

# 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?

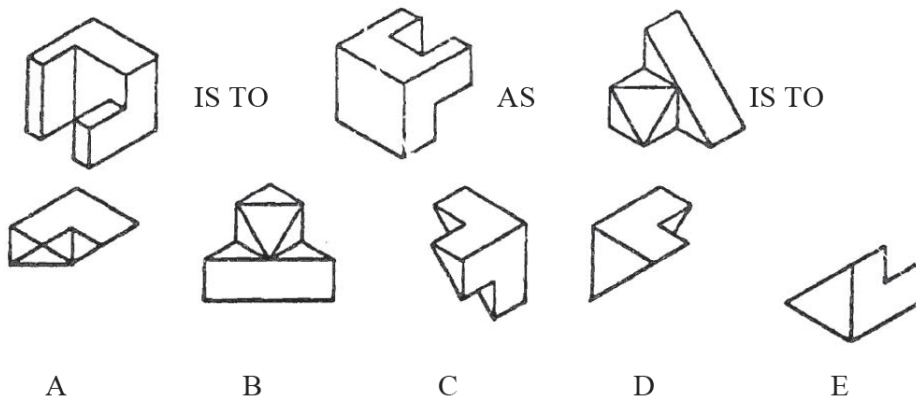


# Key Research Findings

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

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

5.



Spatial Orientation Test

Name: \_\_\_\_\_



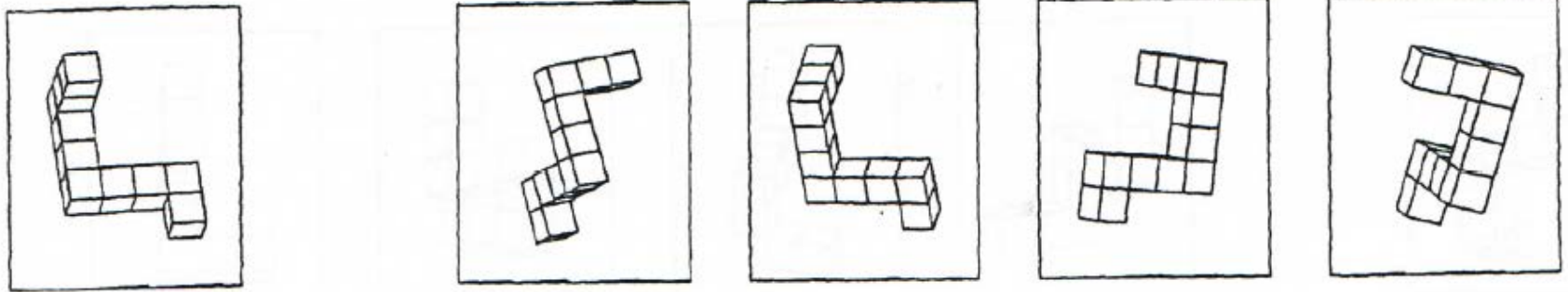
Example:

Imagine you are standing at the **flower** and facing the **tree**.  
Point to the **cat**.

# Key Research Findings

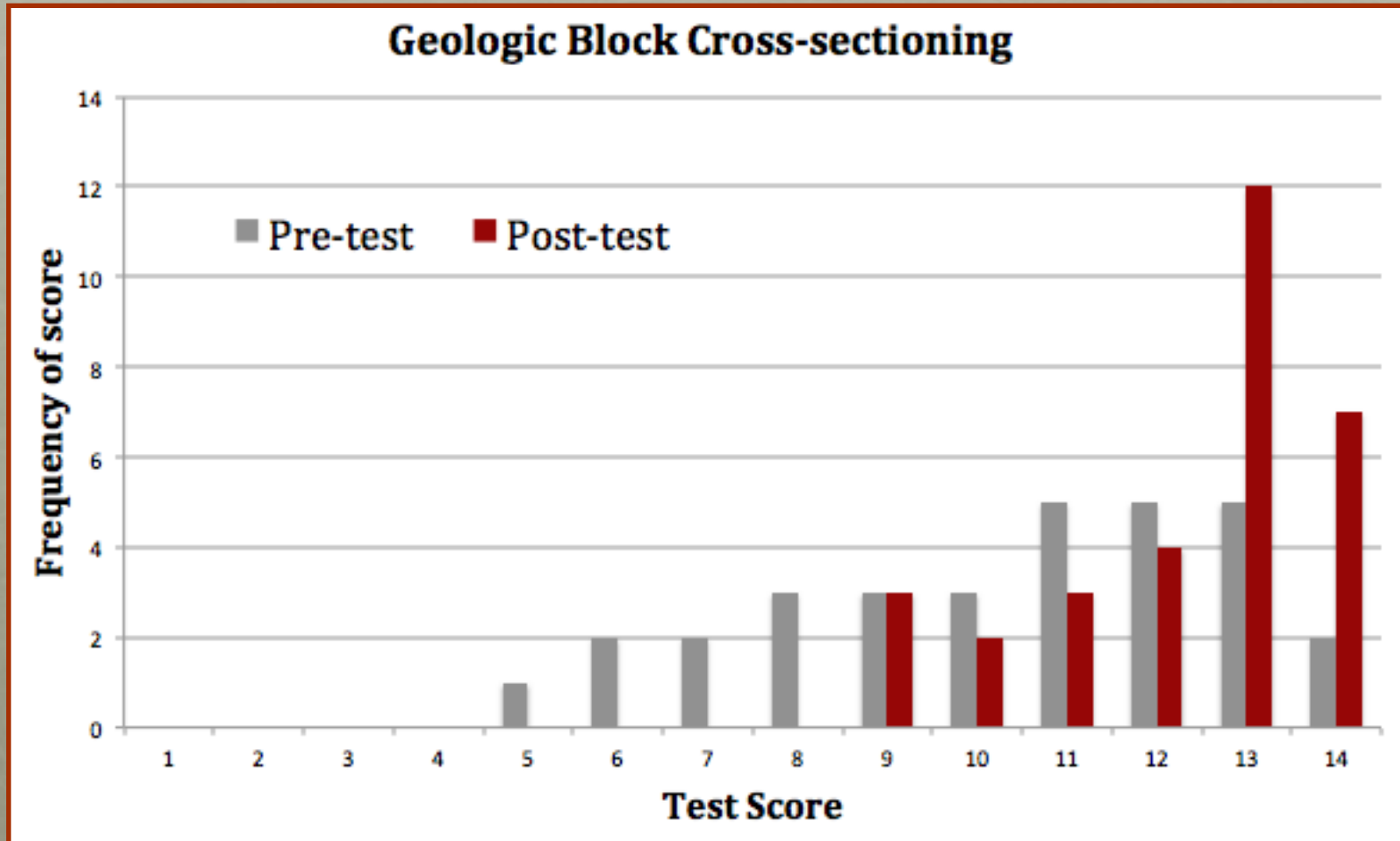
Geologists are comparable to other scientists in some ways, but outperform other scientists on measures of some skills.

5.a



# Key Research Findings

Spatial skills vary widely and improve with practice.

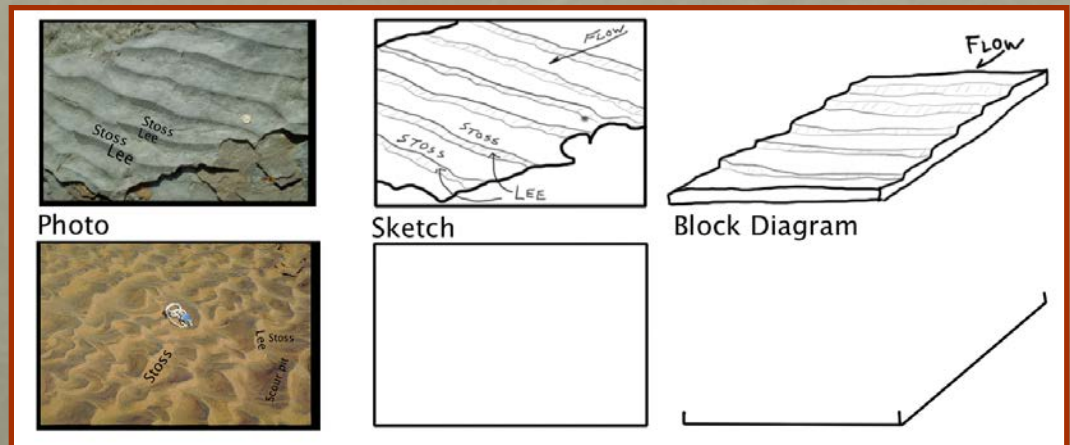
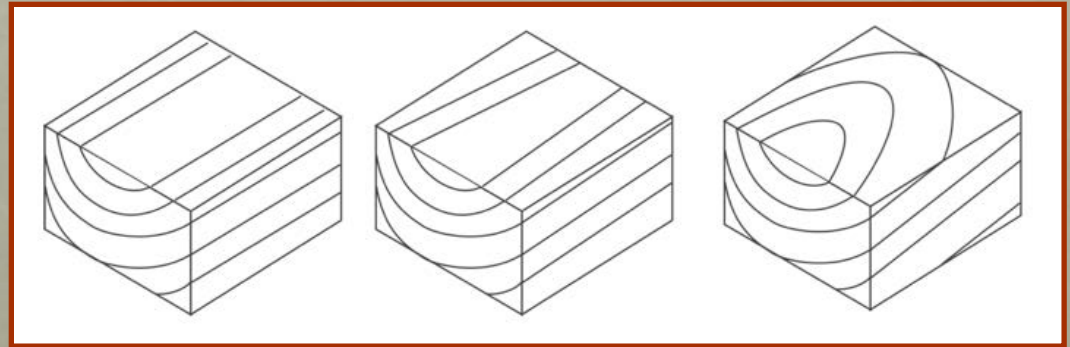
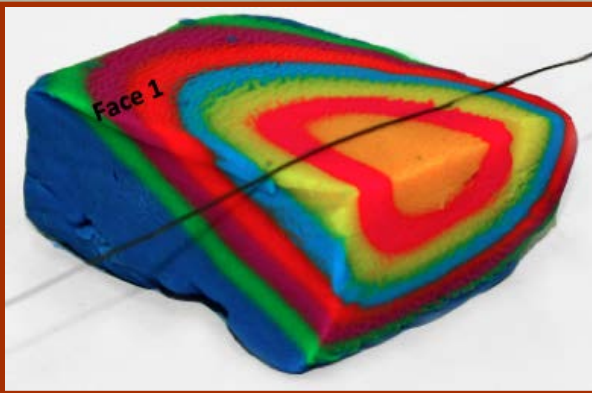


*Data from spring 2012 UW-Madison Structural Geology class*



# Key Research Findings

Particular strategies and tools can be used to move learners along the novice-expert spectrum.



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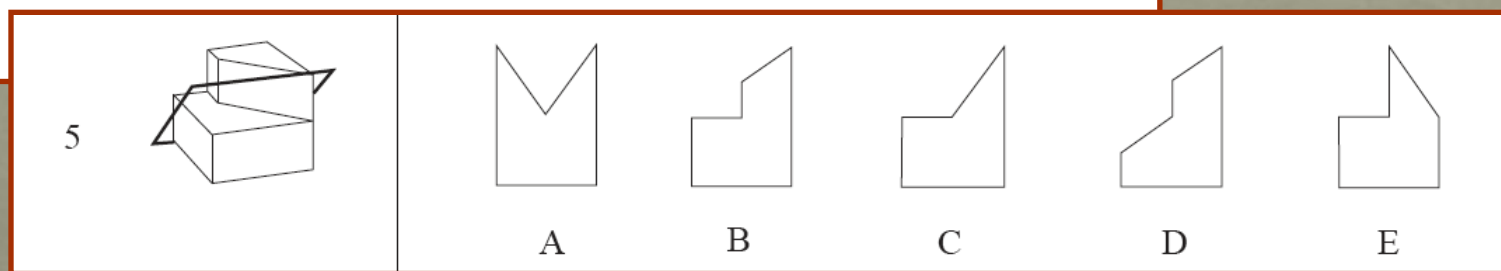
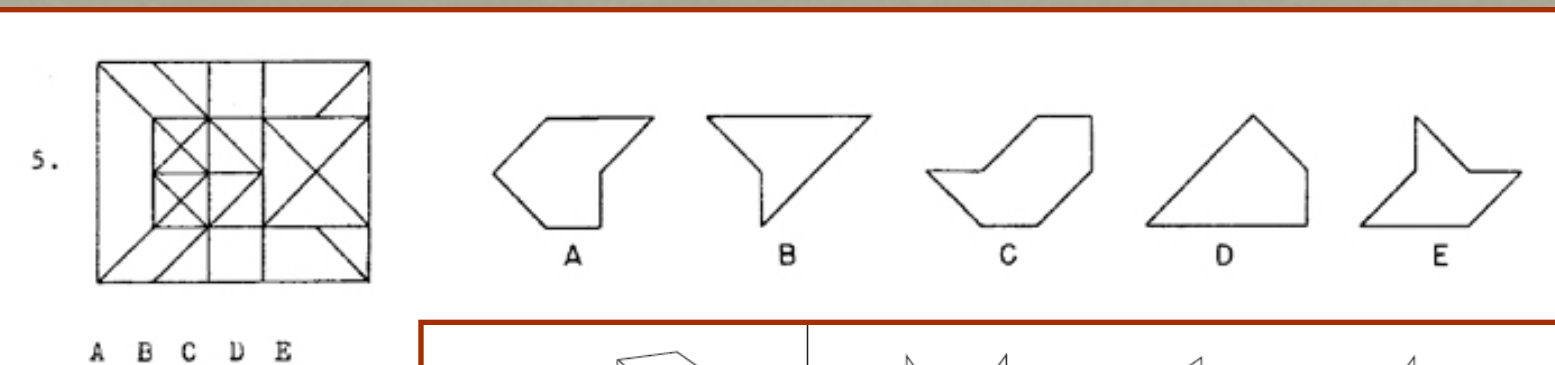
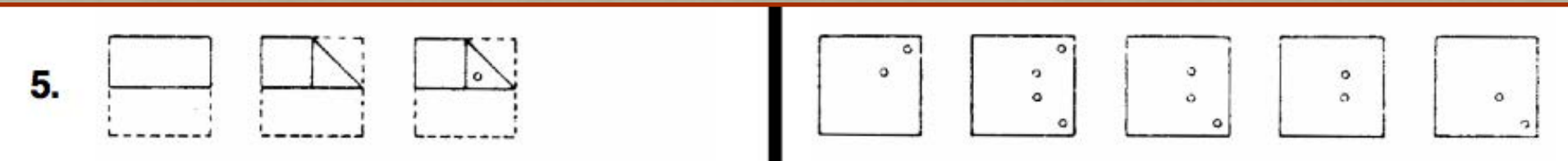
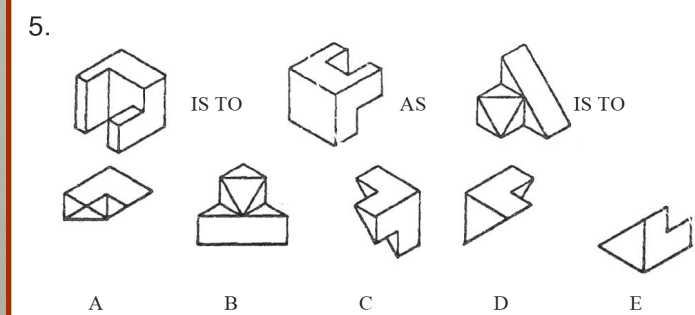
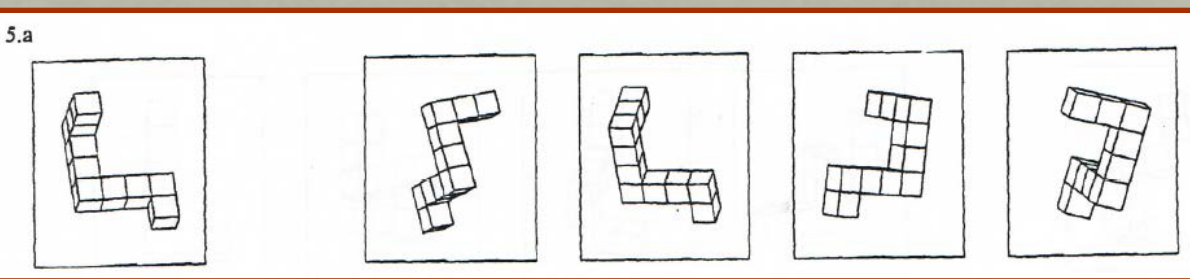


