TEMPLE UNIVERSITY'S

SPATIAL INTELLIGENCE AND LEARNING CENTER

SILC

AN NSF SCIENCE OF LEARNING CENTER

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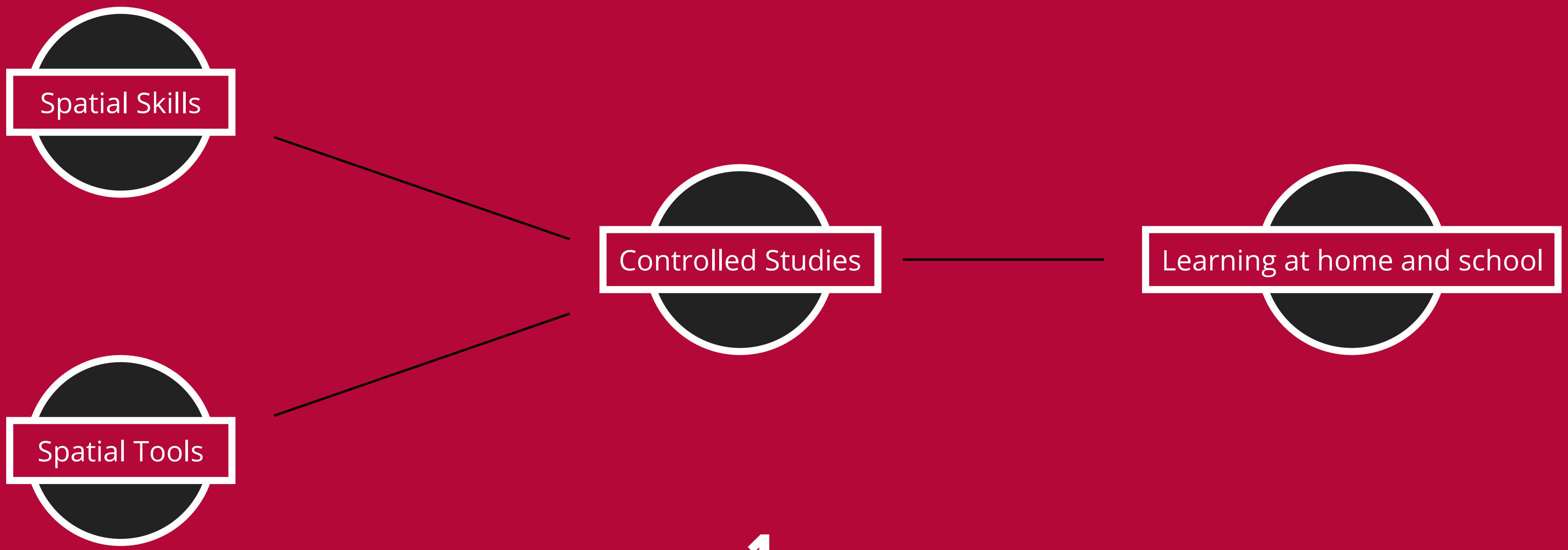
INTRODUCTION

The early connections between spatial thinking and STEM learning were mainly anecdotal-- Francis Crick and James Watson envisioned the three-dimensional structure of DNA with the help of Rosalind Franklin's flat x-ray diffraction images, or John Snow looked at the spatial distribution of cholera outbreaks on a map to identify contaminated water supply as the cause of London's 1953 cholera epidemic.

A decade of NSF funding of SILC and other researchers now supports the conclusion that spatial thinking and STEM learning relate to each other both cross-sectionally and longitudinally. In addition, spatial thinking is malleable.

SILC engaged a broad range of experts to probe the processes and mechanisms that underlie spatial learning and the factors that influence spatial learning. These experts included researchers in gesture, analogy, spatial language, sketching and effective use of diagrams and graphs, and embodied cognition (physical activity that instantiates scientific or mathematical principles).

