Thinking with Internal and External Visualizations: The case of medical education

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“I watched how she swabbed his chest with antiseptic, injected lidocaine, which is a local anesthetic, and then, in full sterile garb, punctured his chest near his clavicle with a fat three-inch needle on a syringe. The patient hadn't even flinched. She told me how to avoid hitting the lung. ("Go in at a steep angle" she'd said. Stay right under the clavicle"), and how to find the subclavian vein, a branch of the vena cava lying atop the lung near its apex.”

(Gawande, 2002) The New Yorker
Spatial Cognition & Medicine

- Anatomy: 3-D Mental models of
  - Shape of anatomical structures
  - Where located
  - How connected
- Medical images: 2-d representations of 3-d structures
- Surgery: Interacting with these complex 3-d structures
Individual Differences in Spatial Ability
“Internal Visualization”

Paper Folding

Mental Rotation

Visualization Of Views
Two Ways of Thinking about Individual Differences

**Ability model:** People have different amounts of spatial ability. There is nothing we can do about that.

- Therefore we should **select** high-spatial people for medical specialties

**Skill model:** Spatial skills can be developed with practice

- Therefore we should find the best ways of **training** professionals
Dentistry: Ability Model

33

1
2
3
4

(A.) 3 - 1 - 4 - 2
(B.) 1 - 3 - 4 - 2
(C.) 1 - 3 - 2 - 4
(D.) 3 - 2 - 1 - 4

52

A
B
C
D
E

87.

A
B
C
D
Surgeons, as a group, adhere to a curious egalitarianism. They believe in practice, not talent. To be sure, talent helps. Nonetheless, attending surgeons say that what's most important to them is finding people who are conscientious, industrious, and boneheaded enough to keep practicing this one difficult thing day and night for years on end.

(Gawande, 2002)
The VIZMED Research Project

- Relations between spatial abilities and spatial skills in medicine?
- Can skills be trained with interactive “visualizations” and virtual reality?
- Are interactive visualizations equally effective for individuals with high and low spatial abilities?
- Can interactive visualizations be redesigned to alleviate problems of low-spatial individuals.
Interactions Between Internal and External Visualizations: 3 Possibilities

• Visualizations may augment cognition equally for high- and low- ability individuals

• Visualizations and simulations may compensate in some way for low spatial ability.

• Using visualizations and simulations effectively may depend on spatial ability.
Specific Topics Studied

(1) Manipulation of an angled laparoscope in minimally invasive surgery
(2) Imagining cross sections of 3-D anatomy-like structures.
(3) Learning Anatomy
Minimally Invasive Surgery
Why is minimally invasive surgery spatially demanding?

- Physical constraints:
  - Fulcrum caused by cannula insertion at abdominal wall
Why is minimally invasive surgery spatially demanding?

- Perceptual constraints:
  - 2D image on monitor represents 3D space
  - Discrepancy between camera angle and orientation of surgeon
  - Limited Range of Motion
  - Lack of haptic cues
  - Poor quality image
  - Angled lens
Spatial Ability and Surgery
(Correlations)

• Open Surgery
  – Spatial relations test (Murdoch, 1994)
  – Embedded figures test (Gibbons, 1983; 1986; Steele, 1992)
  – Visuospatial organization factor (Scheuneman, 1984)

• Minimally Invasive Surgery
  – Mental rotation, form completion, touching blocks tests (Risucci, 2001; Wanzel, 2003)
  – Card rotations, paper folding, perspective-taking tests (Eyal, 2001)
The Pre-Screening Debate

• Hinges on whether the relationship between ability and surgical skill is:
  
  – Transient (important only in the early stages)
  – Enduring (continues to affect performance even after experience is acquired)
Stages in Skill Acquisition

Cognitive Stage - Controlled processing
- High degree of cognitive involvement
- Heavy demands on attentional resources
- Performance depends on cognitive ability (Ackerman)

Associative Stage – Development of Procedural Knowledge

Autonomous stage- Automaticity
- Little cognitive involvement
- Proceduralized behavior
- Less dependent on cognitive ability
Preliminary Study
(Keehner et al, 2004, Am. J. Surgery)

• Do surgeons self-select for spatial ability?
• Does the correlation between spatial ability and operative skills change with experience?
Participants

Low Experience

• 45 surgeons in an introductory lap. urology course
• Mean = 13 (0-105) procedures
• Paper Folding Test Mean = 10.45, SD = 3.49

High Experience

• 48 surgeons in an advanced videoscopic surgery course
• Mean = 302 (63-1,020 procedures)
• Paper Folding Test Mean = 9.83, SD = 3.98
Results

• Surgeons are not self selected for spatial ability!
  – (at or below average levels of college students on the spatial test).