# Measuring spatial skills in the geological sciences

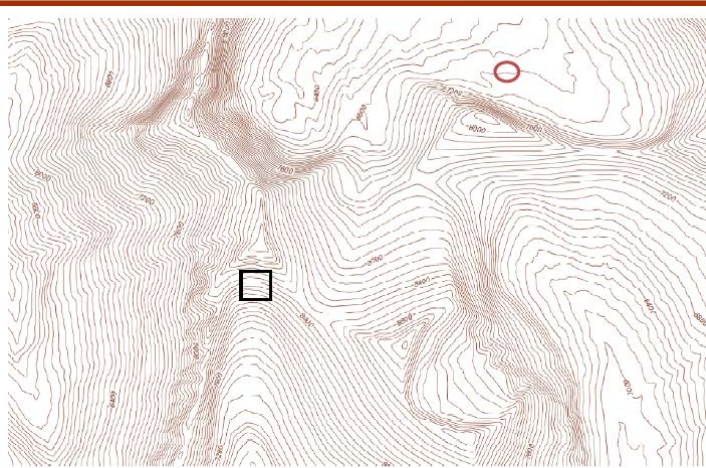
- Psychometric tests
  - PVRT, Vandenberg & Kuse, ETS hidden figures, Paper Folding, and many others
- Assessments developed by SILC researchers:
  - Faulted words, Geologic Block Cross-sectioning Test, Crystal Slicing Test, Topographic Map Assessment, and many others
  - Assessments from Mary Hegarty's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

<http://www.silccenter.org/index.php/resources/testsainstruments>

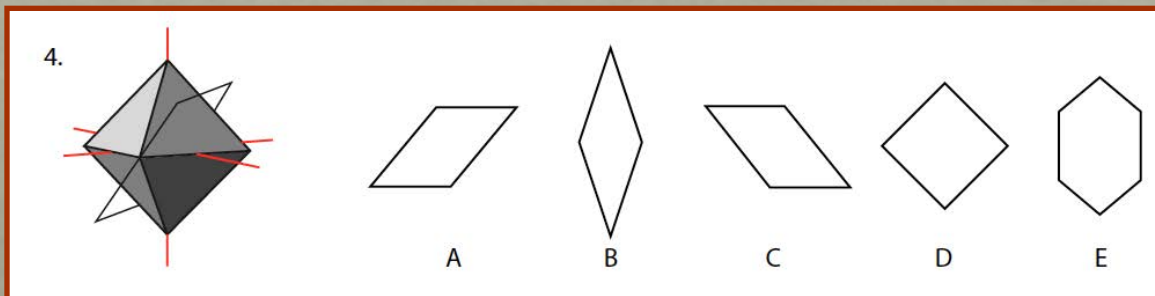
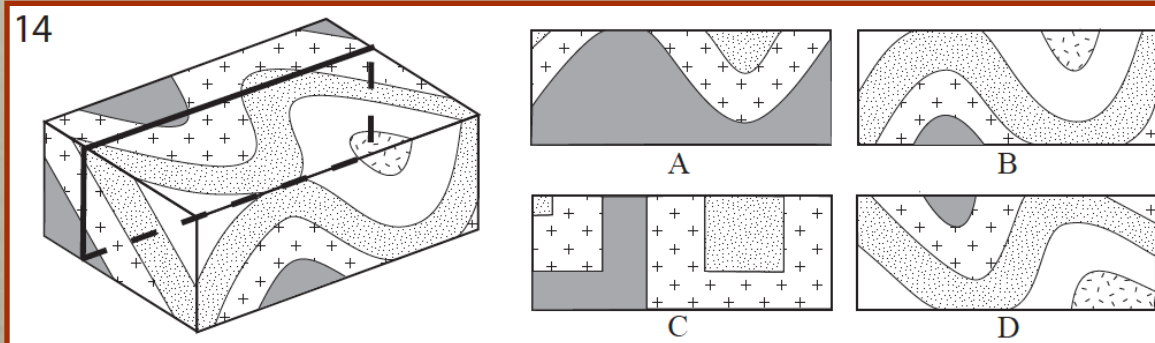
# Measuring spatial skills: standard psychometric tests



# 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:

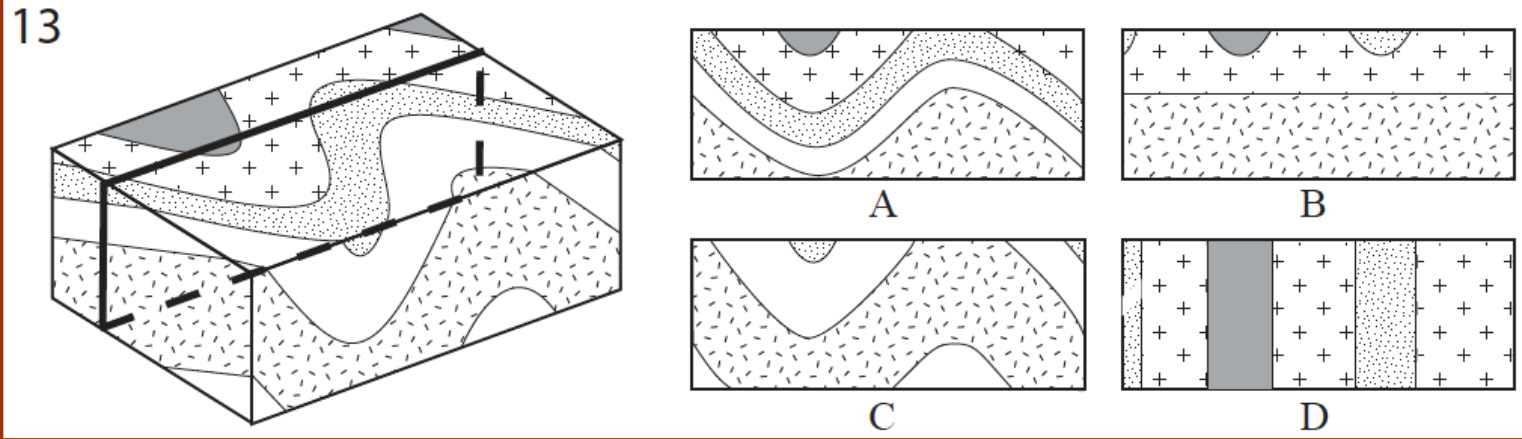
உதாரணம்



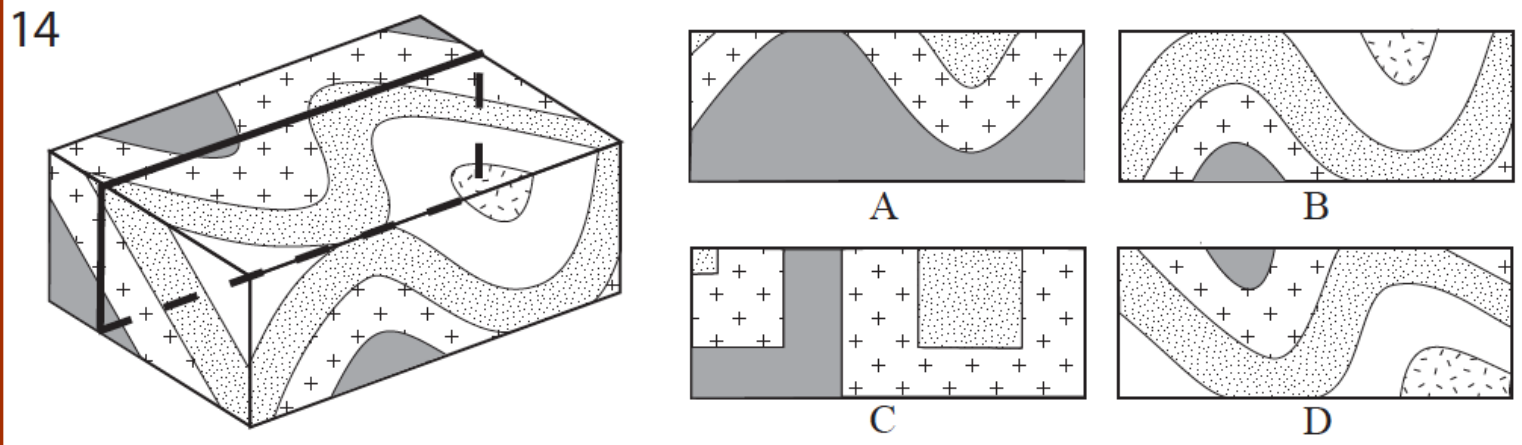


# Measuring spatial skills: developing the Geologic Block Cross-sectioning Test

Not  
reliable:

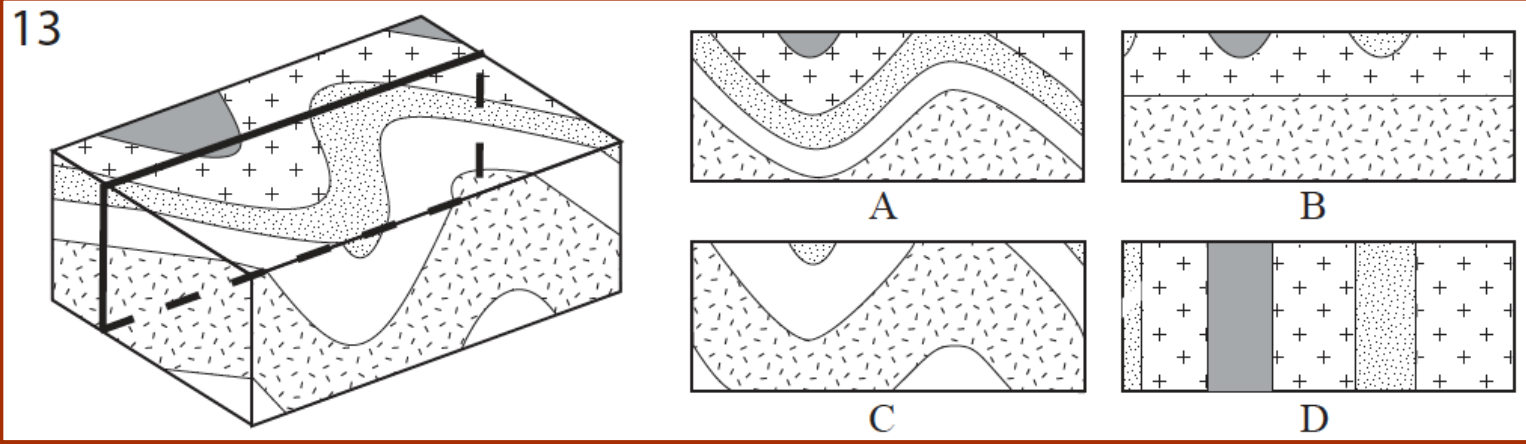


Relplaced  
with:

