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Thinking spatially in the science classroom

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Much scientific thinking is spatial in nature, and even non-spatial information is often communicated using maps, diagrams, graphs, analogies and other forms of spatial communication. Students' spatial skills are correlated with their success in learning science, both concurrently and predictively. Given that spatial skills are malleable, can spatial thinking be used to improve science education? This article reviews two ways in which we might proceed. Strategy 1 is to enhance students' spatial skills early in life, or at least prior to instruction. Strategy 2 is to make more effective use of spatial teaching techniques that allow for spatial as well as verbal learning, even by students with weaker spatial skills. Recent evidence suggests optimism about both approaches.

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Introduction

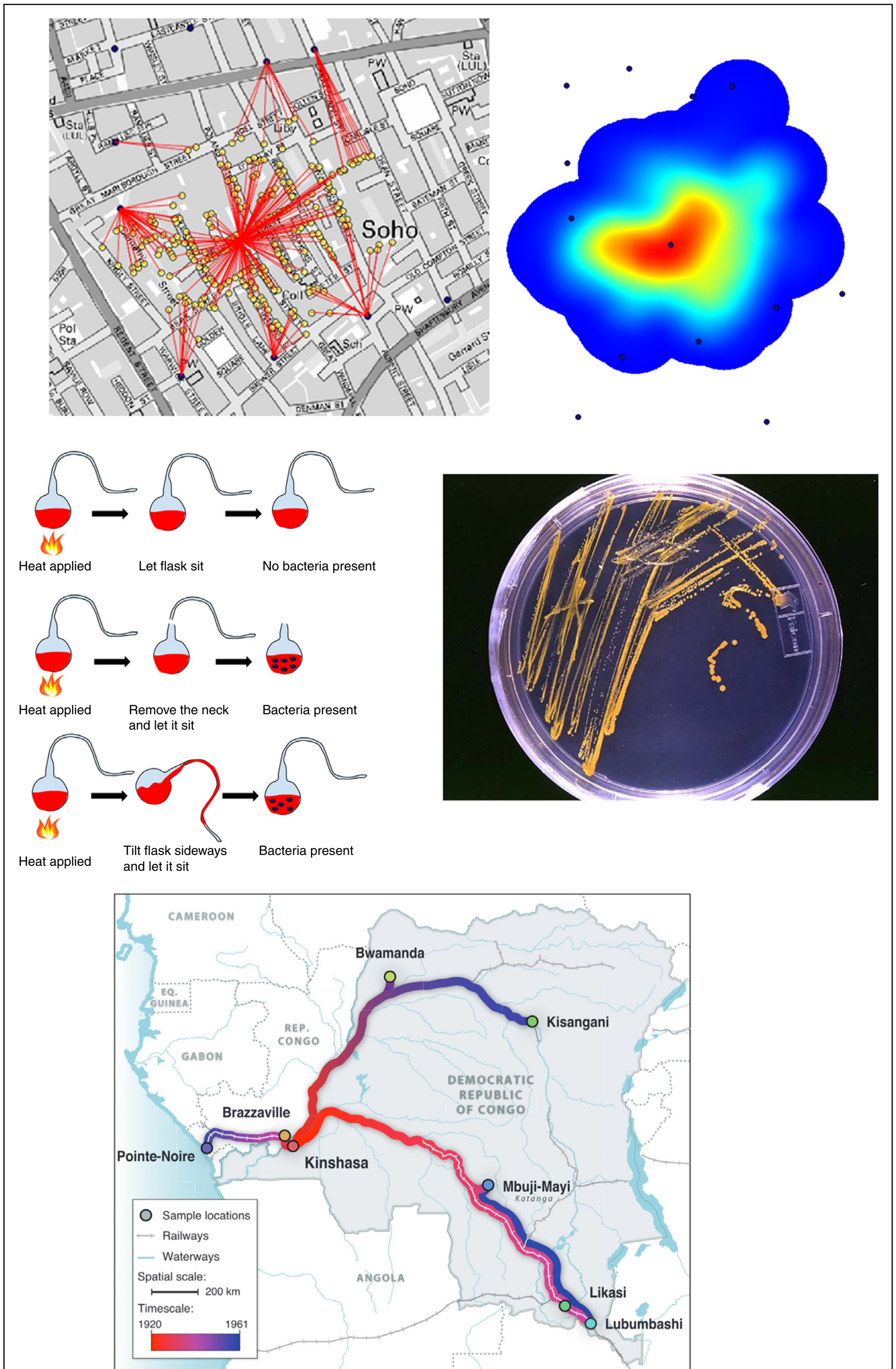
An important aspect of many scientific discoveries stems from the spatial nature of the relevant data. Consider, as an example, the history of understanding infectious disease. Ignaz Semmelweis, a careful observer with a brilliant hunch, made a start by observing in the 1840s that washing hands between examining obstetric patients reduced the incidence of puerperal fever. But *why* should washing help? One step toward a germ theory of disease was taken in the 1850s, when John Snow put his observations of cholera cases in London on a map in juxtaposition with the location of water pumps, showing clustering around the pump on Broad Street (see Figure 1, top panel, for two modern visualizations of the data). Visualizations continue to play a role in scientific work on infectious disease, as shown in research on the history of the HIV virus (Figure 1, bottom panel). In addition, scientific education often uses spatial displays to communicate key ideas. Continuing with the science of infectious disease as an example, in the 1860s, Louis Pasteur conducted experiments on pasteurization, effectively shown in a modern diagram as often found in science textbooks (Figure 1, middle left). Also in the 1860s, Robert Koch figured out how to grow bacteria on agar, using a microscope for visualization (an example of such a preparation is shown in Figure 1, middle right).