FOUR INITIATIVES



1
Characterize spatial skills relevant to STEM and chart their development

2
Understand tools for spatial learning

3
Controlled studies of spatial learning

4
Educate using spatial learning at home and at school

FIVE CROSSCUTTING THEMES

1. Although space itself is continuous, human representations of space are often qualitative, organized into distinct categories; these qualitative spatial representations are crucial to STEM education.

2. Spatial skills vary by whether representations and processes apply to the intrinsic properties of objects or the extrinsic relations between objects (and/or external reference systems), and by whether these properties are statically represented or dynamically transformed.

3. Learning and using spatial language, diagrams and maps is a major route by which we form articulated representations of space, including the qualitative distinctions needed for STEM learning.

4. Spatial analogies can reveal common spatial patterns that apply across spatial situations, and can highlight specific differences between them. Analogical processes are also instrumental in applying spatial representations to nonspatial domains, as in the use of a spatial diagram to capture causal information.

5. Human representations of objects and actions are often grounded in sensorimotor interactions with the world. These embodied representations remain potent even among STEM experts.

SIX TOOLS FOR SPATIAL LEARNING

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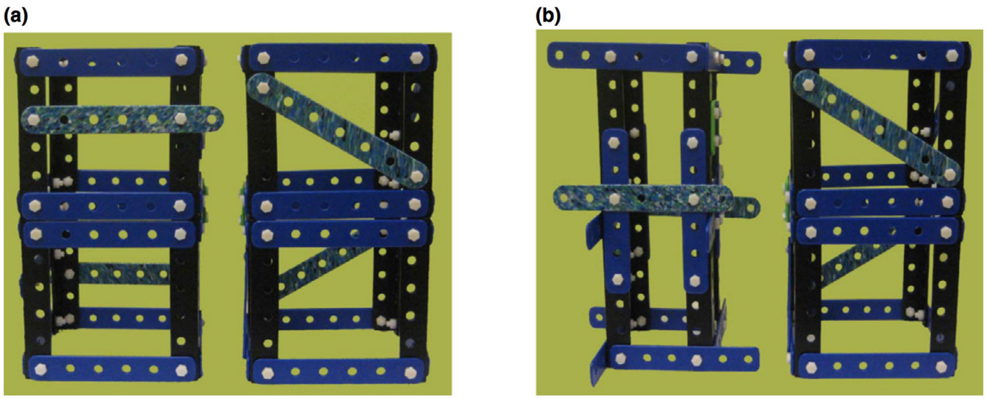
ANALOGICAL REASONING

Analogical comparison and mapping is a powerful domain-general learning mechanism for causal and conceptual learning. The alignment of two structures can facilitate learning. For example, providing children with two model buildings that can be spatially aligned makes it more likely that the children will discover how important a diagonal brace is in creating a stable structure. Analogical processing is also crucial in mapping from spatial structure to other domains, as in graphs and diagrams