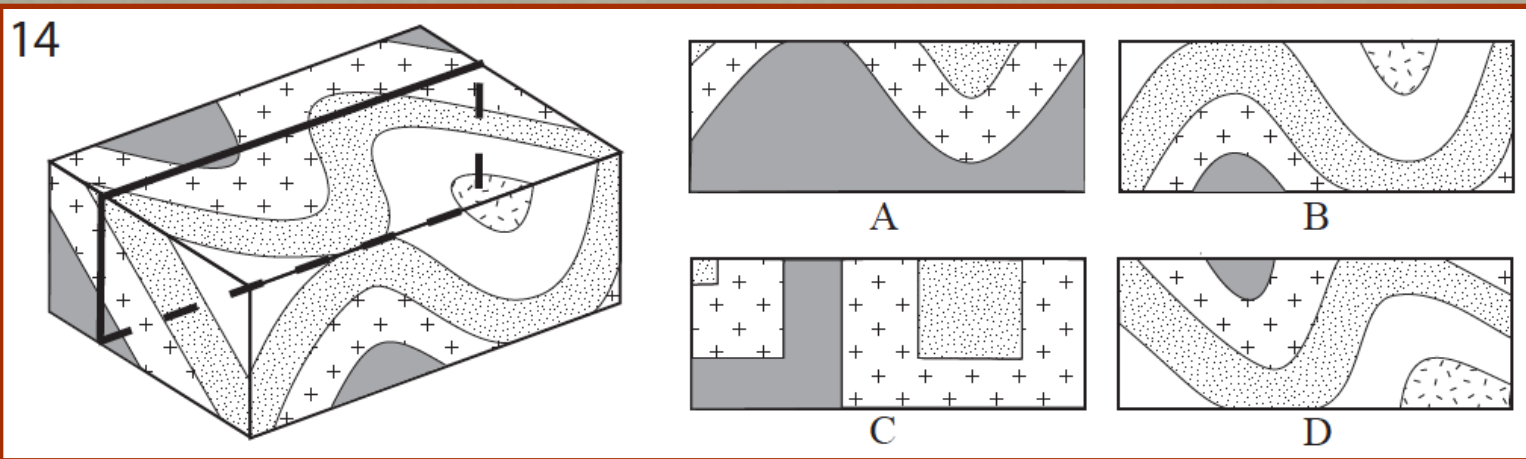


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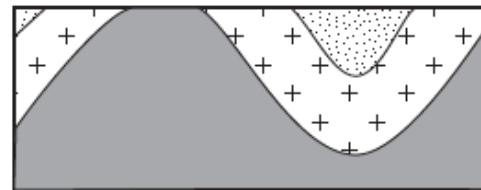
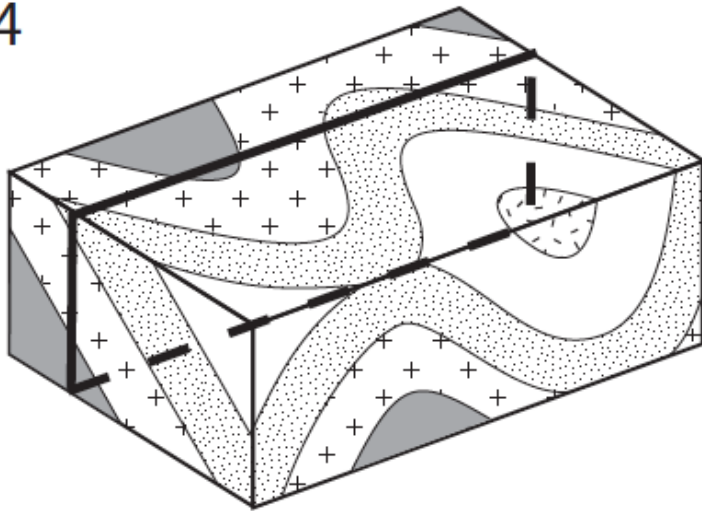


*Can you figure out why #13 is not reliable?  
(Why did students who did poorly on the rest of the test ace this item?)*

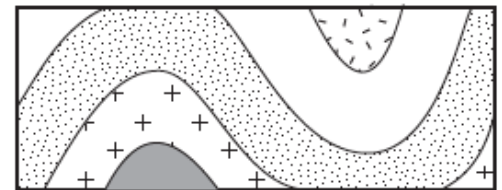
# Measuring spatial skills: developing the Geologic Block Cross-sectioning Test

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.

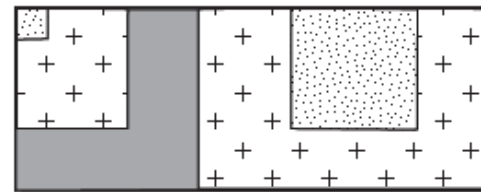
14



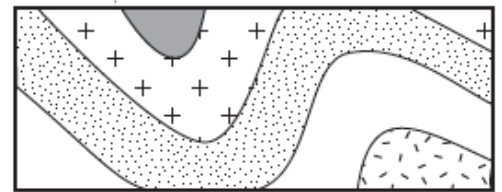
A



B



C



D

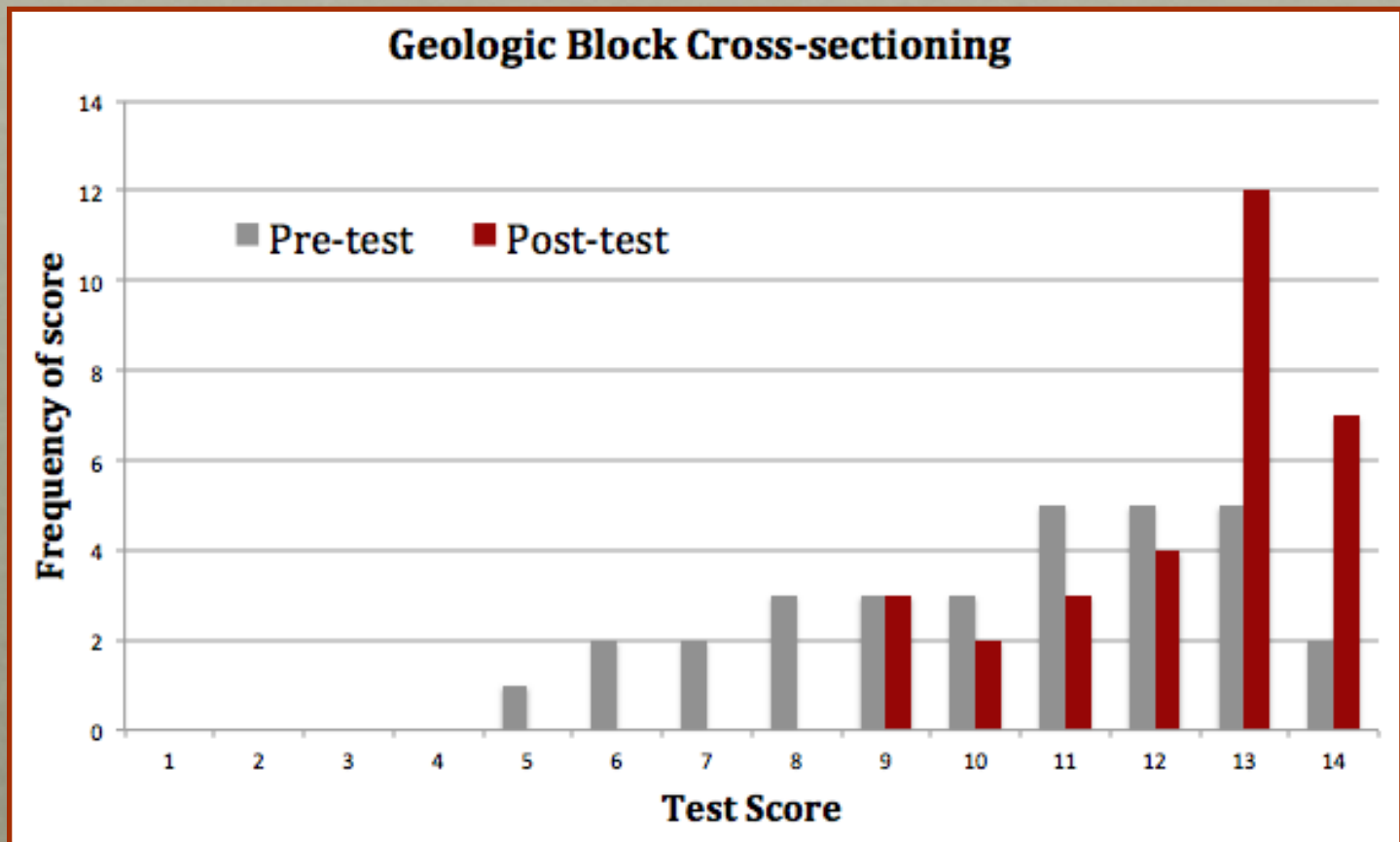
Ormand, Carol J., Thomas F. Shipley, Basil Tikoff, and Cathryn A. Manduca. Developing a Valid, Reliable Psychometric Test of Visual Penetrative Ability: The Geologic Block Cross-sectioning Test. In preparation for submission to the Journal of Geoscience Education.



# 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*
- Uttal and Cohen, 2012, *Spatial Thinking and STEM Education: When, Why, and How?*
- A whole bunch of cognitive science studies
- Studies in other STEM disciplines

# Measuring spatial skills in the geological sciences

Questions?



# Outline

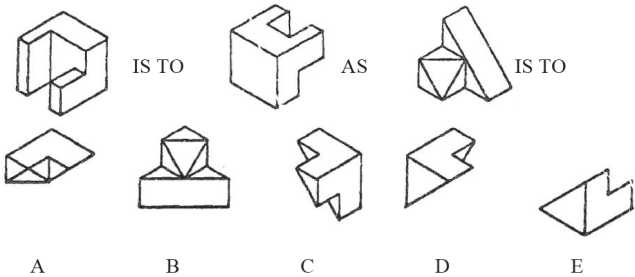
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# Characterizing spatial skills in the geological sciences

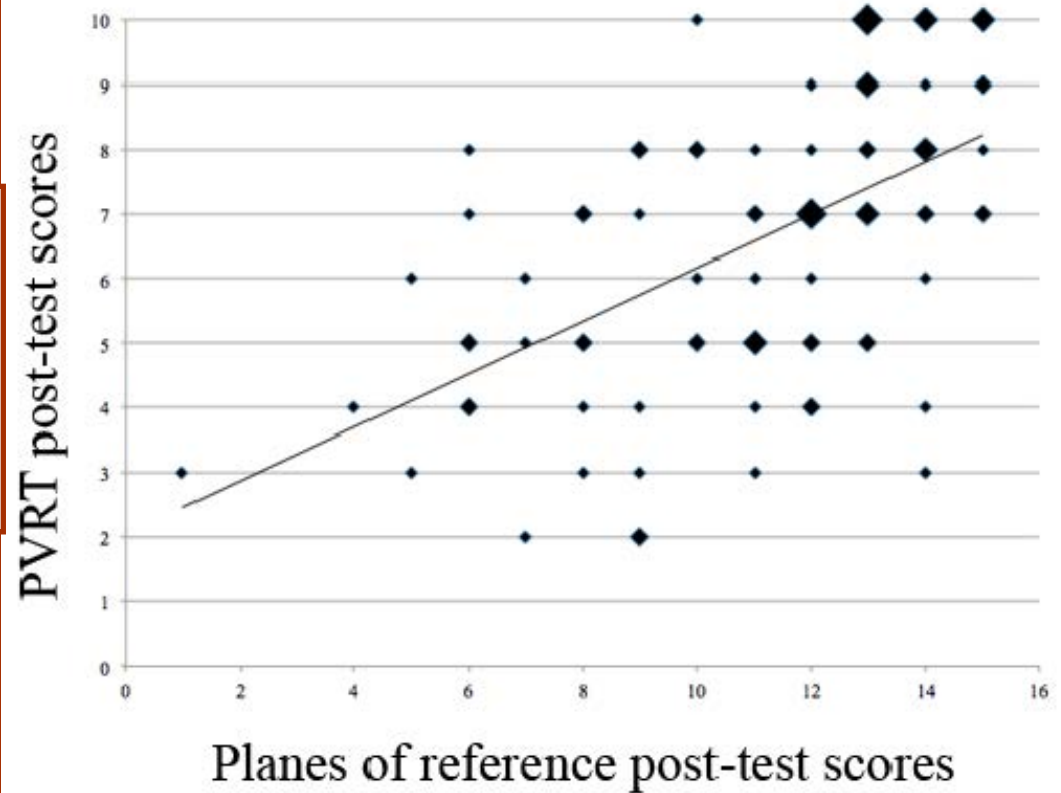
- How closely are different spatial skills related?
  - If one of my Intro Geo students is proficient at mental rotation, or reading a topo map, will he/she be good at visualizing the subsurface geology, too?
- How closely are psychometric tests and domain-specific tests related?
  - If a student is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

5.



a. PVRT score vs. Planes of reference score, post-test ( $R=0.56$ )