If scientific thinking is spatial, could spatial learning be harnessed to support more effective education in science and mathematics? There is in fact empirical support for the idea, based on various observations, for example, the fact that students with higher spatial skills show better learning of topics such as kinematics [1] or a finding that gender differences in spatial ability mediate gender differences in science achievement in middle school [2••]. However, this general idea could play out in two different ways in the educational system. Strategy 1 might be to enhance students' spatial skills early in life, or at least prior to instruction, to enable better science learning. Strategy 2 might be for science educators to make more effective use of spatial teaching techniques that could allow for spatial as well as verbal learning, even by students with weaker spatial skills. That is, the focus would be on the curriculum, not on the learner. These possibilities are not mutually exclusive — both strategies might be important and effective. In that case, they could either be used together, or choices could be made between them on practical grounds, such as whether time and resources are available for pre-instruction spatial skills training. The purpose of this paper is to review recent evidence on these two strategies: (a) whether improving spatial skills affects science learning, and (b) how to spatialize the science curriculum.

Strategy 1: Improving spatial skills

Strategy 1 would be a non-starter if people were born with some innately-determined fixed level of spatial ability, with some individuals destined to be spatial geniuses while others are doomed to a permanent spatial fog. Fortunately, this belief, though common, is a myth. Meta-analysis of a wide variety of spatial training studies shows that spatial skills can be improved, for both men and women, and for adults as well as children. Furthermore, these improvements seem to be durable and transferable [3]. These findings give rise to the hope that right-shifting the distribution of spatial skill in a population would increase the pool of people qualified to become part of the science and technology workforce ([3,4]; see Figure 2). Interest in the malleability of spatial skills is growing, and experimenters continue to design engaging programs for spatial training suited to various ages and different spatial skills [5].

Figure 1



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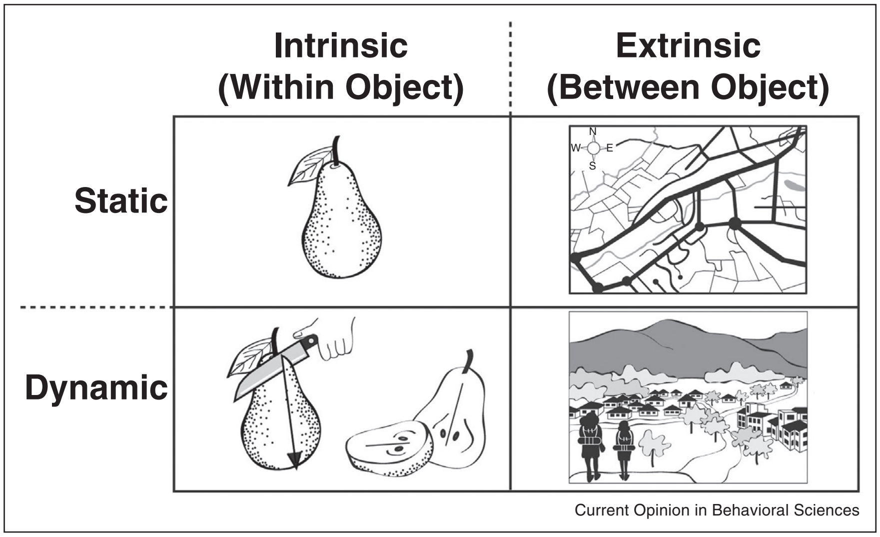
At top, two examples of modern visualization created from John Snow's cholera data http://qgissextante.blogspot.com/2012/10/analyzing-john-snows-cholera-dataset.html. In the middle panel, a diagram of Pasteur's experiment on the left and bacteria growing on agar on the right https://en.wikipedia.org/wiki/Petri_dish#/media/File:Agar_plate_with_colonies.jpg. At bottom, how the HIV virus spread and changed http://www.wired.com/2014/12/best-science-graphics-visualizations-2014/#slide-12.

