensions, and many animals still do. It is therefore likely that the brain has evolved a method for representing volumetric space in a cognitive map, but the properties of this map are not yet understood. Studies of the representation of space at the single neuron level are providing clues, however. In ordinary, horizontal environments, place cells in the hippocampus encode location while grid cells, in the neighbouring entorhinal cortex, encode an integrated signal of distance and direction. Jeffery's lab has studied for the first time how place and grid cells respond to travel in the vertical dimension. Using rodents as an animal model, it was found that while grid cells are highly insensitive to vertical distances, place cells do show some responsiveness, though at a coarser scale than for horizontal distances (Hayman, Verriotis, Jovalekic, Fenton & Jeffery, 2011). The findings suggest that the representation of vertical space, or perhaps space in the dimension normal to the body plane of the animal, is represented differently, and maybe non-metrically. Preliminary behavioral studies support this notion, finding that rats and mice can encode goal locations in three dimensions but prefer to organize their search behavior in horizontal bands.

From the above findings, it seems that the so-called "cognitive map" of space may perhaps not be uniform in all dimensions, despite our subjective experience to the contrary, a finding that has implications for those navigating in volumetric spaces (astronauts, pilots, deep sea divers, virtual reality explorers etc).

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