5



A

B

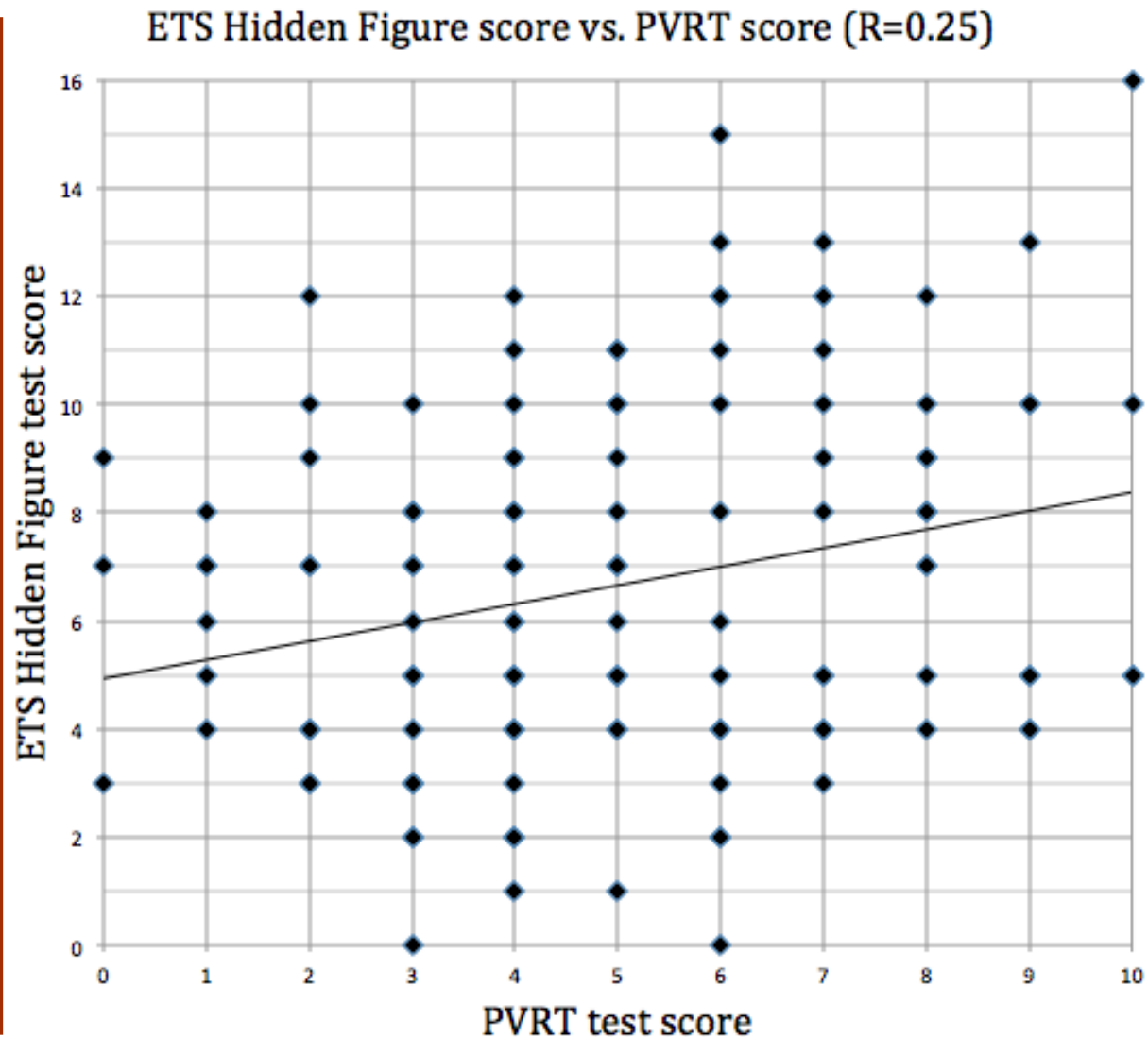
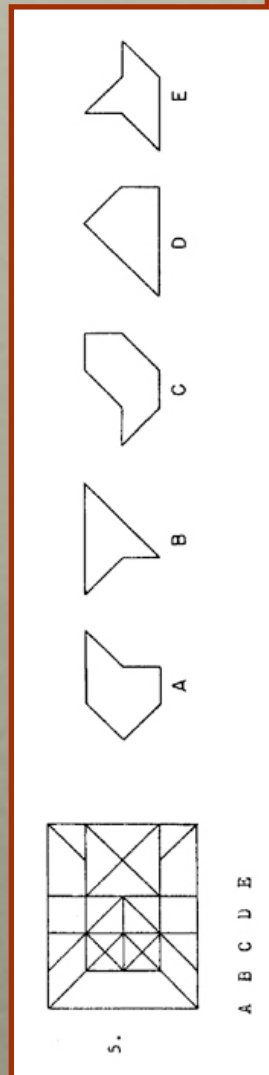
C

D

E



# Characterizing spatial skills in the geological sciences

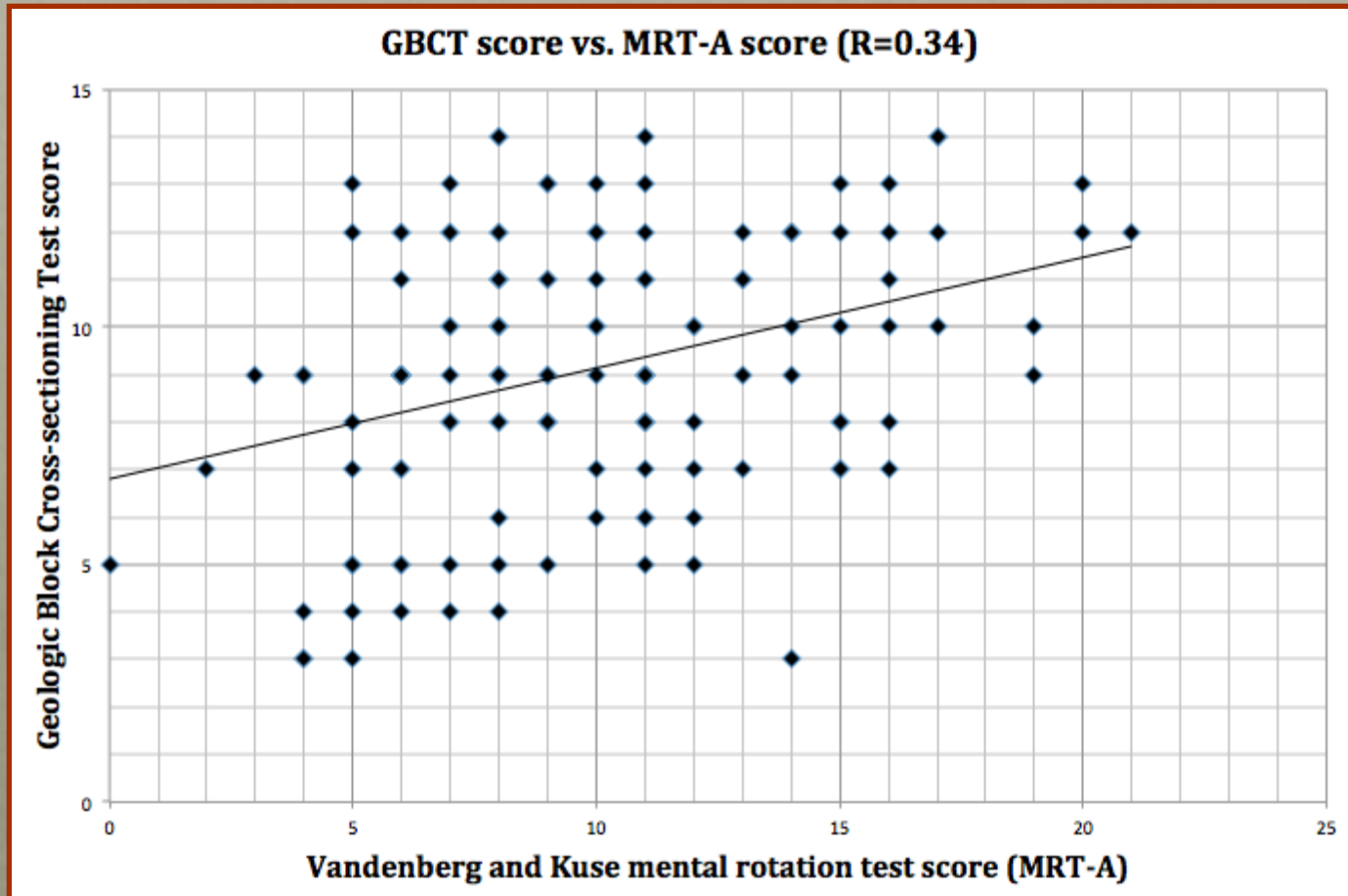


# Characterizing spatial skills in the geological sciences

- 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???

# Characterizing spatial skills in the geological sciences

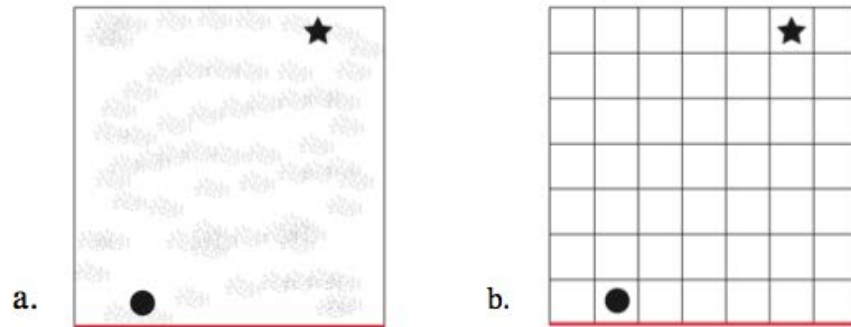
If one of my students is proficient at mental rotation, will he/she be good at visualizing the subsurface geology, too?



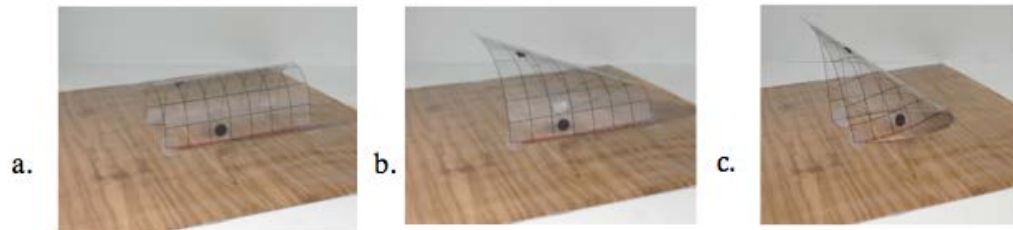


# Characterizing spatial skills in the geological sciences

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



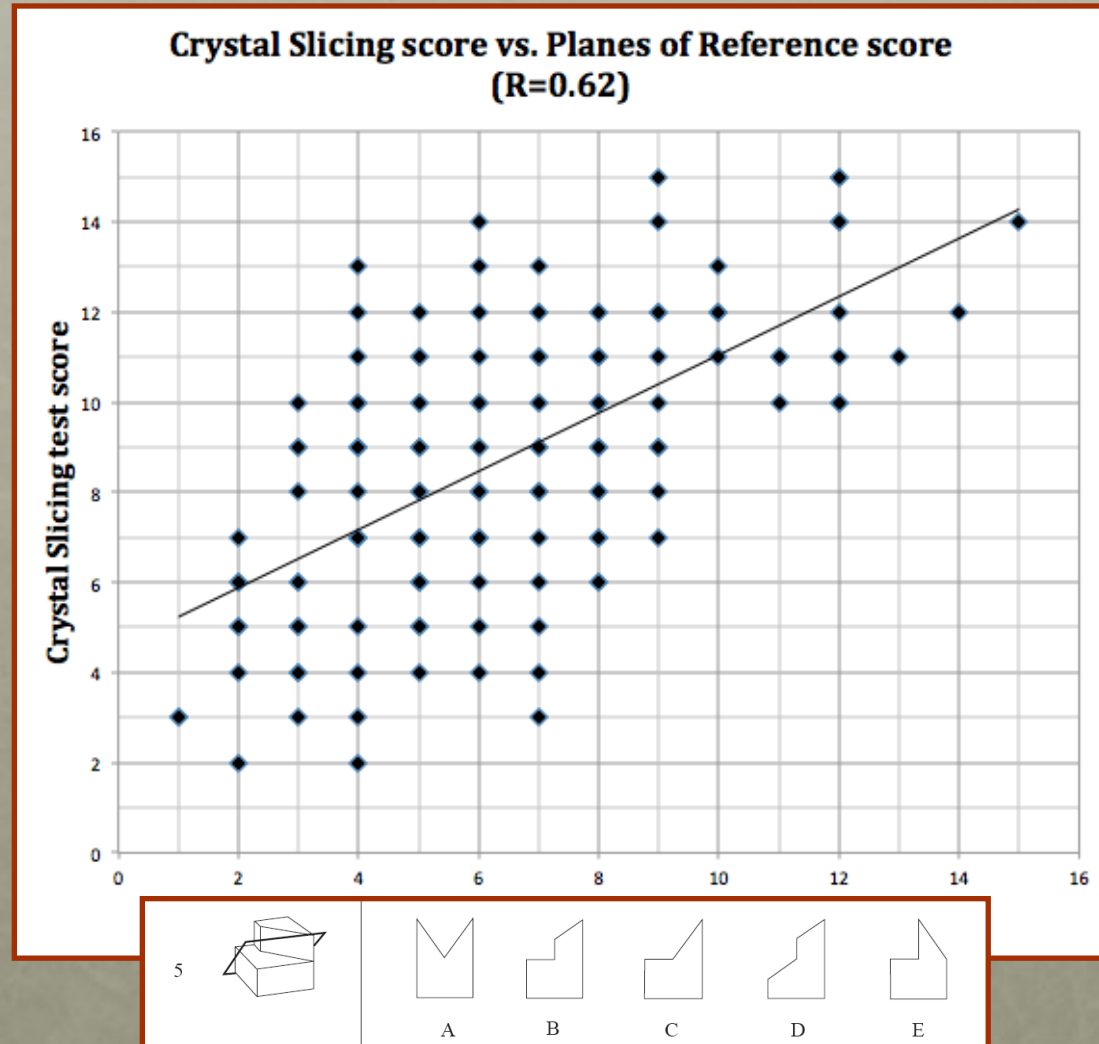
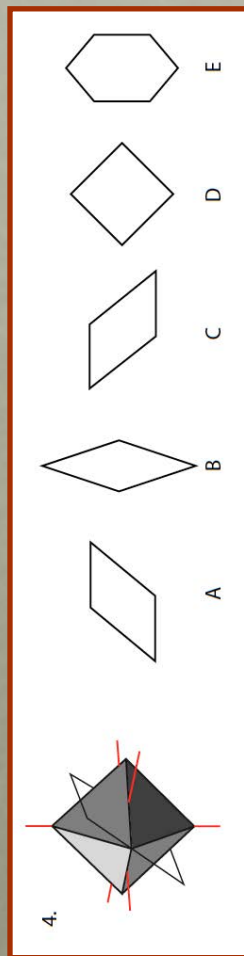
Illustrations of the plastic sheets used to generate the stimuli in the Non-rigid Bending test: a) Textured background condition, b) Gridlines background condition.