Figure 2



Spatial training could potentially double the number of students 'spatially qualified' to become engineers. Based on Uttal *et al.* [4].

Randomized control trials

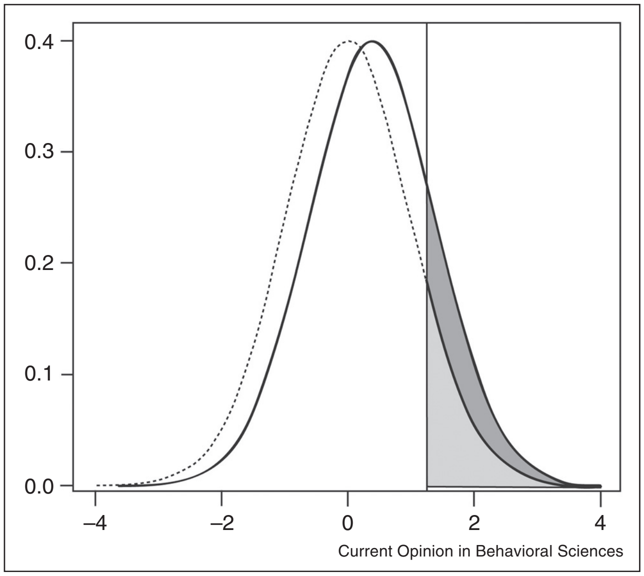
Note, however, that Figure 2, while built from facts, is still a thought experiment. The hope embodied in the figure would be more directly supported by experimental trials in which students were randomized to spatial skills training versus an active control group, with STEM achievement as the outcome [6]. There have so far been few such efforts but, in the past few years, there are at least three publications with some positive findings. First, highly-capable physics students got higher grades after spatial training than a control group, although the effects did not appear as students went on to take later courses [7]. Second, using a regression discontinuity design, investigators observed a positive effect of spatial training on performance in calculus, for less-capable students [8]. Third, although this study lacked an effective active control group, education majors playing either of two kinds of video games seemed to improve on math performance as well as on other cognitive skills [9]. Further studies of this kind are in progress, so we can expect more news in the next few years.

Varieties of spatial skills

The three studies we have just examined used very different kinds of spatial training: practice on mental rotation and cross-sectioning [7], a one-credit course using a workbook designed to help engineering students with a variety of visualization skills and incorporating a good deal of drawing with feedback [8] and action-oriented video games of two different kinds, a first-person shooter game that requires a variety of spatial skills, and a low-stress game [9]. Such heterogeneity is typical of the spatial training literature [3]. However, there may be a variety of different spatial skills, each with different relevance to various scientific disciplines. Which should we train? There are hundreds of spatial tests, but how can they be grouped into kinds? One effort at a typology [3,10] suggests that skills that focus on coding the structure of objects are different from skills involved in coding relations among objects in a wider world, and that intrinsic and extrinsic coding can each be static, or can involve active mental manipulation of the encoded information (see Figure 3). This typology, however, has yet to be thoroughly examined empirically. It may be too simple, because a close comparison of two skills (mental rotation and mental folding) that are both conceptually located in the bottom left of the figure as intrinsic-dynamic skills, reveals differences as well as similarities [11]. Notably, mental rotation reliably shows a large sex difference whereas mental folding does not, but we do not know why they should be different in this regard. Even for mental rotation, a skill that has been the focus of considerable attention in cognitive science over the past decades, we are still uncovering new facts about its nature [12] and how it develops [13]. Neural data might help to develop and differentiate this typology but only mental rotation has yet been studied extensively at the neural level [11].

Furthermore, even though there are hundreds of spatial tests, they have been devised over the past century almost entirely by psychometricians who were not interested in the particular kinds of spatial skills needed for success in specific scientific disciplines. One way to remedy the situation is to work closely with disciplinary experts to uncover neglected spatial skills, and to devise assessments for them. Interdisciplinary work between cognitive scientists and geoscientists indeed led to uncovering two

Figure 3



Typology of spatial skills, in which there is a distinction between thinking about objects and thinking about the environment, and also between static representations and dynamic transformations. The upper left cell includes tasks in which people represent the shape and structure of objects, and the lower left shows tasks in which that shape is changed, for example, by cross-sectioning. The upper right cell shows tasks that require representing the relations among many objects in the wider world, and the lower right shows tasks that require imagining those relations changing, for example, by changing vantage point.

such skills, bending and brittle transformation [14,15]. Many more may remain, and of course, fitting them into the typology proposed above will be a further challenge.

