Applying Cognitive Science Research to Improve Geoscience Teaching and Learning

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http://www.spatialintelligence.org
SILC: Spatial Intelligence and Learning Center

- NSF Science of Learning Center
- SILC brings together researchers from cognitive science, psychology, computer science, education and neuroscience with K12 teachers and college/university educators in STEM disciplines to
  - Understand how humans reason about complex spatial problems
  - Use this understanding to improve science education
- Our focus within SILC: the relationship between spatial thinking skills and the ability to perform geoscience tasks
  - Other groups working in chemistry, physics, engineering, etc. etc.
Outline

• Measuring spatial skills in the geological sciences
  • What assessment instruments can we use?
  • What do they measure?

• Characterizing spatial skills in the geological sciences
  • How many are there?
  • Which ones are related? How strongly are they related?
  • Do geological scientists really differ from other STEM experts?

• Improving spatial skills in the geological sciences
  • What works?
Key Research Findings

There are many spatial skills, related to each other to varying degrees.

- mental rotation
- perspective taking
- navigation
- penetrative thinking
- scaling
- 3D visualization (volumetric thinking)
- 4D visualization (mental animation)

Example:
Imagine you are standing at the flower and facing the tree. Point to the cat.
Key Research Findings

Geologists are comparable to other scientists in some ways, but outperform other scientists on measures of some skills.
Spatial skills vary widely and improve with practice.

Data from spring 2012 UW-Madison Structural Geology class
Particular strategies and tools can be used to move learners along the novice-expert spectrum.
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Measuring spatial skills in the geological sciences

- Psychometric tests
  - PVRT, Vandenberg & Kuse, ETS hidden figures, Paper Folding, and many others
- Assessments developed by SILC researchers:
  - Faulted words, Geologic Block Cross-sectioning Test, Crystal Slicing Test, Topographic Map Assessment, and many others
- Assessments from Mary Hegarty’s lab (UCSB)
  - Santa Barbara Sense of Direction, Perspective Taking/Spatial Orientation Test, and others

http://www.silccenter.org/index.php/resources/testsainstruments
Measuring spatial skills: standard psychometric tests
Measuring spatial skills in the geological sciences: SILC assessments

17. You are standing at the square, but you want to get to a place (on the map) where you would be able to see a small lake at the circle. Assume there is no vegetation. Please draw a line from the square to another place on the map that indicates the route you would take to a spot where you can see the circle. Explain below, why you chose the spot as well as the route to get there:

Before fragmentation w/ irrelevant characters:

e?a?t

After fragmentation w/ irrelevant characters example 1:
Measuring spatial skills: developing the Geologic Block Cross-sectioning Test

Not reliable:

Relplaced with:
Measuring spatial skills: developing the Geologic Block Cross-sectioning Test

Not reliable:

13

Can you figure out why #13 is not reliable?
(Why did students who did poorly on the rest of the test ace this item?)
Measuring spatial skills: developing the Geologic Block Cross-sectioning Test

We now have 16-item pre- and post-test versions of the Geologic Block Cross-sectioning Test. Contact Carol Ormand if you’re interested in using it.

Measuring spatial skills in the geological sciences

What can we learn from any one of these tests?
Spatial skills vary widely and improve with practice.

Data from spring 2012 UW-Madison Structural Geology class
Measuring spatial skills in the geological sciences

Well, okay, but we knew that…. e.g.,

- Reynolds et al., 2006, *The Hidden Earth*
- Titus and Horsman, 2009, *Characterizing and Improving Spatial Visualization Skills*
- Sorby, 2009, *Developing 3D Spatial Skills for Engineering Students*
- A whole bunch of cognitive science studies
- Studies in other STEM disciplines
Measuring spatial skills in the geological sciences

Questions?
• **Measuring** spatial skills in the geological sciences
  - What assessment instruments can we use?
  - What do they measure?

• **Characterizing** spatial skills in the geological sciences
  - How many are there?
  - Which ones are related? How strongly are they related?
  - Do geological scientists really differ from other STEM experts?

• **Improving** spatial skills in the geological sciences
  - What works?
Characterizing spatial skills in the geological sciences

• How closely are different spatial skills related?
  • If one of my Intro Geo students is proficient at mental rotation, or reading a topo map, will he/she be good at visualizing the subsurface geology, too?