• Operative skill related to spatial ability for low experience group \( (r = .39, p < .01) \)

• Operative skill **not** related to spatial ability for high experience group.
Laboratory Study
Applied Cognitive Psychology

• Observe the changing correlations between spatial abilities and performance under controlled conditions
• Examine the separate roles of spatial abilities and more general cognitive abilities (i.e., general intelligence)
Method

- Task: maneuvering a simulated angled laparoscope (45°)
- Desktop virtual environment
- N = 22 (graduate and undergraduate students)
- 12 learning sessions over 3 wks
- Time to target = seconds taken to look inside each box
Psychometric tests

• Spatial abilities:
  – Visualization of views
  – Mental rotation
    • Scores were aggregated

• General ability:
  – Non-verbal reasoning test
Results: Learning curves

• Practice attenuated initial variability
  – SD reduced by 89%
  – Initial mean = 33.3s
  – Final mean = 4.9s

• All learners achieved proficiency

• Learning transferred to a novel set of trials
High and low ability groups

- General ability most important early on
- Spatial ability important throughout learning
General vs. Spatial Abilities

- General and spatial measures overlap
- Regression analysis: calculated *spatial residual* (spatial ability controlled for general ability)

<table>
<thead>
<tr>
<th></th>
<th>Abstract reasoning</th>
<th>Mental Rotation</th>
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</thead>
<tbody>
<tr>
<td>Mental rotation</td>
<td>.56*</td>
<td></td>
</tr>
<tr>
<td>Visualization of views</td>
<td>.45*</td>
<td>.70*(.60**)</td>
</tr>
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![Venn diagram showing overlap between General and Spatial abilities](image-url)
Changing correlations

- Initial vs. final performance
  - Correlation with general ability diminished
  - Correlation with spatial residual showed opposite trend

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<thead>
<tr>
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<th>Initial (trials 1,2,3)</th>
<th>Final (trials 10,11,12)</th>
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<tbody>
<tr>
<td>General reasoning ability</td>
<td>$r = -.46$ ($p = .03$)</td>
<td>$r = -.16$ ($p = .48$)</td>
</tr>
<tr>
<td>Spatial ability</td>
<td>$r = -.46$ ($p = .03$)</td>
<td>$r = -.42$ ($p = .05$)</td>
</tr>
<tr>
<td>Spatial-residual (spatial ability controlled for general reasoning)</td>
<td>$r = -.19$ ($p = .18$)</td>
<td>$r = -.43$ ($p = .04$)</td>
</tr>
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Conclusions

- Early correlation with spatial ability appears due to shared variance with general ability
  - Strategic, executive processes (explicit) more important at the beginning of learning a new skill

- Important to distinguish between domain-general and domain-specific cognitive functions
  - “Pure” spatial ability more important once consistent strategy is developed
  - Previous research: spatial or general ability?
Implications for Selection and Training

• This skill can be learned in a virtual environment
  – Laparoscopic Fellows’ data confirms validity
• Spatial ability contributed to performance even after skill was acquired
• Importance of (1) longitudinal studies, (2) separating spatial and general abilities
• Of course, this is only one aspect of laparoscopic performance
Comprehension of 3D Anatomical Structures
Importance of Cross Sections

- Learning anatomy (textbooks are full of them!)
  - Drawing cross section as a measure of 3-D mental model
- Interpreting and using imaging techniques (x-ray, ultrasound, MRI)
Questions

• How well can people infer cross sections?
• How might they use interactive 3-D visualizations to help them do this?
• Related to spatial ability?
Cross Section Task

Pictured above is the same egg-shaped object pictured in the animations. Imagine that you are looking at the object from the perspective of the arrow.

Now imagine cutting a slice of object at the green line.

In the space above, use a pencil to draw the cross-section you will see if you slice the egg-shaped object on the left at the green line. The size of the drawing should be proportional to the size of the object.

You can view the animations at any time.
Interactive Visualization

- Interactive Animations:
  - rotate in depth, horizontal or vertical axis,
  - controlled by slider bar
- Cross sections: horizontal or vertical
Task Analysis

- encode object
- assume arrow perspective by
- mental perspective taking
- imagine part of object cut away
- imagine resulting cross section
- draw cross section
- mental rotation
- rotating external visualization
Study 1: Correlational

- Task: Draw Cross Sections
- Use of External Visualization
  - Horizontal or vertical direction
- Spatial Ability
  - Mental Rotation test
  - Visualization of Views test

(Cohen & Hegarty, 2007, Applied Cognitive Psychology)
Slice 10

Low spatial

High spatial
Coding of Drawings

Number of ducts:
Outside shape:
Spatial relations between the ducts:
Spatial relation between duct and outside shape:
Interactive vs. Non-Interactive Animations

Keehner, Hegarty, Cohen, Khooshabeh & Montello (2008)
Cognitive Science, 37, 1099-1132

