Thinking about Spatial Thinking: New Typology, New Assessments

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Our world is a world that exists in space, and a world without space is literally inconceivable. Given this basic truth, it is clear that living in the world requires spatial functioning of some kind. Being creative in this world, and designing new tools and new habitats, probably requires even higher levels of spatial functioning. And people vary in their levels of spatial ability. What do these facts mean for the field of design? There are certain obvious practical questions. For example, should design schools accept only applicants who test high in spatial ability, following the lead of dental schools, which assess spatial thought on the Dental Admissions Test or with practical exercises in assignments such as tooth modeling? Or should design schools strive to enhance the spatial ability of anyone with the desire to do creative design, following the lead of selection committees for surgical residencies, which do not assess spatial ability in any way? The latter course is arguably supported by evidence showing that spatial skill is malleable (Uttal, Meadow, Hand, Lewis, Warren & Newcombe, under review). As another example of a practical question for design, consider what designers should or could know about the potential users of a product. What kinds and levels of spatial abilities should they assume that users will have? How would they be able to predict when a new tool will be too hard to master for many users, or when a building design will result in an environment in which many people easily get lost?

It might seem easy to answer these fairly straightforward and very practical questions. However, in order to answer them, it turns out that we need a new framework for thinking about them. Prior approaches to these issues have often taken “spatial ability” to be a unitary concept. But there are literally hundreds of spatial tests, and many factor-analytic studies have suggested that there are several kinds of spatial abilities. So a unitary approach will not do: the answers to the questions might vary for different kinds of spatial ability or skill. Other past approaches have distinguished among various types of spatial abilities, so on the face of things, they are more promising. The problem here is that various researchers have proposed various typologies, but they do not align well with each other. Sadly, the truth is that a hundred years or so of work with existing tests and statistical techniques has not arrived at a cohesive view of the structure of spatial intellect (see review by Hegarty and Waller, 2005). In addition (and oddly, given how many tests there are), key aspects of spatial functioning have been neglected by test makers. Given the current lack of understanding of the overall structure of spatial intellect, it’s difficult to think about what design schools should consider testing for, or what they should consider teaching, or what skills designers should think about end users as having or lacking.

In this paper, we offer a typology for thinking about the structure of spatial intellect that derives from a top-down analysis of the nature of spatial thinking, rather than from a bottom-up inductive approach of the kind used in traditional psychometrics and factor analysis. Some of this thinking has been grounded with respect to work in teaching science, technology, engineering and mathematics, i.e., the STEM disciplines (especially in geoscience), rather than with respect to design. But we think that the typology has promise for informing thinking about what goes into making and using design, as well as other kinds of human endeavor.

We begin with the foundational question of what spatial thinking really is, from a theoretical and conceptual point of view motivated by a great deal of research in linguistics, cognitive science, and neuroscience. We go on to present our organizing schema and compare it to prior typologies. We then present work using our schema to think about spatial skills in STEM disciplines and in child development, and for identifying priority areas for developing novel assessments. [1]

What is spatial thinking?

Rich lines of research in the cognitive, neural and linguistic domains motivate a distinction between spatial representations that are *intrinsic* to objects (their shapes and part-based representations) and those that are *extrinsic* (relations among objects and between objects and frames of reference) (e.g., Chatterjee, 2008; Freksa, Barkowsky & Klippel, 1999; Palmer, 1978). So, for example, the spatial information that distinguishes a fork from a spoon is intrinsic information, while the spatial relations between the fork and the spoon and the relations of each object to the wider world are extrinsic. In addition, each of these kinds of information can either be represented statically, or dynamically transformed, as when an object is rotated or bent, or when it moves. Chatterjee (2008) reviewed the linguistic and neuroscientific data that motivates these distinctions. In terms of linguistic evidence, he noted that this way of thinking maps onto linguistic distinctions, so that nouns pick out objects with distinctive shapes, prepositions refer to locations of objects relative to each other, and verbs code dynamic change, but with manner verbs referring to changes in intrinsic properties of objects and path verbs referring to changes in the locations of objects. In terms of neural evidence, Chatterjee reviewed evidence from studies of people with focal brain damage and of individuals without brain damage studied using fMRI showing that intrinsic and extrinsic information, represented statically or dynamically transformed, call on different brain areas.