...es background condition in the Non-rigid Bending trial – an image of a sheet with an orthogonal bend, ...l – an image of a sheet with a moderate oblique ...rial – an image of a sheet with a complex oblique

# Characterizing spatial skills in the geological sciences

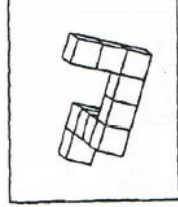
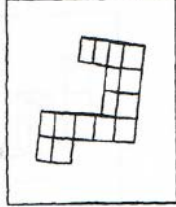
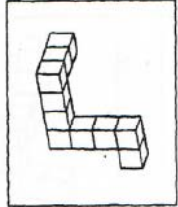
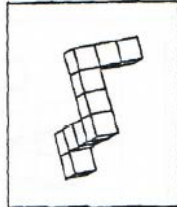
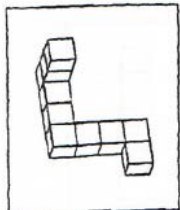
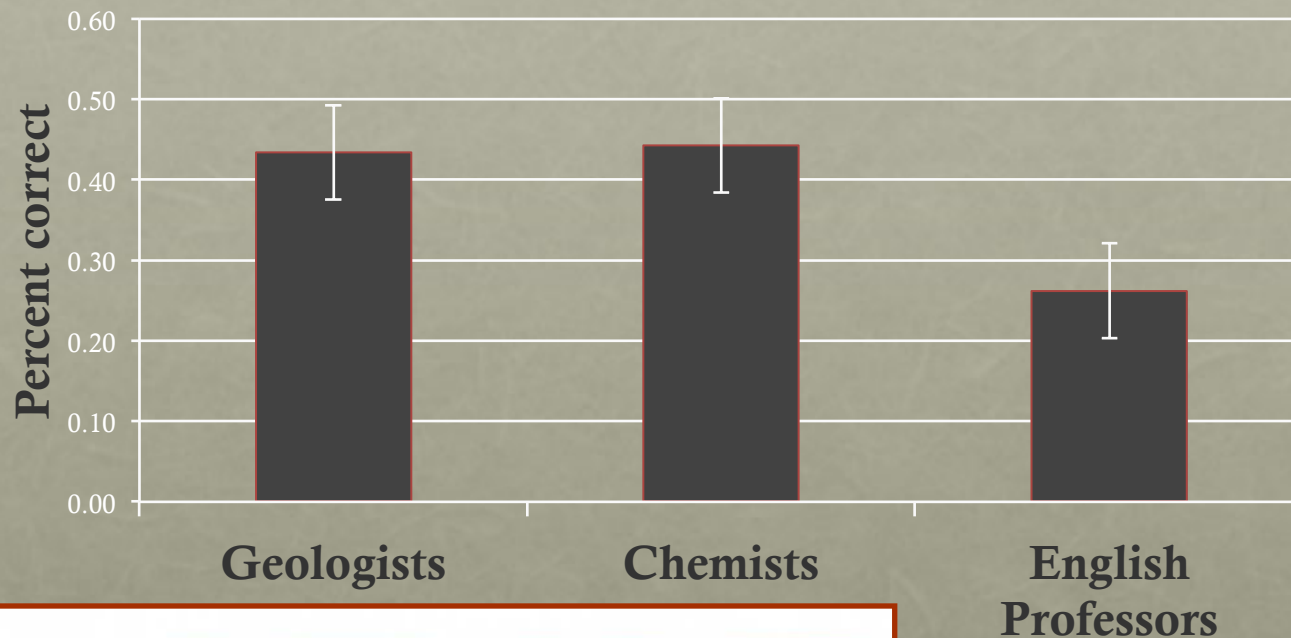
How closely are psychometric tests and domain-specific tests related?



# Characterizing spatial skills in the geological sciences

How ~~special~~ spatial are geologists?

## Mental Rotation





# Characterizing spatial skills in the geological sciences

How ~~special~~ spatial 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...



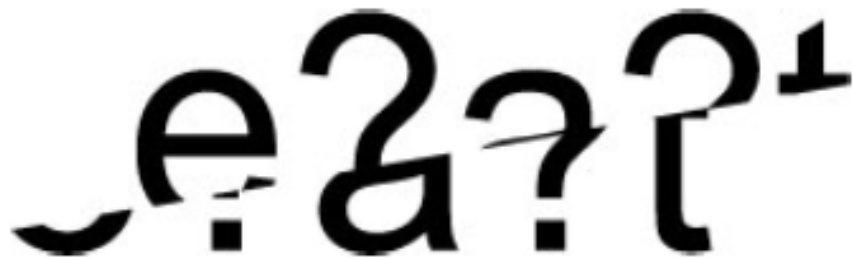
Photo by Basil Tikoff

Imagine this





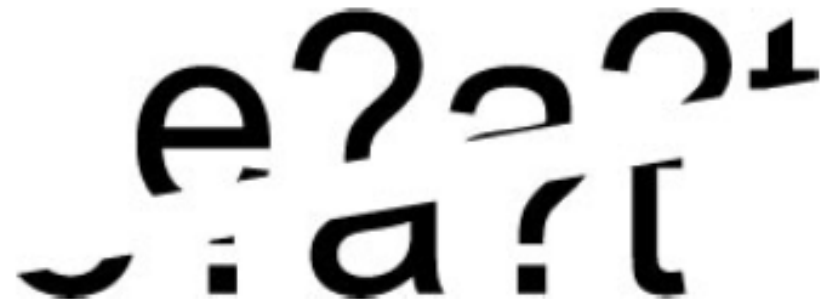
# Characterizing spatial skills in the geological sciences



Is that unusual?

Is that unusual?

Can we transfer that skill to related tasks?





# Characterizing spatial skills in the geological sciences



e? a? t

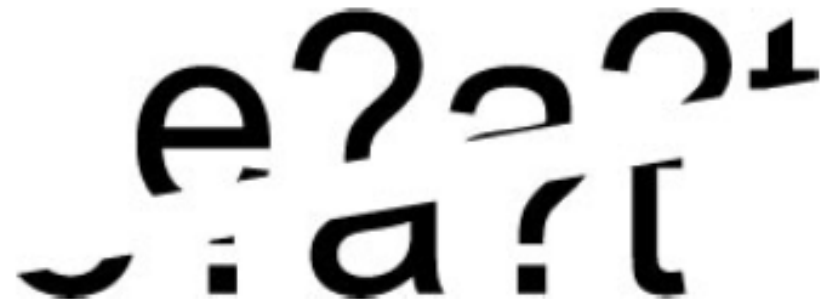
Is that unusual? Can we transfer that skill to related tasks?



e? a? t



e? a? t



e? a? t

# Characterizing spatial skills in the geological sciences

# အိန္ဒိယ

# நிபந்தனை

# Stimuli from Tim's “Faulted Words” test

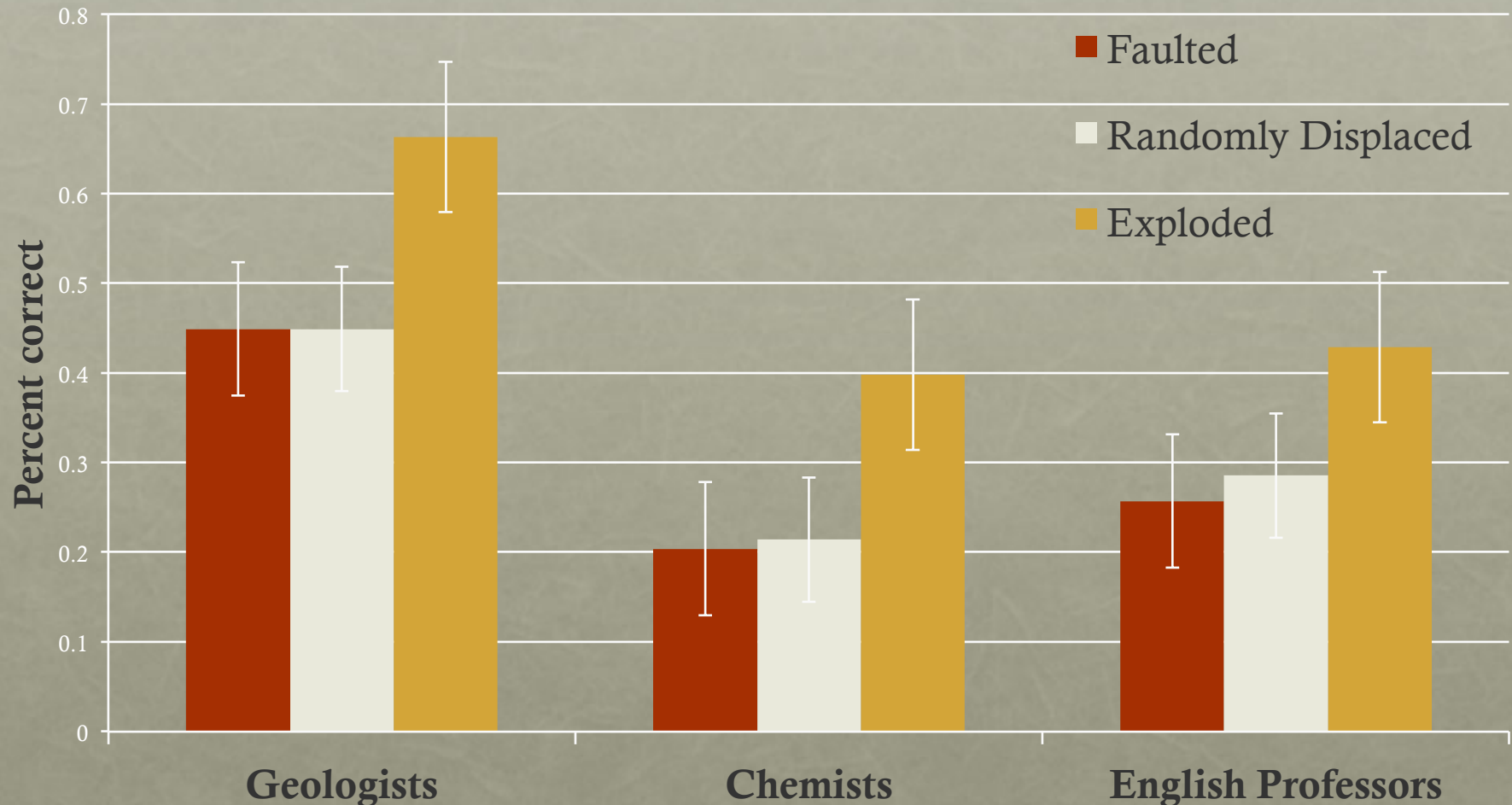
(Each word has an interrupting character)

# Can you decipher them?

1. **Prüfungsausschuss**  
 2. **Prüfungsausschuss**  
 3. **Prüfungsausschuss**

# Characterizing spatial skills in the geological sciences

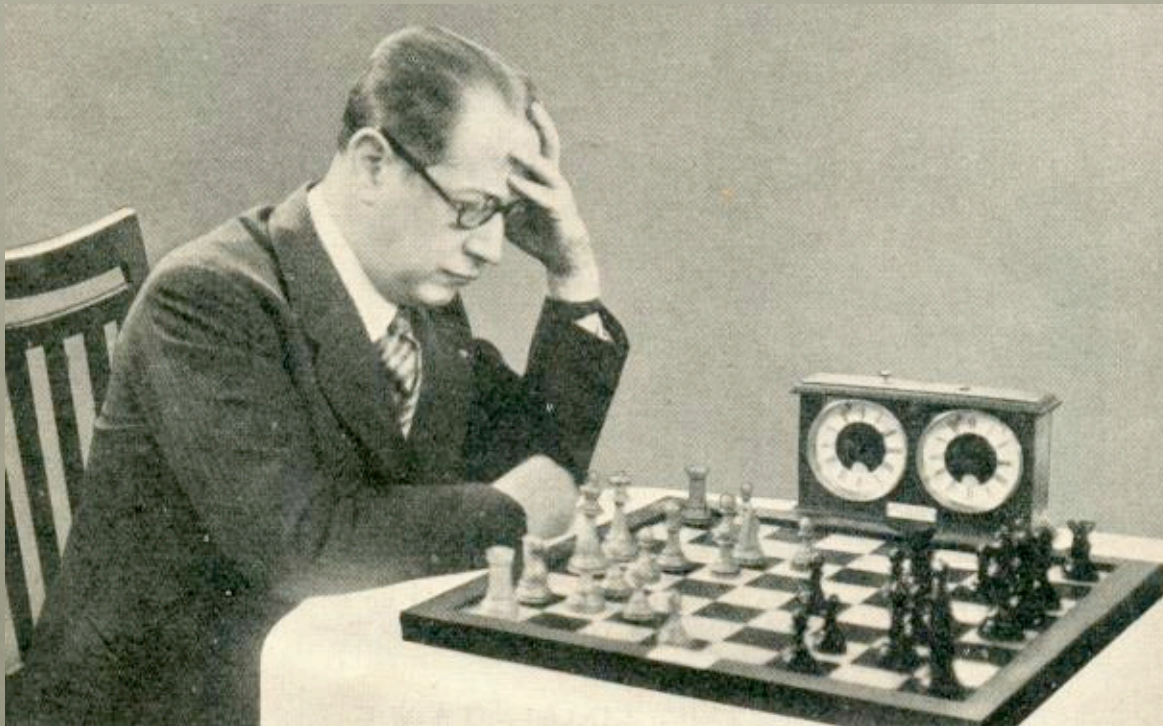
## Faulted words





# 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.



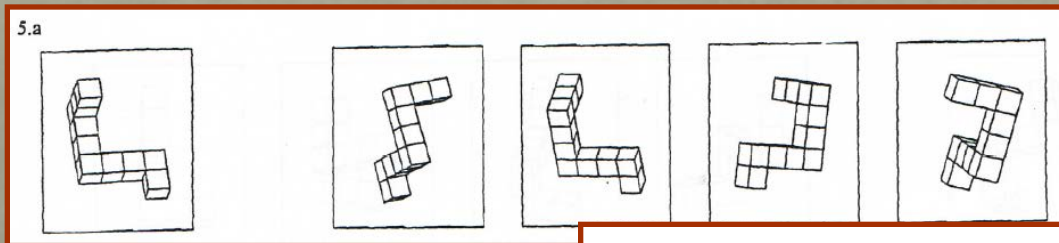
*We are unusual not only for our ability to undeform faults, but also for our ability to transfer that reasoning skill to non-geological objects.*