• How closely are psychometric tests and domain-specific tests related?
  • If a student is proficient at mentally slicing abstract objects, will he/she be equally proficient at mentally slicing geological objects? Or vice versa?
Characterizing spatial skills in the geological sciences

N=89
Characterizing spatial skills in the geological sciences

N=130
Characterizing spatial skills in the geological sciences

- How closely are different (domain-general) spatial skills related?
  - Modest correlations indicate that mental rotation, paper folding, and the planes of reference test all assess “related” but different skills
  - Mental rotation and perspective-taking, while related, are also different skills (I find this fascinating)
  - Low correlation indicates that disembedding is essentially unrelated to (requires different cognitive skills than) mental rotation (correlations this size are attributed to general intelligence)

- Where does navigation fit in? Scaling? Volumetric thinking (3D visualization)? Mental animation (4D visualization)? Other spatial skills???
If one of my students is proficient at mental rotation, will he/she be good at visualizing the subsurface geology, too?

N=131
If one of my students is proficient at visualizing brittle deformation, will he/she also be good at visualizing ductile deformation? (Not necessarily.)

Characterizing spatial skills in the geological sciences

How closely are psychometric tests and domain-specific tests related?

N=154
Characterizing spatial skills in the geological sciences

How special spatial are geologists?

Mental Rotation

Percent correct

Geologists

Chemists

English Professors

5.a
Characterizing spatial skills in the geological sciences

How special are we? Geologists report mentally “undeforming” rocks:

See this…

Photo by Basil Tikoff
Characterizing spatial skills in the geological sciences

How special spatial are we? Geologists report mentally “undeforming” rocks:

See this…

Imagine this

Photo by Basil Tikoff
Characterizing spatial skills in the geological sciences

Is that unusual?
Can we transfer that skill to related tasks?
Characterizing spatial skills in the geological sciences

Is that unusual? Can we transfer that skill to related tasks?
Characterizing spatial skills in the geological sciences

Stimuli from Tim’s “Faulted Words” test
(Each word has an interrupting character)
Can you decipher them?
Characterizing spatial skills in the geological sciences

Faulted words

Percent correct

Geologists

Chemists

English Professors

Faulted
Randomly Displaced
Exploded
Characterizing spatial skills in the geological sciences

Previous studies suggest that experts can only reason at high levels about things in their own domain. For example, chess experts are only good at remembering real chessboards, not pieces randomly positioned on a board.

We are unusual not only for our ability to undeform faults, but also for our ability to transfer that reasoning skill to non-geological objects.
Key Research Findings

There are many spatial skills, related to each other to varying degrees.

  e.g. mental rotation, perspective taking, navigation, penetrative thinking, scaling, 3D visualization (volumetric thinking), 4D visualization (mental animation), ....

Geologists are comparable to other scientists in some ways, but outperform other scientists on measures of other skills.
Characterizing spatial skills in the geological sciences

Questions?
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Improving spatial skills in the geological sciences

- Strategies and tools:
  - Predictive sketching, paired with immediate feedback (aboratory experiments)
  - CogSketch software (classroom experiments)
  - Gesture (laboratory experiments)
  - Analogy/comparison (laboratory and classroom)
- Combinations of strategies/tools may be most effective

- How can you tell whether a new teaching method/strategy/tool works better than what you were doing before?
Laboratory experiments explored the effect of sketching vs. visualizing on students’ ability to visualize object interiors.

- 64 undergraduate psychology students (half in each condition)
- Pre- and post-test: 7 items from the GBCT
- Experimental condition: make predictive sketches, for each of a series of progressive slices through PlayDoh “models” of geologic structures
- Control condition: place colored dots where you expect the center of each layer to be, for each of the same series of progressive slices through the same models
Improving spatial skills in the geological sciences: sketching

Sketching Condition

Cut 1
Face 1

Cut 2
Face 2

Cut 3
Face 3

CROSS-SECTION
Cut 1
Face 2

Cut 2
Face 3

Cut 3
Face 4

SKETCH

CROSS-SECTION

SKETCH

SKETCH
Improving spatial skills in the geological sciences: sketching
Improving spatial skills in the geological sciences: sketching
Improving spatial skills in the geological sciences: sketching
Improving spatial skills in the geological sciences: sketching from 3D “models”

Laboratory experiments explored the effect of *sketching* vs. *visualizing* on students’ ability to visualize object interiors.

- How many of you think sketching will be more effective than visualizing?
- How many think visualizing will be more effective than sketching?
- How many think they will be equally effective?
- How many of you don’t have an intuition about which will be more effective?
Improving spatial skills in the geological sciences: sketching

Improving spatial skills in the geological sciences: “sketching”

Classroom experiments explored the effect of using a sketching software program vs. paper versions of the same exercises on Introductory Geology students’ spatial skills and understanding of course content.