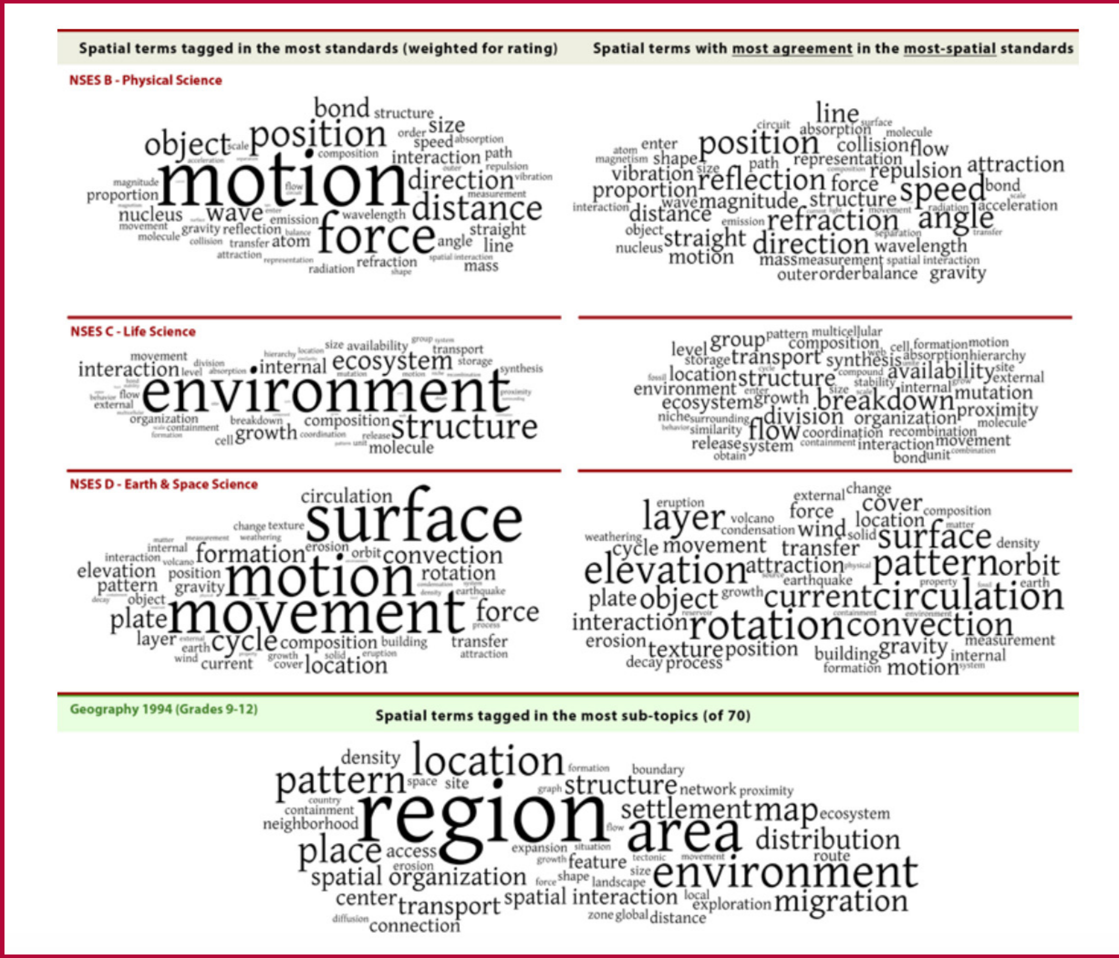
A child places a diagonal brace to stabilize a non-sturdy building during the repair task.



SIX TOOLS FOR SPATIAL LEARNING

LANGUAGE

All languages contain words that convey spatial relations (e.g., in, on, under, through). These words impose categories on what are, in fact, continuous dimensions. Learning and using these words is likely to affect how spatial relations categorized and thus has the potential to facilitate (or hinder) spatial thinking. Second, syntax organizes words into frames. If we say the cat is on the mat, we focus attention on the cat, in relation to the ground, mat. If we say the mat is under the cat, we focus attention on the mat as figure, and situates it in relation to the cat as ground. Thus, language organizes space in a particular way, which could serve as a tool for spatial thinking.