# 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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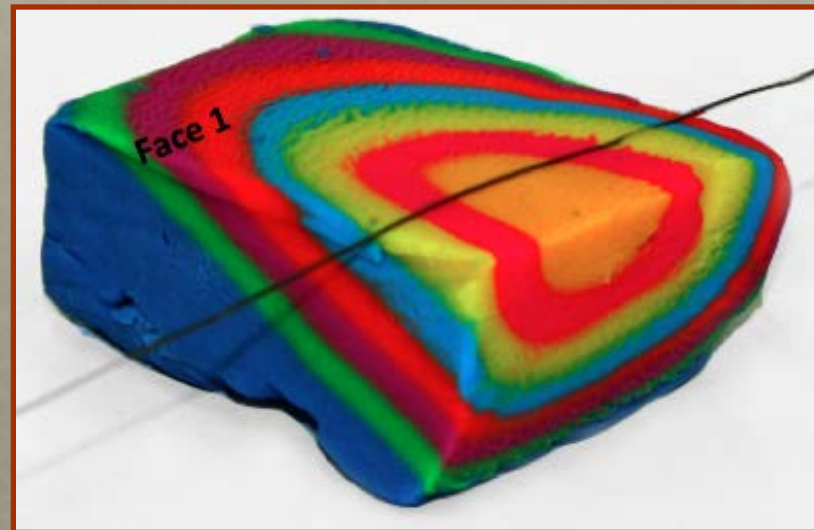
# Improving spatial skills in the geological sciences

- Strategies and tools:
  - Predictive sketching, paired with immediate feedback (laboratory 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?*

# 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.

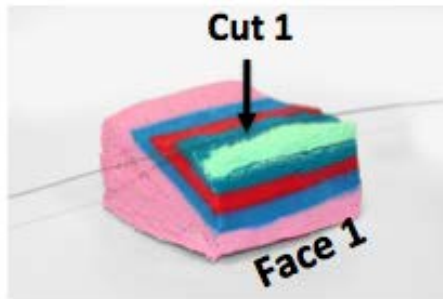
- 64 undergraduate psychology students (half in each condition)
- Pre- and post-test: 7 items from the GBCT
- Experimental condition: make predictive sketches, for each of a series of progressive slices through PlayDoh “models” of geologic structures
- Control condition: place colored dots where you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



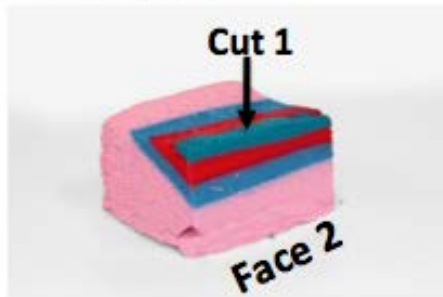


# Improving spatial skills in the geological sciences: sketching

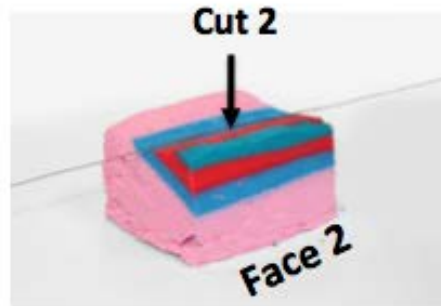
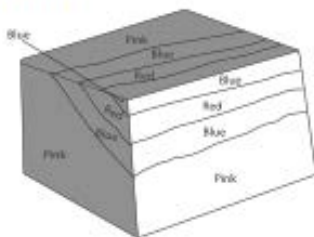
## Sketching Condition



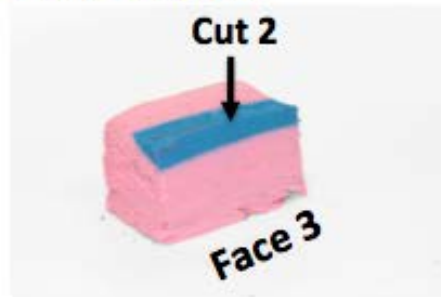
CROSS-SECTION



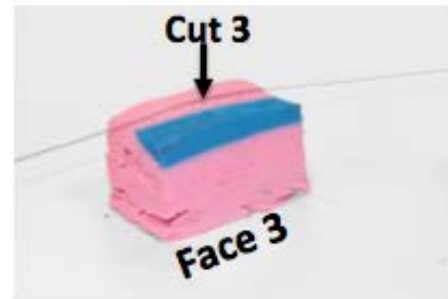
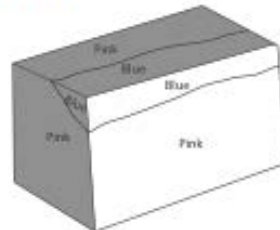
SKETCH



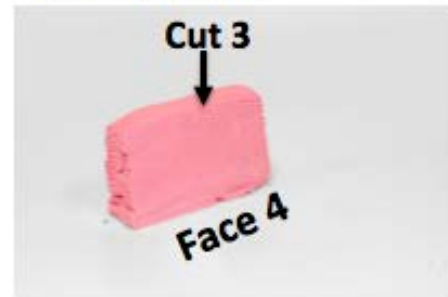
CROSS-SECTION



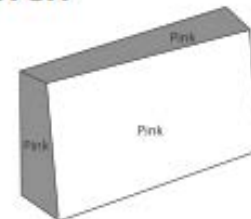
SKETCH



CROSS-SECTION

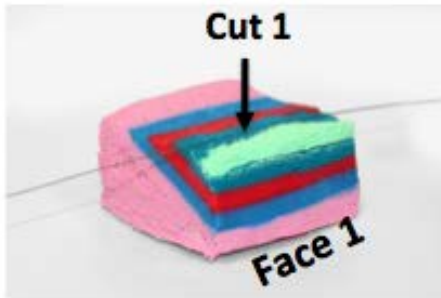


SKETCH



# Improving spatial skills in the geological sciences: sketching

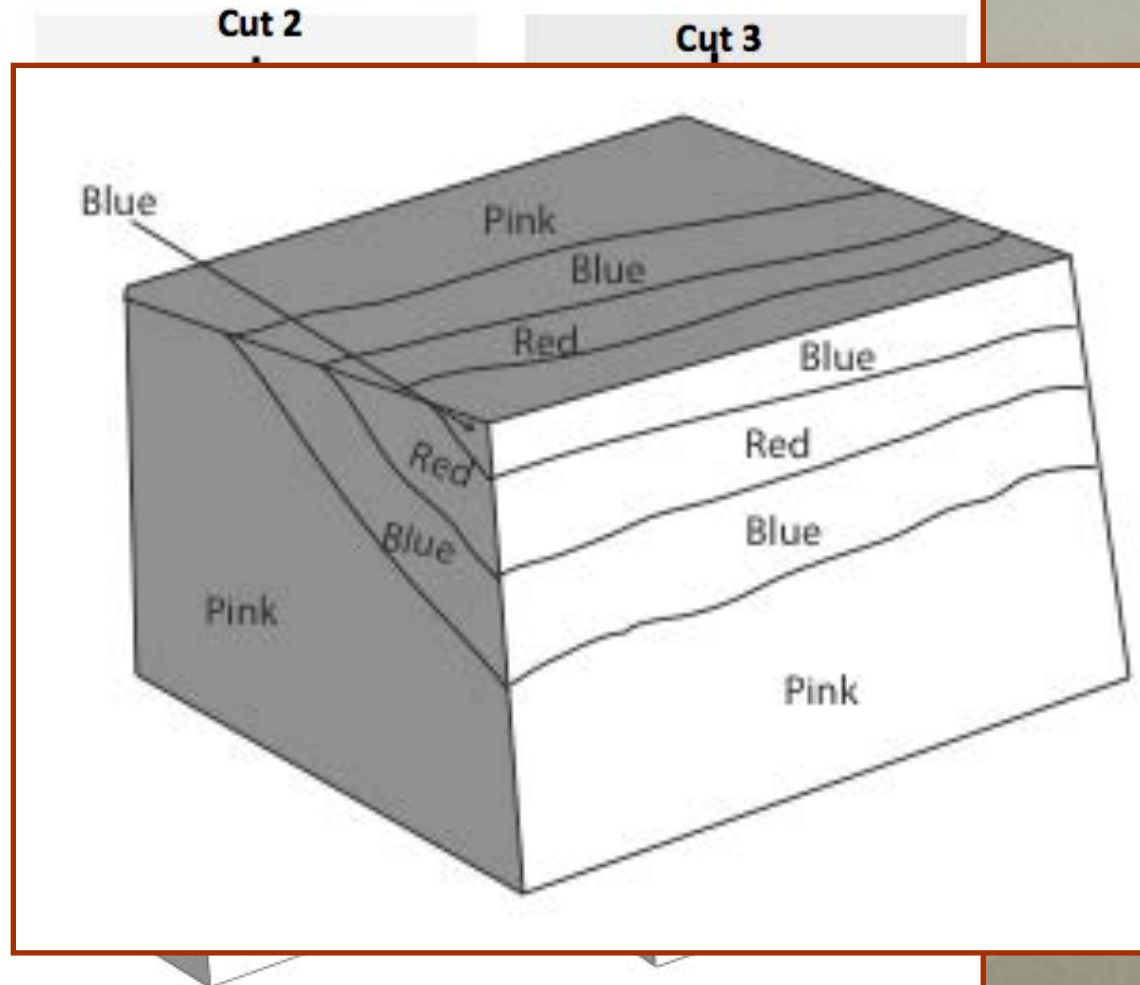
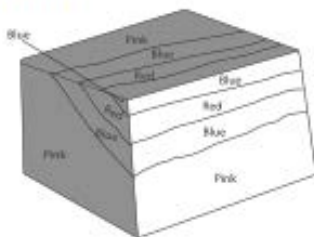
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CROSS-SECTION

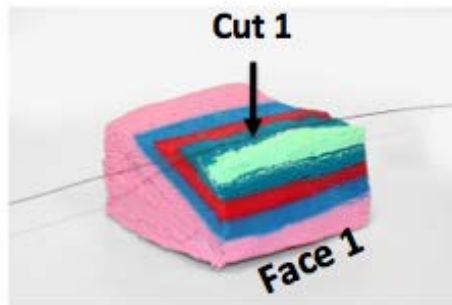


SKETCH

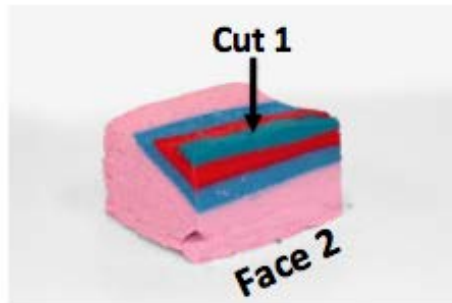


# Improving spatial skills in the geological sciences: sketching

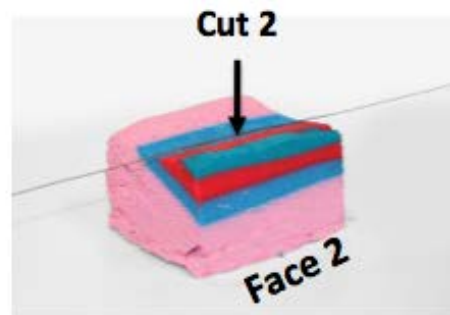
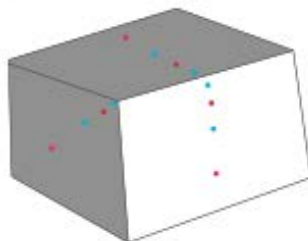
## Visualization Condition



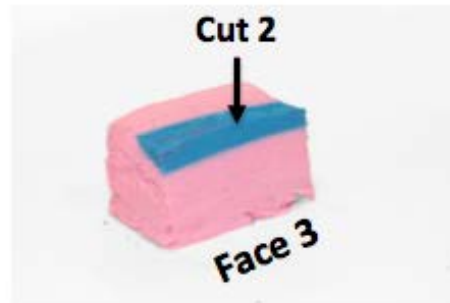
CROSS-SECTION



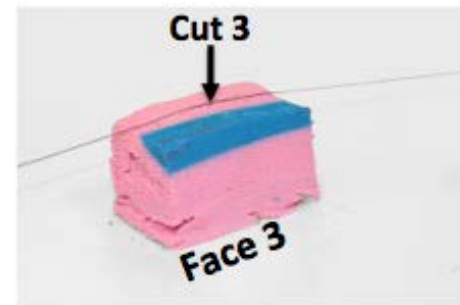
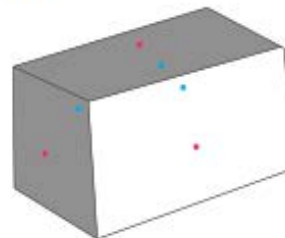
SKETCH



