Teaching Spatial Thinking: Perspectives from Cognitive Psychology

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Abstract. Cognitive psychology primarily focuses on understanding of how humans represent and process spatial information. Cognitive psychology approaches to spatial thinking consider how we think about space (i.e., thinking in space, and thinking about space) and how we use space to think (i.e., thinking with space). This paper outlines topics to be covered on each of these topics in a course on spatial thinking, with recommended readings for each topic. Depending on the audience, it might be appropriate to put more emphasis on fundamental understanding or to also address applications of spatial cognition research, for example in education or to the development of spatial technologies. An important goal of any course in spatial thinking is to give students an appreciation of research methods in spatial cognition, including the types of inferences that can and cannot be made from different types of evidence to enable students to be critical readers of the literature.

1 Introduction

Marr [1] proposed that a complex information processing system such as the brain or a computer should be understood at three different but independent levels of analysis – the computational level (i.e., What is computed and why? What is the system capable of doing?), the representational level (i.e., How is the information represented in memory? What processes operate on these representations?), and the implementation level (i.e., How is the system physically realized?). Within this framework, research approaches are primarily defined by one of the three levels of analysis and constrained by the other levels. Cognitive psychology is primarily concerned with the representational level that is how information is represented and what processes operate on these representations to accomplish cognitive tasks. In contrast spatial information theory might be more concerned with the computational level, whereas neuroscience addresses how the system is physically realized in the brain. The study of representations and processes is challenging methodologically because these mental structures and processes cannot be directly observed.

Spatial cognition is concerned with how people acquire, organize and use spatial knowledge. Researchers sometimes make a distinction between spatial cognition and spatial thinking. Spatial thinking is usually considered to be more complex often involving multi-step processes to solve problems or attain goals. Spatial thinking includes but goes beyond the study of implicit or automatic processes in that it is strategic and goal-directed and involves volition. For example, spatial cognition might include automatically updating our location as we move through the environment, whereas planning the best route from work to home when your usual route is blocked by roadwork might be an example of a more strategic, spatial thinking process.

Cognitive psychology approaches to spatial thinking consider how we think about space and how we use space to think (i.e., thinking with space) (see Figure 1). In terms of thinking about space, we can distinguish between spatial thinking at two broad scales of space, (1) small-scale or object-based space, which includes activities such as imagining object transformations and planning interactions with objects, and (2) large-scale or environmental space, which includes activities such as learning the layout of a new environment, and planning a route. Another distinction is between thinking about space and using space to think. Using space to think includes situations in which we use spatial representations to think about other entities, both abstract and concrete. One example is spatial metaphors. For example, we follow the path of life, feel "down" when we are sad, and climb the corporate ladder [2]. We also use spatial representations to reason, for example when we represent premises in a reasoning problem as Euler circles [3] or use diagrams, maps, and graphs, which enable us to "use vision to think" [4].

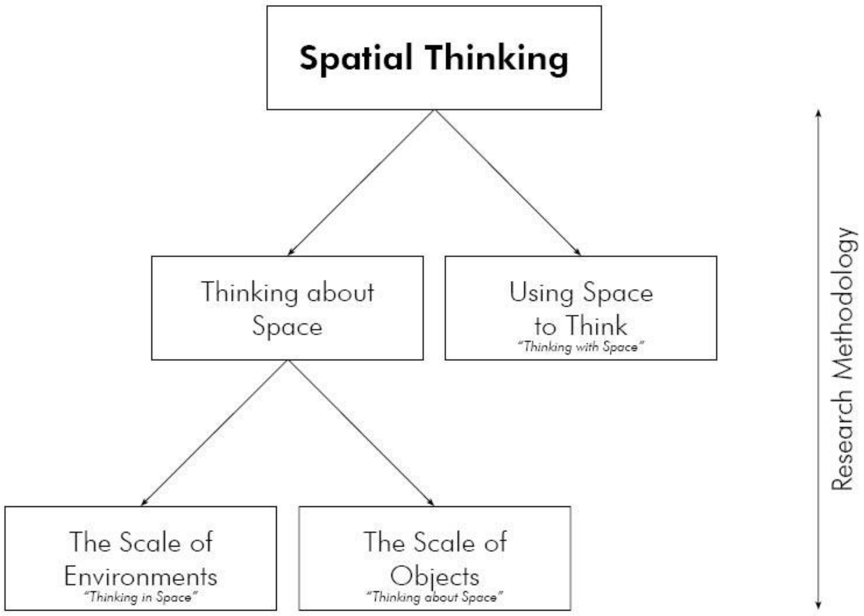

Fig. 1. A Cognitive Psychology Framework for Spatial Thinking.