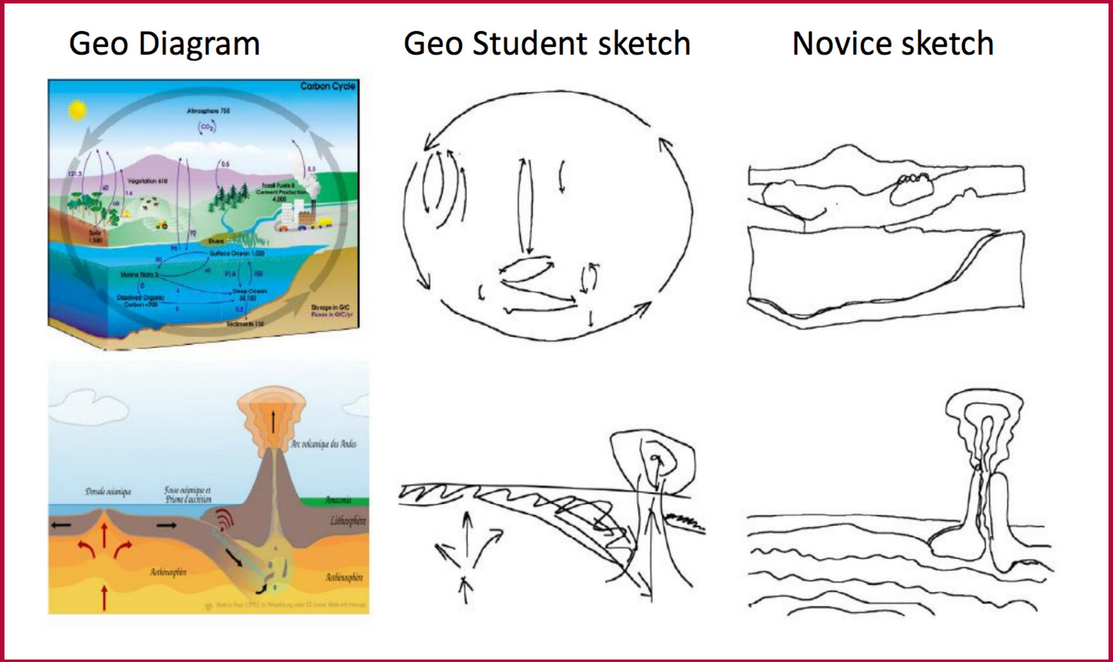


GESTURE

Gesture is inherently spatial – we gesture in space. Gesture can capture the imagistic and continuous aspects of space that are often lost when a spatial situation is described in language (e.g., saying turn right indicates the direction the listener should take but does not convey whether the turn is a hard or soft right, information that can easily be conveyed in gesture). Gesture can thus add continuous information to the categorical information in language. Moreover, when learners are encouraged to gesture while explaining their solutions to a math problem, they are subsequently more likely to profit from a lesson in how to solve the problem.