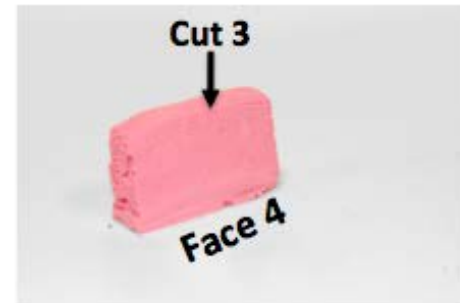
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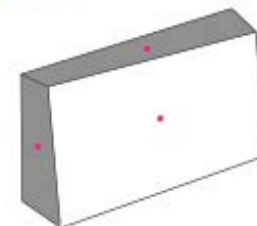
SKETCH



CROSS-SECTION



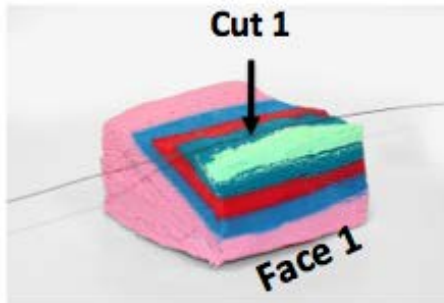
SKETCH



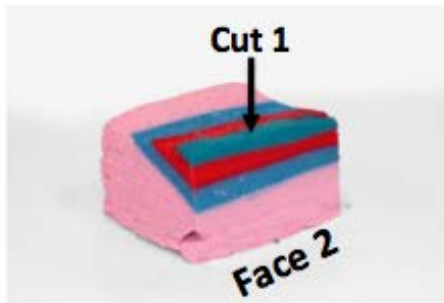


# Improving spatial skills in the geological sciences: sketching

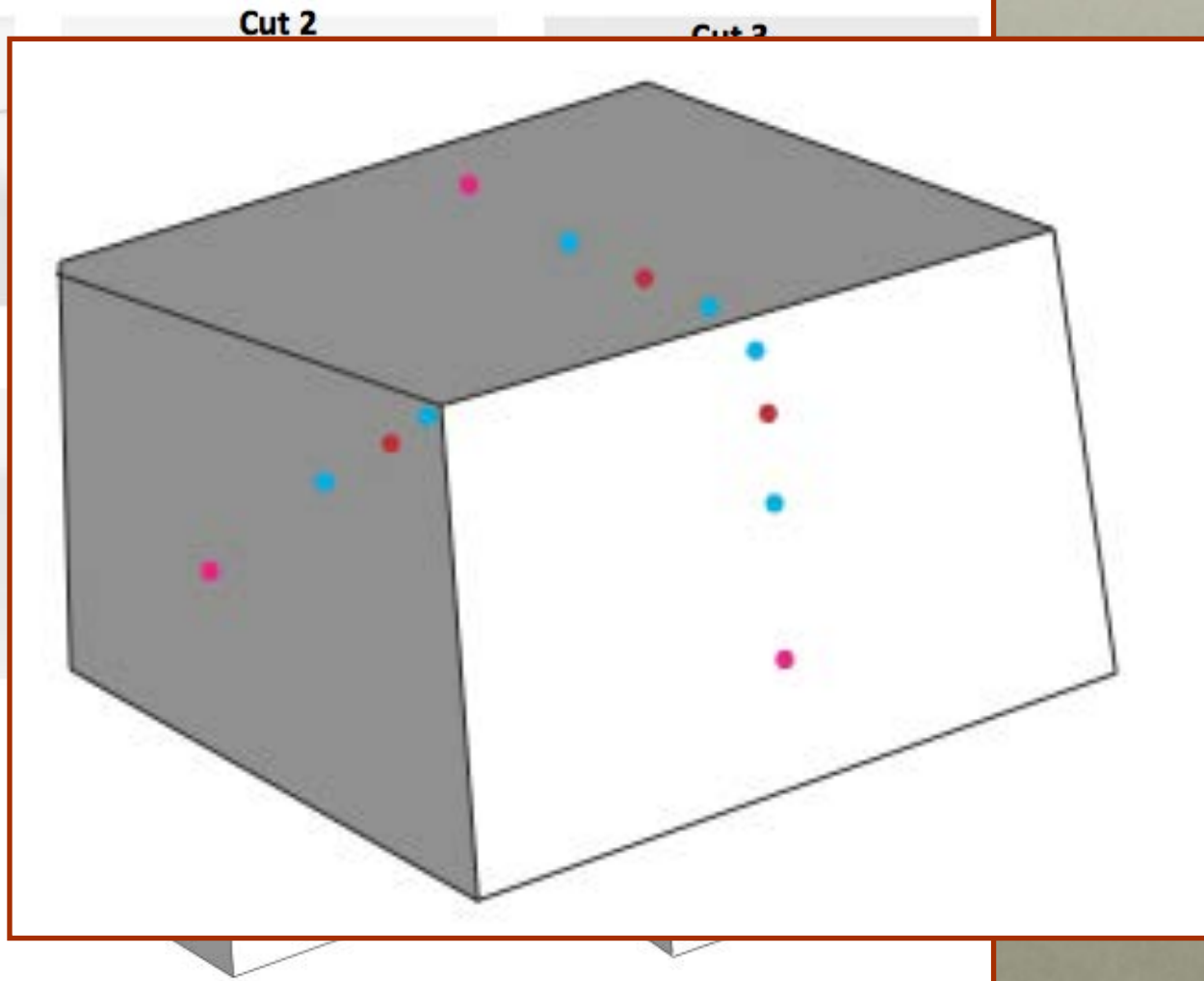
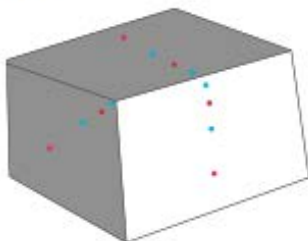
## Visualization Condition



### CROSS-SECTION



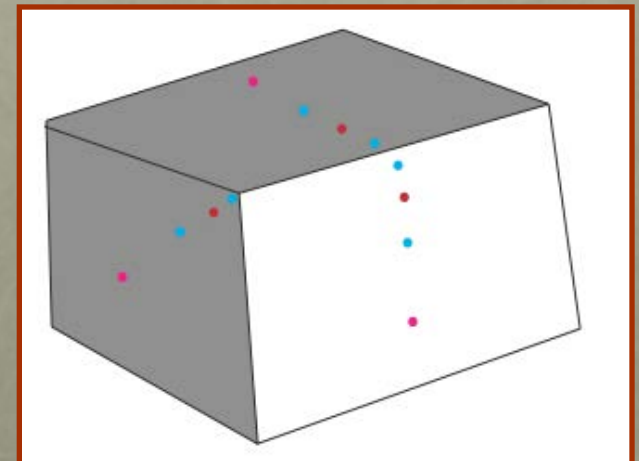
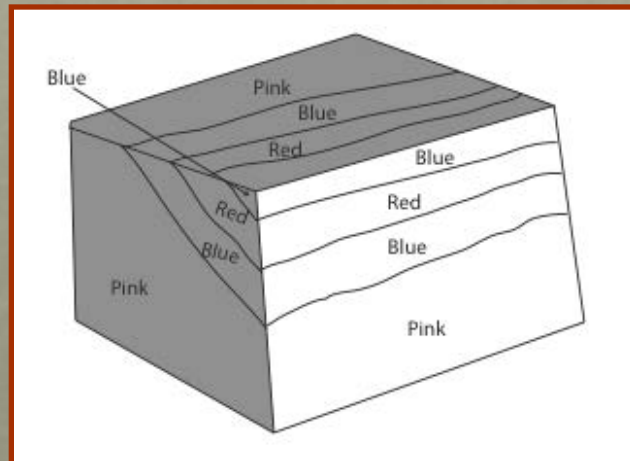
### SKETCH



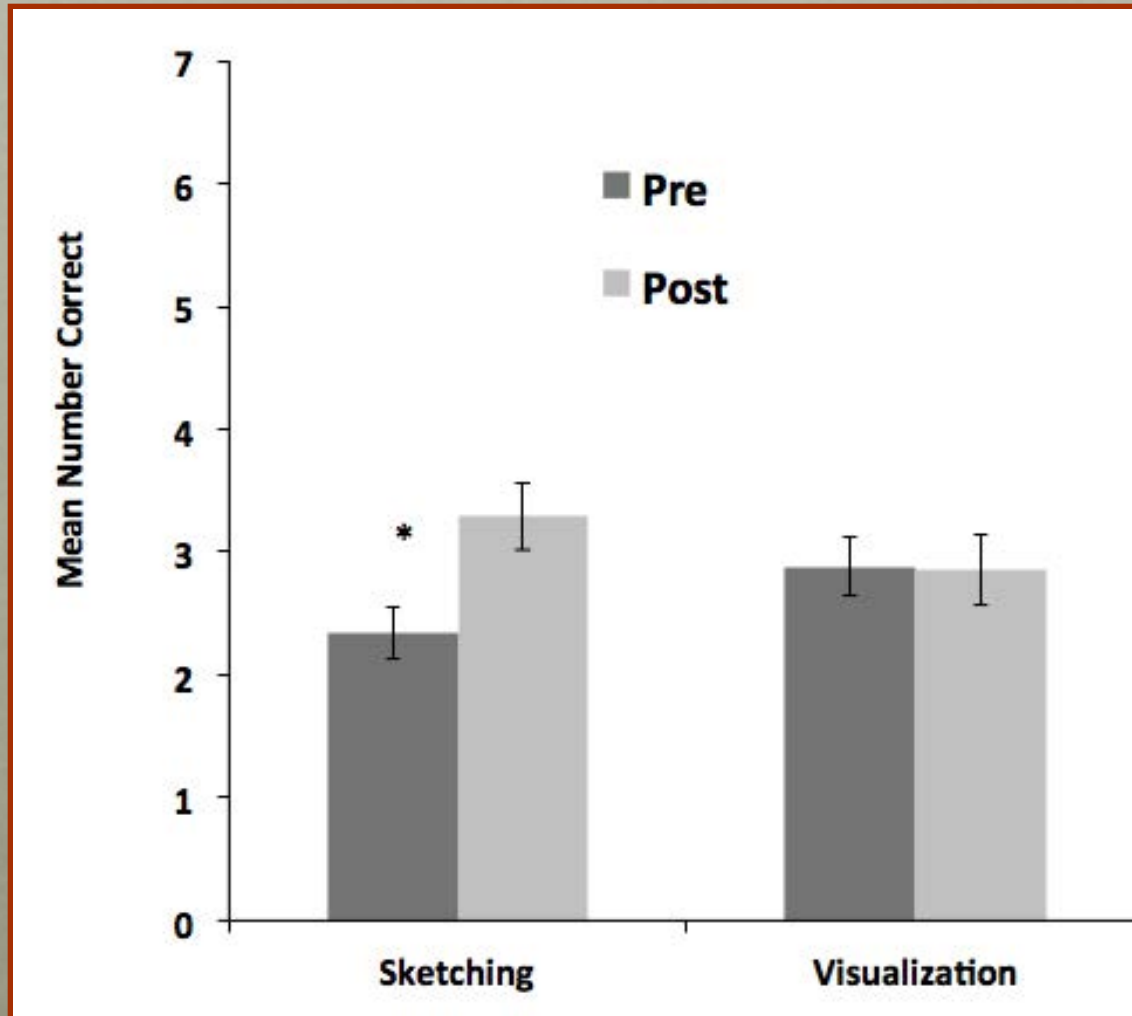
# Improving spatial skills in the geological sciences: sketching from 3D “models”

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



Gagnier, Kristin Michod, Kinnari Atit, Carol J. Ormand, and Thomas F. Shipley. Comprehending Diagrams: Sketching to Support Spatial Reasoning. In preparation.