What exactly are the intrinsic characteristics of an object? The core intrinsic information is the arrangement of constituent *parts* (sub-objects), considered relative only to each other. In addition, the *orientation* of the object and its size (or *extension)* could be considered intrinsic, even though the external world enters into determining what orientation means (relative to what) and what size means (compared to what?). These characteristics can also be transformed: *bending*, *rotation*, and *scaling* affect arrangement of parts, orientation, and extension respectively. Another important kind of spatial transformation of intrinsic object-related spatial information involves relating 2D and 3D views (i.e., *cross-sectioning a 3D object into 2D slices* and *reconstructing a 3D structure from 2D slices*).

What exactly is extrinsic information? Every object in the world has a *location* (relative to other objects or to a reference frame). Reference frames can be either objective (or allocentric) or body-relative (and egocentric). There is an extensive literature on the processing of both allocentric and egocentric information across a wide range of species, including data on the neural substrates of the various kinds of egocentric coding and how they combine (or don't).

Note that what we call intrinsic and what we call extrinsic may vary depending on the grain of our analysis. Specifically, what we call *objects* will vary at different spatial scales. For example, an astrophysicist may treat a galaxy as an object, whereas a microbiologist may treat a cell as an object. For any given spatial task, the appropriate scale is determined by specifying what constitutes an object (a molecule, a chair, a house, a country, a planet, a solar system, etc.). An object can, in principle, be defined at any scale, although some objects are privileged by virtue of being the entities that humans naturally manipulate in their everyday lives.

The intrinsic-extrinsic distinction is supported by many lines of behavioral research in addition to the linguistic and neural evidence reviewed by Chatterjee. This literature is too large to review completely here. One result that gives a flavor of the supportive data is Kozhevnikov and Hegarty's (2001) finding of dissociation between the intrinsic-dynamic skill of mental rotation and the extrinsic-dynamic skill of perspective taking, a distinction also supported by cognitive research dating back to Huttenlocher and Presson (1973). Further, as would be expected given our schema, the extrinsic-dynamic skill of perspective taking is more closely related to navigation skills than is the intrinsic-dynamic skill of mental rotation (Kozhevnikov, Motes, Rash & Blajenkova, 2006). Another illustrative result is Hegarty et al.'s (2006) finding of a partial dissociation between performance on intrinsic (object-based) spatial ability measures and extrinsic (environmental) measures.

There is also behavioral support for the static-dynamic distinction, as well as for the intrinsic-extrinsic one. For example, Kozhevnikov, Hegarty and Mayer (2002) and Kozhevnikov, Kosslyn and Shepard (2005) found that object visualizers (who excel at intrinsic-static skills in our terminology) are quite distinct from spatial visualizers (who excel at intrinsic-dynamic skills). Artists are very likely to be object visualizers, while scientists are very likely to be spatial visualizers.

Proposed typology

This approach to thinking about the structure of the spatial world picks out four broad categories of spatial skills. These categories give us an organizing schema for thinking about what spatial skills might be important and what skills might need to be assessed and worked on. In summary, the categories are:

1. **Intrinsic-Static.** Coding the spatial configuration (or shape) of objects; picking shapes out from overlapping objects or other perceptual information; identifying regions of space as constituting categories.
2. **Intrinsic-Dynamic** Transforming the spatial codings of objects, including expansions or reductions in size, rotation, cross-sectioning, folding, bending, breaking and sliding; accumulating sequences of such changes and visualizing change over time and an end product; relating 2- and 3-dimensional views to each other.
3. **Extrinsic-Static.** Coding the spatial location (or position) of objects relative to other objects or to a reference frame, including gravity; aligning location codings that differ in scale.
4. **Extrinsic-Dynamic** Transforming the inter-relations of objects as one or more of them moves, including the viewer (e.g., to maintain a stable representation of the world during navigation and to enable perspective taking).

Comparison to prior work

Can the four cells of our typology encompass the existing literature on spatial skills? Uttal, Meadow, Hand, Lewis, Warren and Newcombe (under review) identified five classes of spatial skills on which training research has been done, and mapped them onto two prior attempts to classify spatial abilities. They identified one intrinsic-static skill (disembedding), two intrinsic-dynamic skills (mental rotation and what has been called spatial visualization, which includes folding, bending and 2d/3D tasks), one extrinsic-static skill (which has been called spatial perception but which is essentially the ability to accurately code horizontal and vertical dimensions as defined by gravity) and one extrinsic-dynamic skill (perspective taking). It is encouraging that a mapping was possible with studies done in the traditional psychometric tradition.