SKETCHING

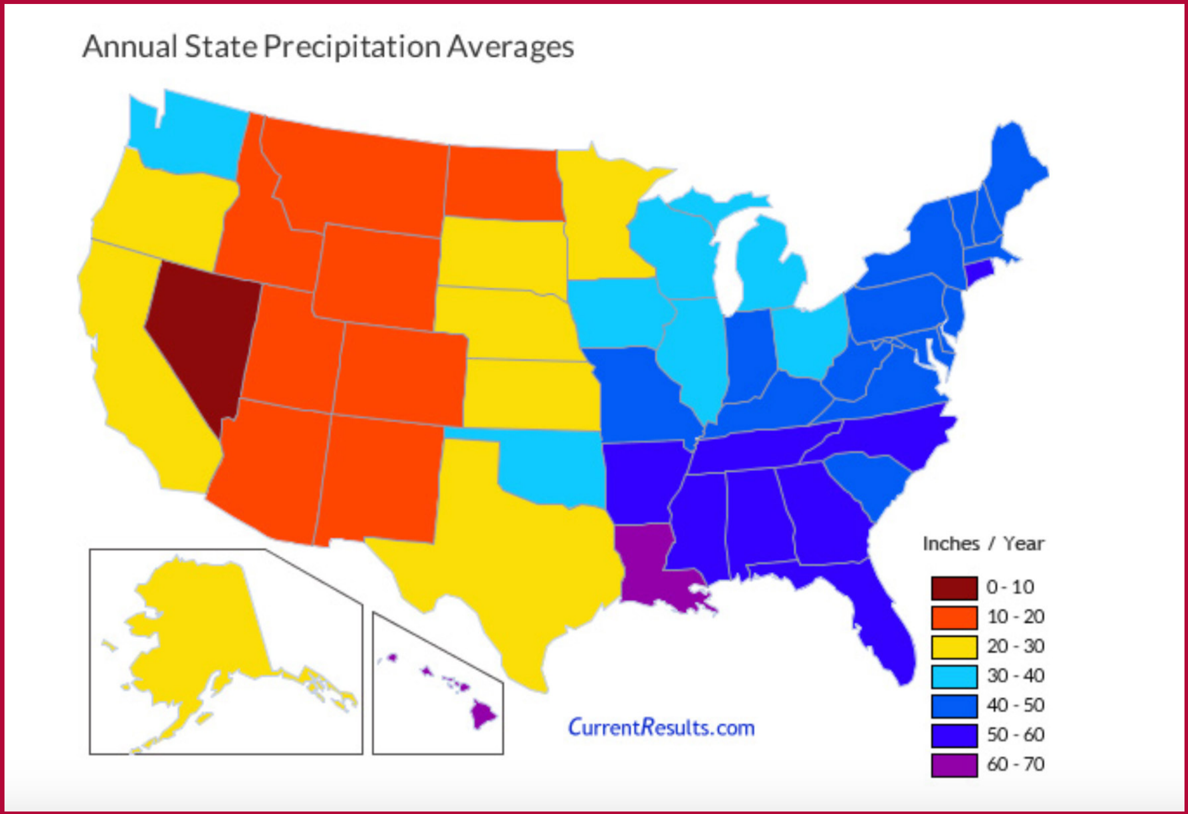
Sketching is also inherently spatial, and, like gesture, can easily capture continuous information. Sketching, however, leaves a permanent trace, allowing students and t eachers to externalize and communicate ideas naturally within an intrinsically spatial format. Indeed, teachers in STEM disciplines often use sketches in instruction, and state that students' sketches are deeply revealing of their degree of understanding. Yet scoring sketches is extremely time-consuming for instructors, and the time course of drawing is lost when people use pencil and paper to sketch. Consequently, we created CogSketch, which can serve both as a cognitive science research instrument and to support STEM education.