# 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.

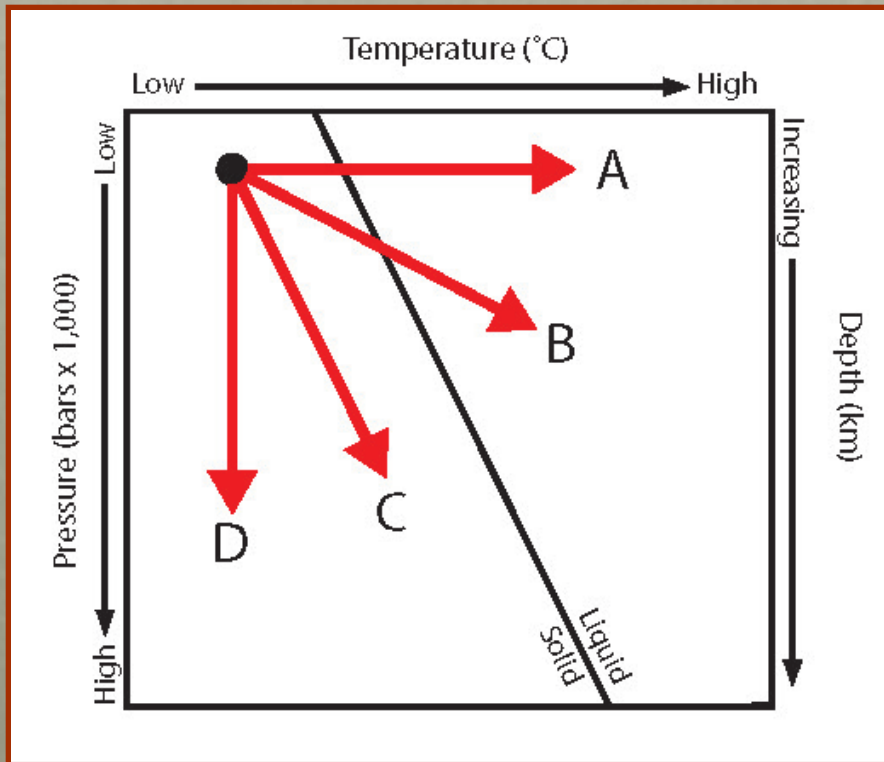
- >250 Intro Geology students (~1/4 CogSketch; 3/4 paper)
- Pre-test: a few spatial skills test items, plus 3 questions about course content covered in each worksheet
- Immediate post-test: 3 questions from the pre-test
- Delayed post-test: spatial test items & new content questions
- Students completing 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”

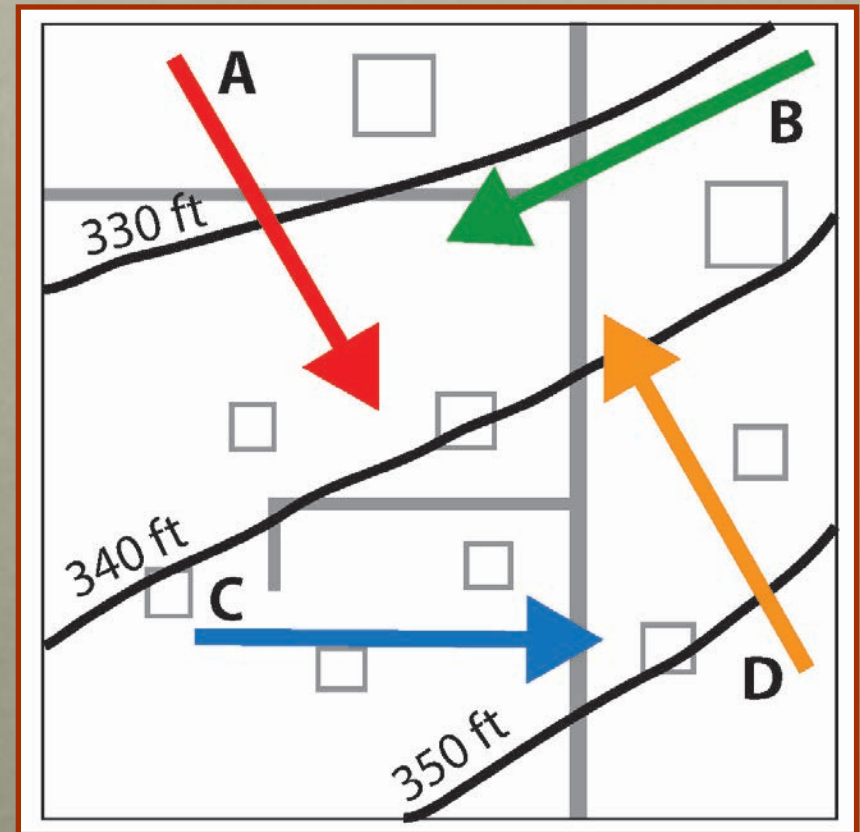
Topics covered in an introductory geology class	Scaling	Disembedding		Dynamic Processes	Penetrative Thinking
Plate Tectonics	Earth's Interior	Magnetic Reversals		Magnetic Field	
Mineralogy		Grain Boundaries			Cleavage Planes
Igneous	Igneous Composition Chart			Pressure/Temperature Diagram	
Sedimentology		Stratigraphic Map & Column		Transgression & Regression	
Metamorphic	Metamorphic Facies Diagram	Metamorphic Outcrop Photos			
Structural Geology + Topo maps		Structural Outcrop	Topo Maps		Strike/ Dip & Block Diagrams
Earthquakes		Stick-Slip Faulting and Earthquakes		Fault Basics	
Geologic Time/Biogeography	Geologic Time Scale	Fossil Succession			
Mass Movement				Slope Stability	
Streams and Floods	Flood Recurrence				
Oceans and Coasts		Ocean Coasts & Waves		Ocean Currents	
Groundwater				Water Table Contours & Contamination	Groundwater Flow
Glaciers & Ice		Glacial Geomorphology		Glacial movement	

# 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”

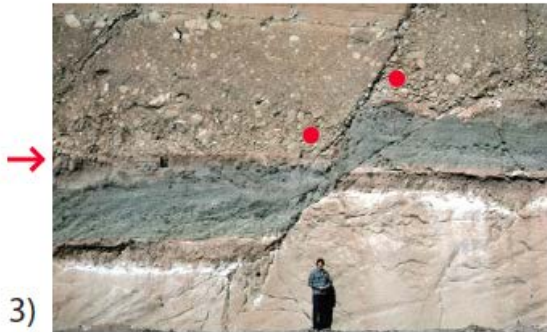
1)



2)



3)



4)



5)



6)





# Improving spatial skills in the geological sciences: “sketching”

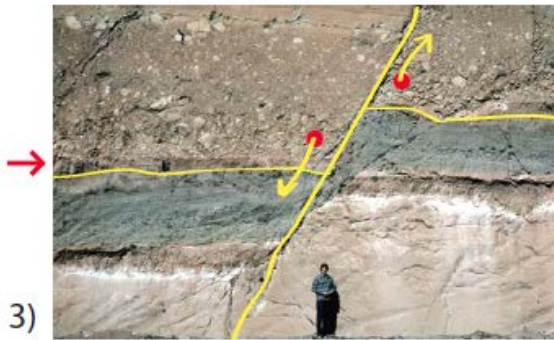
1)



2)



3)



4)



5)



6)



# 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....



# Improving spatial skills in the geological sciences: gesture

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



Photo by Tim Shipley

# Improving spatial skills in the geological sciences: gesture

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”

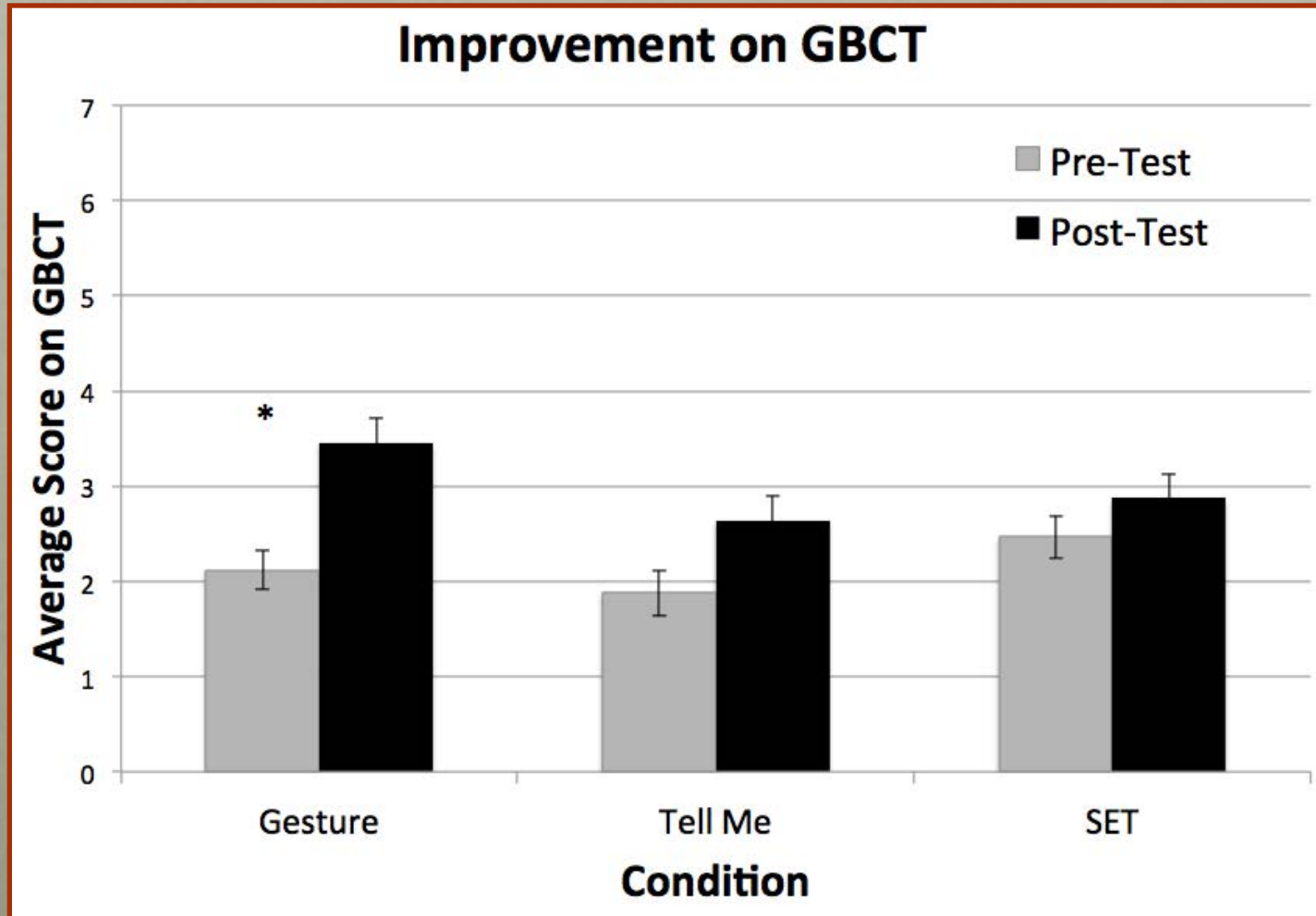
Laboratory experiments explored the effect of *gesturing* vs. *verbally describing* the structures shown in geologic block diagrams on students' ability to visualize interiors.

How many of you think playing “Set” will be the most effective strategy?





# Improving spatial skills in the geological sciences: gesture



Atit, Kinnari, Barbara Dutrow, Carol Ormand, and Thomas F. Shipley (2013). Gesture and Three-Dimensional Visualization: AAPG Hedberg Conference on 3D Structural Geologic Interpretation (Reno, NV).

# 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.

Resnick, I., Shipley, T., Newcombe, N., Massey, C., & Wills, T. (2012). Examining the Representation and Understanding of Large Magnitudes Using the Hierarchical Alignment model of Analogical Reasoning. In N. Miyake, D. Peebles, & R. P. Cooper (Eds.), *Proceedings of the 34th Annual Conference of the Cognitive Science Society* (pp. 917-922). Austin, TX: Cognitive Science Society.

See also Resnick, Ilyse, Hierarchical Alignment of Temporal Magnitude: <http://serc.carleton.edu/NAGTWorkshops/time/workshop2012/essays/resnick.html>.

# 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.

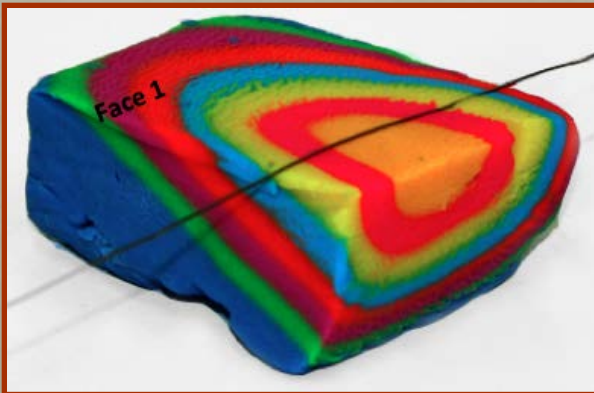
- The “Trail of Time” in the Grand Canyon is built on this premise.
- Implications: It might be a good idea to consider how many orders of magnitude we are asking students to leap over in comparing micro-, meso-, and macro-scale features. Working from familiar scales toward unfamiliar scales is a strong strategy.



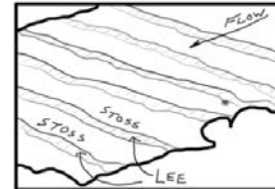


# Improving spatial skills in the geological sciences

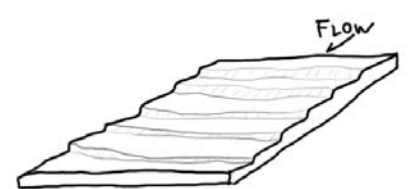
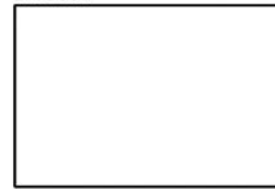
Combinations of strategies/tools may be most effective.  
This will be one area of focus for our near-future work.



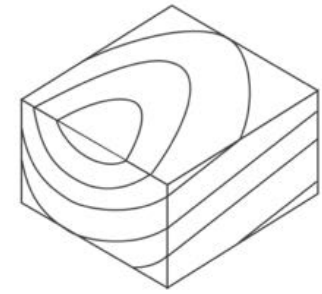
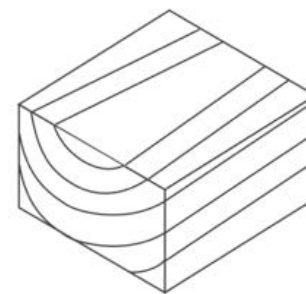
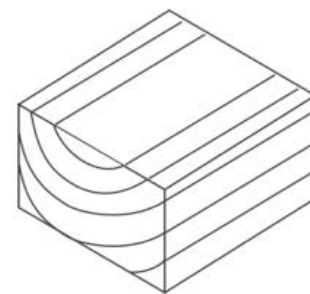
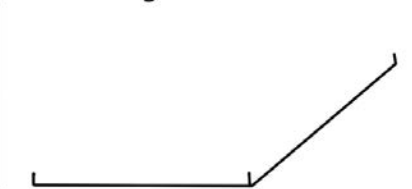
Photo



Sketch



Block Diagram



# 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.

# Key Results

**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.**