1.1 Thinking about Space

The Scale of Environments. Understanding spatial thinking at the scale of environments is concerned with the representations and cognitive processes that enable us to navigate in the world, including learning the layout of new environments and planning routes to distant locations. Wolbers and Hegarty [5] provide an overview of the sensory cues, perceptual and cognitive processes and spatial representations involved in human and animal navigation. The following is a list of possible topics to be addressed in a course on spatial thinking at the scale of environments:

1. The idea of a cognitive map, stemming from classic research by Tolman including critiques that question the ubiquity of this type of representation [6, 7].
2. Research on distortions in cognitive maps [8-10]
3. An understanding that location, orientation and movement must be specified with respect to some reference frame and distinctions between allocentric and egocentric reference frames and between intrinsic, absolute and relative frames of reference [11, 12]
4. An understanding of orientation dependency in spatial memories and the factors such as experience, environmental geometry that influence the orientation dependency [13-15]
5. Spatial updating & perspective taking [16-19]
6. Cognitive mapping, that is learning spatial layout and how the nature of the resulting spatial representations depends on the learning experiences, including learning from direct experience and from different media [20-22]
7. Individual differences in navigation abilities and strategies including questions of measurement of these abilities [23-29]
8. Processes of wayfinding [30]

The Scale of Objects. Understanding spatial thinking at the scale of objects is concerned with representations of objects, including visuospatial mental images and action and how these are used when we interact with objects and in more complex processes of reasoning and problem solving. The following are topics about spatial thinking at this scale of space that might be covered in a course on spatial thinking.

1. Classic research on mental rotation. This includes classic research on mental rotation as an analog process arguing for the functional importance of mental imagery in spatial thinking [31].
2. Research on the role of visuospatial imagery more generally in spatial thinking and problem solving [32, 33]. For example, our understanding of mental imagery transformations continues to grow as researchers uncover more specialized functions such as non-rigid transformations of bending and folding [34], or in imaging biomechanical movement [35].

3. Research indicating the importance of embodied and multimodal representations in spatial thinking [36-39].
4. Research on alternative strategies in spatial thinking at the scale of objects including mental simulation (involving analog imagery processes) and more analytic rule-based strategies. For example mental imagery and analytic thinking can be used in conjunction with each other, in mechanical reasoning and other spatial problem solving [40-42].
5. Research on individual differences in spatial ability which historically depended on paper and pencil measures of spatial transformations at the object scale. This includes classification of spatial abilities and cognitive analyses of spatial ability measures [28, 43, 44].
6. Research on sex differences in spatial ability, which are particularly evident in tests of mental rotation but do not occur in all measures of spatial abilities [45, 46].

1.2 Using Space to Think

In addition to thinking about space, at the scale of objects and environments, visuospatial thinking includes situations in which we use spatial representations to think about other entities, both abstract and concrete. The following are optics on using space to think that might be included in a cognitive psychology course on spatial thinking.

1. Spatial metaphors in language When thinking about more abstract domains, such as mathematics, time, or feelings, we can utilize a more concrete domain to help us think [47]. Spatial metaphors help us conceptualize things like time [48, 49], or numbers [50].
2. Use of spatial representations in reasoning including classic research by [51-54].
3. How spatial representations in graphics, such as maps, diagrams, and graphs, support our memory, convey relational information, and helps maintain a mental model [55-57].
4. How spatial cognition research can inform the design of graphics given that task performance can differ between different displays of the same information [58-61].

2 Applications of Spatial Thinking Research

Depending on the audience, a course on spatial thinking might also cover applications of research on this topic. One area in which spatial cognition research has been applied is to education in the STEM (i.e., science, technology, engineering and mathematics) disciplines. Importantly Wai, Lubinski and Benbow [62] showed that spatial abilities predict success in STEM, which has raised questions about whether training students in spatial thinking might enhance their success in the STEM. While there is now good evidence that aspects of spatial thinking can be trained [63, 64] there is little evidence to date that general spatial training transfers to success in

STEM disciplines [65]. Rather than attempting to train domain general spatial thinking processes, an alternative approach is to analyze the demands of spatial thinking in different STEM disciplines such as chemistry [66], geology [67, 68], and GIScience [69]. Educational interventions can then focus on these particular spatial demands. Another promising area of research in the education of spatial cognition has shown that arts pedagogy is uniquely effective in training spatial thinking [65, 70]. In addition to research on innate and acquired spatial ability in the STEM disciplines, education in spatial thinking can be informed of account of the outstanding performance of spatial experts, including professional geologists [71], architects [72], and London taxi cab drivers [73].

When teaching spatial thinking from a cognitive psychology perspective, the course material should be adapted to the background of the students in the class. For students in cognitive psychology, an emphasis would be placed on a robust theoretical understanding of spatial thinking, starting with the object scale then the environmental scale and concluding with topics on using space to think. The course topics would include small scale spatial cognition and thinking (i.e., basic spatial transformations, embodied representations, spatial thinking in problem solving, strategic differences, and individual differences in spatial thinking), large scale spatial cognition (i.e., spatial representations and memories, and processes in orientation, reorientation and navigation) and using space to think (i.e., spatial metaphors, reasoning and problem solving, and graphics). For students interested in enhancing spatial thinking through education and/or spatial technologies, the course might include a basic theoretical understanding of spatial thinking in addition to studies on education, expertise, and human interaction with spatial technologies.

Other learning objectives centered on cognitive psychology methodology can be easily integrated into the course format. It is important to enable students to be critical readers of the literature and to be able to distinguish between good and bad experimental designs, particularly in terms of statistical power (the likelihood of detecting an effect if there is one). Students should know what inferences can be made based on the method of measuring spatial cognition (self report v. objective measures; virtual reality v. real world, etc.). A basic understanding of statistics is also important, including understanding correlations (e.g., what can and cannot be inferred; correlation does not imply causation), effect sizes, and statistical significance, is necessary.

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