SIX TOOLS FOR SPATIAL LEARNING

MAPS

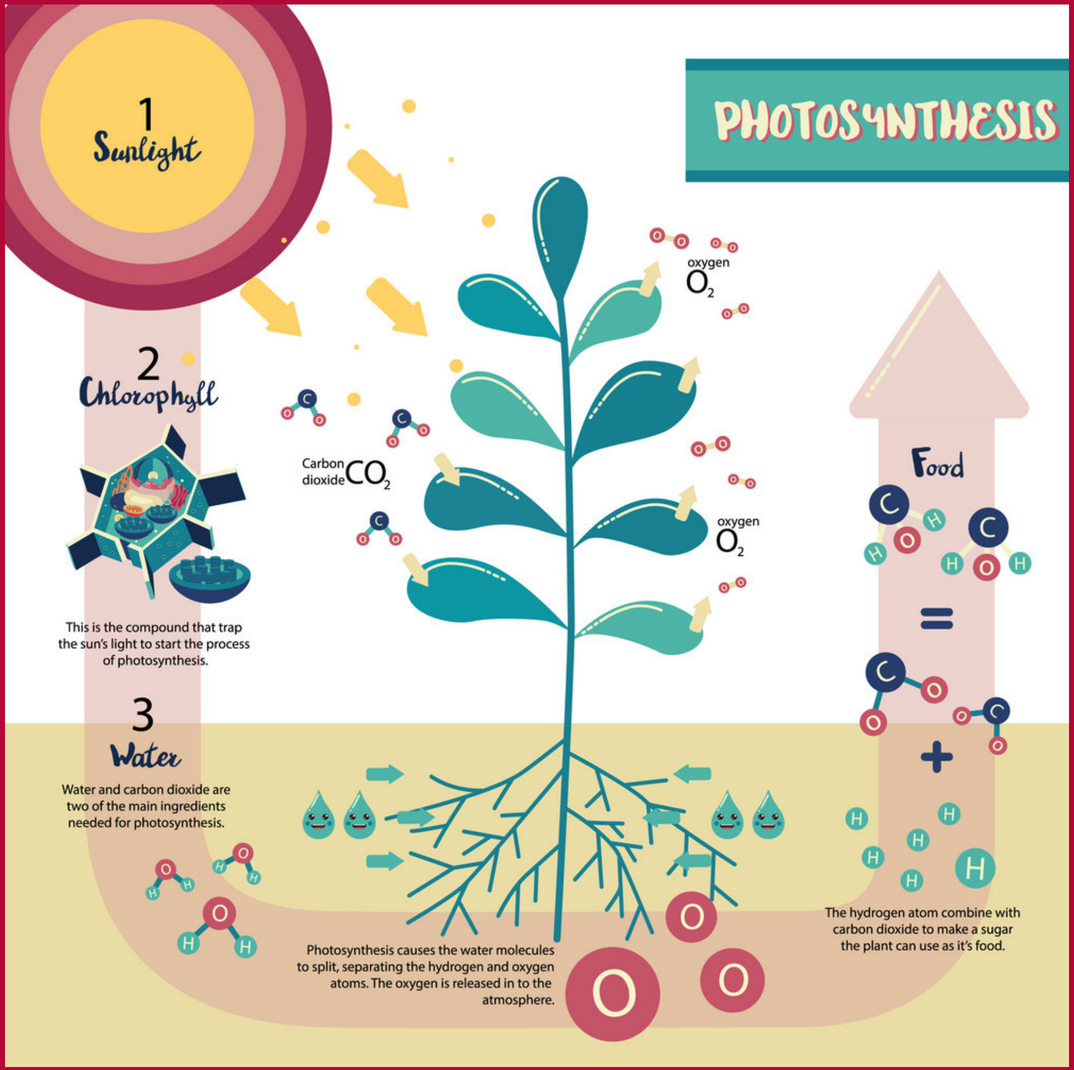
These symbolizations are also inherently spatial. However, as with language, maps also have systematized conventions that, once understood, can facilitate learning. Maps highlight spatial relations that can be difficult or even impossible to perceive from direct experience. For example, by looking at a map, one can easily see the relative spatial position of several cities across the United States. The unique perspective and scale of maps make spatial relations that are not directly perceptible cognitively tractable. Maps can also convey non-spatial information as a function of locations in space (e.g., precipitation as a function of location).



SIX TOOLS FOR SPATIAL LEARNING

DIAGRAMS

Diagrams are conventionalized and well-rendered sketches, made with the reader in mind. They allow us to display any type of information in a spatial format. Understanding the spatial conventions needed to interpret diagrams is essential to becoming proficient in the STEM disciplines.



FOUR INITIATIVES

INITIATIVE 1:
CHARACTERIZE SPATIAL SKILLS RELEVANT TO STEM AND CHART THEIR DEVELOPMENT.

The focus of Initiative 1 was on spatial skills. We aimed to measure them, and understand how they develop, why individuals vary and how to help people improve. We concentrated on three areas:

- Examining spatial skills in young children,
- Devising an objective assessment of navigation skills in adults,
- Assessing the performance of students and experts in geoscience (a field with high spatial demands).

SAMPLE PUBLICATIONS

Atit, K., Shipley, T. F., & Tikoff, B. (2013). Twisting space: are rigid and non-rigid mental transformations separate spatial skills?. *Cognitive Processing,* 14(2), 163-173.

Frick, A. & Newcombe, N. (2012). Getting the big picture: Development of spatial scaling abilities. *Cognitive Development*, 27, 270-282.