Evaluating the relevance of intrinsic and extrinsic spatial skills to learning

Prior work on predictors of success in science, technology, engineering and mathematics (STEM) has shown that intrinsic-dynamic skills have strong longitudinal relations to STEM, even with verbal and mathematical skills controlled (Wai, Lubinski & Benbow, 2009). Are there also relations of extrinsic skills to STEM? We conducted a large self-assessment study to determine the relevance of both of these two broad classes of skill to STEM expertise (Hegarty, Crookes, Dara-Abrams & Shipley, 2010). Experts in a variety of intellectual areas rated themselves on intrinsic and extrinsic skills, using two self-report measures consisting of a set of items relating to each type of skill. In accord with prior work on predictors of STEM success (e.g., Wai et al., 2009), self-assessed intrinsic skills on the new Philadelphia Spatial Ability Scale (PSAS) seemed to be higher in a variety of STEM disciplines, with the exception of biology. In addition, it turned out that extrinsic skills, as self-assessed on the Santa Barbara Sense of Direction Scale (SBSOD), also showed relations to STEM expertise.

This work shows that there are multiple spatial reasoning skills, and that success in some STEM disciplines requires both intrinsic spatial skills, such as those measured by mental rotation tests, and extrinsic spatial skills such as those required for navigation. It would be interesting to pursue this research for design professionals as well as STEM experts.

Applying the framework of spatial skills to geoscience

Can the four cells of our typology encompass thinking about spatial skills required for STEM? Kastens and Ishikawa (2006) proposed an analysis of the nature of spatial thinking in the geosciences. In the abstract of their paper, they write that they consider:

> *major tasks that professional geoscientists and geoscience learners deal with, focusing on the spatial nature of the tasks and underlying cognitive processes. The specific tasks include recognizing, describing, and classifying the shape of an object; describing the position and orientation of objects; making and using maps; envisioning processes in three*

> *dimensions; and using spatial-thinking strategies to think about nonspatial phenomena.*

Kastens and Ishikawa's "recognizing, describing and classifying the shape of an object" is identical to our definition of intrinsic-static tasks. "Describing the position and orientation of objects" is extrinsic-static in our terminology, as is "making and using maps" (although there may be some dynamic aspects as when a map must be rotated to align with an environment). "Envisioning processes in three dimensions" is ambiguous; it could be intrinsic-dynamic if the processes apply to an object or extrinsic-dynamic if the processes apply to an array of objects. Their fifth task points to an area outside our typology although important: the use of spatial reasoning in non-spatial reasoning has been widely discussed in cognitive science and neuroscience, as for example when Chatterjee (2008) discusses spatial metaphor.

Using the framework of spatial skills discussed above, Kastens and Ishikawa's work, and interviews with expert geoscientists, we have identified ten specific spatial skills used in geoscience that can be grouped into our four broader categories. Whether this set is complete, and the relative importance of these skills to STEM disciplines other than geoscience, are important open questions. For now, we suggest

- two intrinsic-static skills:
    - disembedding
    - carving space into categories
- four intrinsic-dynamic skills:
    - relating 2- and 3-D representations,
    - penetrative thinking (including cross-sectioning but also relating multiple cross-sections simultaneously),
    - mental transformations (including mental rotation, folding and bending),
    - sequential thinking (or visualizing a series of mental transformations over time)
- two extrinsic-static skills:
    - locating an object (including the self) with respect to a frame of reference,
    - alignment (or relating different ways of location coding, including coding at different scales, or coding in space and coding in time)

- two extrinsic-dynamic skills:
    - updating static representations given movement of objects
    - updating static representations given self-movement (perspective-taking)

To develop tools to support students that have difficulty with one or more skill, we require reliable ways to measure each student's skill level. These tests can readily be used by teachers to identify students who will need support, and by researchers to measure the effectiveness of potential interventions. However, we have few measures for most of the spatial skills employed by geoscientists, and by extension, other STEM disciplines. Test development is a major challenge for advances in this line of research.

As one example of this work, there has been no test of sequential thinking, so we have attempted to devise one (Shipley et al., 2009). Figure 1 shows a word (here the word is red with the letter p interleaved "r p e p d") that has been transformed by a sequence of translations of fragments of the word. In the "Faulted" case the transformations are analogous to a series of low angle faults. By reversing the multiple transformations a subject may identify the word. Interestingly, this test differentiates not only between expert geoscientists and English professors, as might be expected, but also between expert geoscientists and expert chemists. Although chemists may require certain spatial skills (e.g., mental rotation), sequential thinking is not called on in chemistry and is apparently not a part of the chemist's skill set.