**Interactive** group (N=30)
Allowed to rotate and pause the visualization at will during the task
- Motion-based depth cues
- Can access arrow view at will

**Non-interactive** group (N=30)
Presented with a continuous looping rotation during the task
- Motion-based depth cues
Interactive Group Better

Correlation with spatial ability

Interactive
$r = 0.46$  $p < 0.05$

Non-interactive
$r = 0.52$  $p < 0.01$
Interpretation

• Interactivity helped performance
• What helped?
  – Control *per se* OR what they got to see?
• Interactive and non-interactive subjects received different visual information
• Need to match the visual input
Yoked-Design Study

• N = 60
• “Yoked” pairs of participants randomly allocated to
  – Active condition
  – Passive condition
• Active participants controlled computer model via 3 degree of freedom tracker
• Movements were recorded
• Later played back to a passive participant
  – Visual information identical
Results

No advantage of active control

Active control $r = .34$, $p = .06$

Passive viewing $r = .35$, $p = .05$
• No benefit from active control
  – Finding was replicated
• Maybe the key variable is not interactivity \textit{per se}, but what the viewer sees
• Active control allows the viewer to select relevant view for solving the problem
Access of Arrow View

Proportion of trials where Arrow View was accessed

Std. Dev = .32
Mean = .40
N = 30.00
Access to Arrow View affects Performance

Spatial ability and access to arrow view make independent contributions to predictions of performance.

Predictive in both active and passive conditions.
Arrow Views vs. Interactive Control

• Condition 1: Interactive (intertia cube interface)
• Condition 2: Passive Viewing
  – Starts at page view
  – Rotates to arrow view
  – Jitters at arrow view
Arrow Views group somewhat better than Interactive group
Access of Arrow View

Proportion of trials where arrow view was accessed

Std. Dev = .30
Mean = .42
N = 29.00
Difference due to Low Access Group

![Bar chart showing comparison between Low access interactive, High access interactive, and Arrow views with error bars.](image-url)
Summary (Cross-Section Task)

• Highly correlated with spatial ability
• Assisted by an interactive animation, however
  • Not all individuals access the most informative view
  • Performance related to access of the most informative view
  • Access of arrow view not correlated with spatial ability
Why do Some People not Access the Arrow View?

• They are unable to do so:
  – Don’t develop metacognitive understanding of how it can help them
  – Get disoriented when they start moving the visualization
  – Can’t use the information that they get from it

• Choose internal over external
  – External: compute angle of rotation, maintain orientation etc.
  – Perceived effort of using external vs. internal. External may not always win!
Generalization to a Real Anatomical Object

Correlation with Spatial Ability

- Generalizes to a real anatomical object
- Found in dental students (even advanced)
- Drawing vs. multiple choice
- Remains after controlling for general intelligence

Hegarty, Keehner, Khooshabeh & Montello (in press). Learning and Individual Differences
Khooshabeh & Hegarty (submitted)
Anatomy Learning
Struggling with External Visualization

It’s very difficult for me to see…the computer…
I still have a very hard time knowing how far I’ve gone

I’m sure this could be helpful, but…
I don’t know, it isn’t…I can’t connect with it.

So. I’m turning it upside down
which may or may not be a good strategy,
but it feels like it gives me something to do,
to look at it from another way.

The computer, when it turns I have no
…I feel like I have lost my bearings when I go with it,
but with the book at least I have some,
I have some grounding.
Current Project
(with Andy Stull, Rich Mayer)

• Use of interactive visualizations to teach true 3-D representations of anatomy
• Augmenting these visualizations to mitigate disorientation

Task: Learning Anatomy of a vertebra
Learning Process

• Introduced to parts of the anatomy with a “canonical view” diagram

• Practice rotating a 3-D model of anatomy to different orientations and identifying structures

• Tested on ability to recognize anatomical structures from different perspectives
Anatomy Test

Circle the *inferior articular process* on the picture

or check

_____ Not Visible

or

_____ Don't Know
Manipulate whether learners are shown diagrams with “Orientation References” during rotation phase

Overt view-point references vs. NO view-point references
Results

Rotate and Match Task

Angular Error  RT  Directness

(Lower = better)
Anatomy Test

ORs helped Low Spatialss!

75% Accuracy Overall

(Lower = better)
General Conclusions
Applications for Selection

• Performance in a variety of medical tasks is correlated with spatial ability

• Applications for **selection**
  – Low spatials can acquire skills.
  – With training effects of spatial ability are attenuated,
  – But still there!
  – May be important under time constraints, novel situations
Applications for Training

• Promising role for new technologies
• Simulations can be an effective means of training, minimizing risk to patients
• External visualizations can augment internal visualization
• However individual differences in use of visualizations & simulations too
• Importance of metacognitive skills, design of external visualizations
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