- >250 Intro Geology students (~1/4 CogSketch; 3/4 paper)
- Pre-test: a few spatial skills test items, plus 3 questions about course content covered in each worksheet
- Immediate post-test: 3 questions from the pre-test
- Delayed post-test: spatial test items & new content questions
- Students completing the worksheets in CogSketch got immediate feedback, as often as they wanted it, from the built-in “virtual tutor”; students completing the worksheets on paper got delayed feedback (when the worksheets were graded and returned)
### Improving spatial skills in the geological sciences: “sketching”

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<td>Groundwater Flow</td>
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</tbody>
</table>
Improving spatial skills in the geological sciences: “sketching”

Which arrow below best represents a rapid burial of rock in the subsurface without any change in temperature?

Which arrow correctly shows the direction of water flow?
Improving spatial skills in the geological sciences: “sketching”
Improving spatial skills in the geological sciences: “sketching”
Results: Students using CogSketch perform as well as or significantly better than students doing the same worksheets on paper, for almost every worksheet. This, obviously, makes it easy for instructors to incorporate “sketching” in large classes. (We are looking at the data for the anomolous worksheets to figure out why paper was better in those few cases.)

Although we have only tested CogSketch with Intro students, we can imagine uses for it in upper-level courses as well....

Garnier, Bridget, and others. Introductory geoscience worksheets using a sketching program (CogSketch) with virtual feedback. In preparation.
Laboratory experiments explored the effect of gesturing vs. verbally describing the structures shown in geologic block diagrams on students’ ability to visualize interiors.
Laboratory experiments explored the effect of gesturing vs. verbally describing the structures shown in geologic block diagrams on students’ ability to visualize interiors.

- 92 undergraduate psychology students (~1/3 in each condition)
- Pre- and post-test: 7 items from the GBCT
- Three conditions:
  - Show via gesture how you would build each block diagram from the pre-test, gesture the slicing plane, gesture the viewing direction
  - Sit on your hands and tell the experimenter how you would build each block diagram....
  - Control: Play the card game “Set” with the experimenter
Improving spatial skills in the geological sciences: sketching from 3D “models”

Laboratory experiments explored the effect of **gesturing** vs. **verbally describing** the structures shown in geologic block diagrams on students’ ability to visualize interiors.

How many of you think playing “Set” will be the most effective strategy?
Improving spatial skills in the geological sciences: gesture

Improving spatial skills in the geological sciences: analogy & alignment

Laboratory and classroom experiments explored the effect of using spatial analogies and progressive alignment to help Introductory Geology students understand geologic time.

- When students are asked to map all of geologic time onto a single timeline, they fail pretty badly at understanding and remembering events that occurred at different scales of time.

- When students map progressively larger time scales onto a “standard” length timeline, they do better at understanding and remembering events that occurred at different scales of time.


See also Resnick, Ilyse, Hierarchical Alignment of Temporal Magnitude: http://serc.carleton.edu/NAGTWorkshops/time/workshop2012/essays/resnick.html.
Laboratory and classroom experiments explored the effect of using *spatial analogies* and *progressive alignment* to help Introductory Geology students understand geologic time.

- The “Trail of Time” in the Grand Canyon is built on this premise.

- Implications: It might be a good idea to consider how many orders of magnitude we are asking students to leap over in comparing micro-, meso-, and macro-scale features. Working from familiar scales toward unfamiliar scales is a strong strategy.
Improving spatial skills in the geological sciences

Combinations of strategies/tools may be most effective. This will be one area of focus for our near-future work.
Improving spatial skills in the geological sciences

How can you tell whether a new teaching method works better than what you were doing before?

• Test it in laboratory conditions (with a control group approximating current teaching practices)

• In a classroom study, you still need a control group. (Students from before you change your teaching methods? Students in a separate section of the course, with the same instructor?) It’s worth thinking carefully about who that control group will be, so that the comparison between the control group and the experimental group is as compelling as possible. There will be confounding factors; you want to minimize them.
There are many spatial skills, related to each other to varying degrees.

Individual students can excel or struggle at all, most, some, or none…

Geologists are comparable to other scientists in some ways, but outperform other scientists on measures of spatial skills specific to geology.

Spatial skills vary widely and improve with practice.

3D representations (“models”), predictive sketching (with immediate feedback), gesture, analogy, and stepwise scaling can be used to move learners along the novice-expert spectrum.