Figure 1

In addition, the extrinsic skills have been largely neglected in work on individual differences, because of the emphasis on normative questions in cognitive science and neuroscience, and on paper-and-pencil tests in psychometrics. As we have seen, a survey of STEM scientists (Hegarty et al., 2010) suggests that large-scale spatial skills may be as vital to success in some STEM disciplines as the small-scale within-object skills assessed in prior large-scale studies (Wai et al., 2009). Navigation skills certainly seem to be critical in geosciences; for example, they allow accurate placement of field data in maps. More generally, navigation and map skills may be related and much geoscience data is presented in a structured form on a map. In addition, such skills seem extremely relevant to thinking about large-scale design, including architecture or landscape design. These large-scale skills may include several sub-components, such as forming integrated representations (or cognitive maps) from sequential and separated experiences, encoding the slope of the ground and incorporating slope into representations, and relating internal representations to symbolic representations, such as maps, and vice versa.

Currently, self-report measures such as the SBSOD offer basically the only practical means of assessing skills in this area, with the exception of perspective taking. We have initiated work on individual differences in representing ***extrinsic*** spatial relations. We began by confirming the results of Ishikawa and Montello (2006) showing that there are pronounced individual differences in forming cognitive maps, even in a situation in which participants walk rather than being passively driven (Schinazi, Epstein, Nardi, Newcombe & Shipley, 2009). Additionally, Schinazi et al. showed that people who formed cognitive maps showed distinctive neural activation patterns when performing a recognition tests for buildings in the learned environment. We have now built a virtual counterpart of the campus on which we ran the initial experiment, in order to provide the basis for a virtual-reality assessment tool. While Hegarty et al.'s (2006) factor analysis found that learning of environments based on VR or video loaded on a different factor from learning in real environments, VR learning might still be a close-enough proxy to allow for objective assessment. Furthermore, VR learning may in some cases be closer to the learning environments in STEM disciplines than real-world learning is.

This assessment work will provide a basis for exploring how individual differences in various spatial skills affect the learning of spatial representations. For example, does better perspective taking lead to faster learning of a cognitive map? Does better mental rotation, folding, cross-sectioning, etc. lead to better scene representations (where the representations could be assessed both behaviorally and neurally)? We will also be able to examine the neural basis of categorical coding of the environment, for example, to see whether hierarchical structure revealed in behavioral studies is expressed in the hippocampus, retrosplenial cortex, or in other brain regions.

Devising assessment instruments suitable for children under the age of 8 years

Early childhood is a vital period to understand, given the evidence that sex differences and SES differences appear early (Levine et al., 1999, 2005) and that the utility of investment in early intervention is high (Heckman, 2006). Without age-appropriate assessments, we cannot track development, or evaluate the effects of interventions. For example, there is a need for developmentally-appropriate instruments to assess penetrative thinking (Ratliff, McGinnis & Levine, 2010), paper folding (Harris & Newcombe, 2010), scaling (Boyer & Levine, under review; Frick & Newcombe, under review) and proportional reasoning (Boyer, Levine & Huttenlocher, 2008). These instruments are vital for allowing investigation of the sources of individual differences. For example, using an available measure for young children, developed by members of our team some time ago (Levine et al., 1999), we have found that early sex differences in mental rotation relate to early use of verbal versus spatial strategies. We have also initiated work on early individual differences in representing between-object spatial relations (Balcomb, Newcombe & Ferrara, 2009) and aligning spatial patterns (Gentner et al., in preparation).

Conclusion

We have offered a schema for organizing research and assessment of spatial skills, derived from cognitive, linguistic, neural, computational and STEM learning perspectives. Although work using the schema is just beginning, we think that it provides promising avenues for identification of gaps in our existing toolbox of assessments of spatial skill. As these gaps are filled, we will be able to evaluate whether the organizing schema has heuristic value, and explore questions such as the coherence of skills within and across cells, how the skills develop and can be fostered, and whether and how the skills relate to STEM achievement, design creativity, or the ability to use new designs or navigate in new environments.

Footnote

[1] This treatment has benefited from extensive discussion with Anjan Chatterjee, Russell Epstein, Ken Forbus, Dedre Gentner, Susan Goldin-Meadow, Kathy Hirsh-Pasek, Janellen Huttenlocher, Susan Levine, Terry Regier and David Uttal.

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