Assessing young children

One front on which there has recently been considerable progress is a basic practical matter. Many of the skills that have been well-studied in adults have lacked techniques by which they could be examined in young children, especially important if we want to set children on a trajectory of strong spatial thinking. In the past few years, investigators have published new tests that tap mental rotation [16], perspective taking [17], paper folding [18], perception of diagrammatic representations [19], scaling [20] and the sophistication of 3-year-olds' ability to copy designs [21••]. Using these tools, we can demonstrate relations to developing scientific and mathematical skills [21••,22,23] and the importance in such development of activities such as construction play and working memory [24].

Strategy 2: Spatializing the science curriculum

Strategy 2 suggests that spatializing the science curriculum could improve science achievement for all learners. Such changes can occur at all instructional levels, beginning with playful science activities in preschool and extending into advanced science education at the graduate level. This strategy seems at odds with the common assumption that different students learn different ways, but there is encouraging evidence that appropriate modifications can aid weaker learners while not disadvantaging stronger learners, and maybe even helping them as well. In a recent study of organic chemistry classes [25••], women showed best achievement levels when the professor used a combination of spatial and analytic strategies for understanding molecular structure, compared to spatial strategies alone, or analytic strategies alone. Men performed comparably across conditions. If spatial strategies and spatial thinking should be added to existing science curricula, there are several techniques that we have reason to believe would be helpful.

Maps and diagrams

As we saw in discussing the science of infectious disease, maps and diagrams play a ubiquitous role in science instruction and in scientific reasoning. Sadly, however, many instructors assume that these representations are basically pictorial, and that reading them does not require instruction. It turns out, however, that students need to be taught the reading of these representations, and that their science learning benefits [26]. Further, they need to learn how to coordinate their reading of text and their reading of diagrams [27]. One area of active investigation is when static representations (e.g., a diagram of a machine) are sufficient and when dynamic representations (e.g., a video or animation that shows the machine in action) add value, and for whom [28]. We also need to specify better for early educators when and how to introduce these symbols [29,30], although it is clear that their use should not be delayed, but rather start early but with careful sequencing and support.

Sketching

Sketching is the active creation of diagrams or maps by the learner. As a form of active learning, it is likely to be helpful, and its spatial nature is suited to science. However, this common belief needs further empirical assessment, although a recent study suggests support for the idea [31]. Additionally, the nature of student sketches is diagnostic of their conceptual understanding [32], and sketching is thus likely to be helpful as a formative assessment in the classroom.

Action-to-abstraction

If active learning is helpful, then one might expect that literally active learning might be yet more helpful, that is, physical experience of relevant scientific concepts. There is impressive cognitive and neural support for this idea, at least for concepts such as angular momentum that have obvious ways in which they can be felt [33••]. However, not all scientific concepts can be directly experienced, and even for those concepts that can be, science eventually requires abstraction for generality. These considerations give rise to the hypothesis that learning works best when arranged on an action-to-abstraction continuum [34]. Gesture may be helpful in advancing the learner along this continuum, as it is both physical and abstract. It can express spatial relations at least as well as language, better in some ways because it can more easily show several relations close to simultaneously and also can indicate relations in an analog fashion rather than making categorical cuts. Indeed, two recent studies support the efficacy of gesture, showing the involvement of the motor system in understanding others' gestures [35] and showing that gesture can work better than action, even action that is accompanied by words [36].

Analogy

Science instruction often uses analogy, as when the atom is compared to the solar system, or as when students are asked to understand the geologic time scale by analogy to the human life span. Analogies may be pictorial or verbal, but even when they are verbal, they have a spatial aspect in that they involve a structure mapping between elements in the two entities being compared. We are getting an increasingly good idea of when and how and why analogies work in the elementary classroom [37,38••], in children's museums [39] and for university students [40,41], as well as some idea of the neural underpinnings of analogical reasoning [38••]. Basic behavioral research continues on children [42] and adults [43].

Conclusion

Research on the use of spatial thinking in improving science education is entering a new phase. It is now well established that spatial thinking is intimately interwoven with science learning, that spatial skills are predictively as well as concurrently predictive of science success, and that spatial skills are malleable. We now need to rigorously specify and evaluate how to use this information. We can improve students' spatial skills, but we need to use randomized control trials to evaluate effects on science achievement, as well as the durability of such effects and whether there is transfer to other domains. Improved specification of the domain of spatial skills would improve the incisiveness of such experiments and analyses, and research using brain imaging might aid such work. Expansion of inquiry into navigation skills and their relevance for scientific visualizations such as mapping would be welcome, especially given the probable plasticity in such skills and existing knowledge of their neural substrates (see for example, [44,45]). We can also improve how a variety of spatial tools are used in the science classroom, but those changes also need to be rigorously evaluated, and we need a sophisticated and deep understanding of how the tools work, at both the behavioral and the brain levels, to enable educators to adapt the tools for new contexts.

Conflict of interest statement

Nothing declared.

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