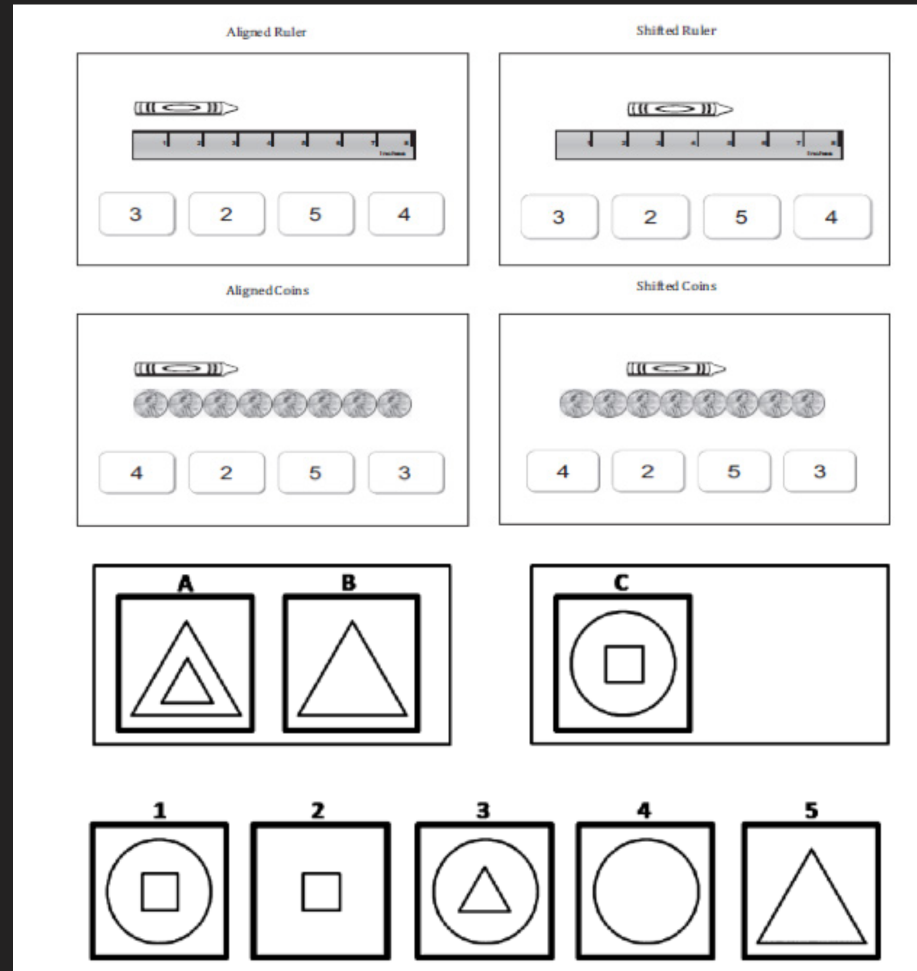
Resnick, I., & Shipley, T. F. (2013). Breaking new ground in the mind: an initial study of mental brittle transformation and mental rigid rotation in science experts. *Cognitive Processing*, 14(2), 143-152.

Weisberg, S.M., Schinazi, V.R., Newcombe, N.S., Shipley, T.F., & Epstein, R.A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 40(3), 669-682.

Verdine, B.N., Golinkoff, R.M., Hirsh-Pasek, K. & Newcombe, N.S. (2017).Links between spatial and mathematical skills across the preschool years. *Monographs of the Society for Research in ChildDevelopment*, 82, 1, Serial Number 124.

INITIATIVE 2:

UNDERSTAND TOOLS FOR SPATIAL LEARNING.



The goal of Initiative 2 was to learn more about several cognitive tools that teachers and students can apply to spatial problems.

SAMPLE PUBLICATIONS

Lovett, A., Tomai, E., Forbus, K. & Usher, J. (2009). Solving geometric analogy problems through two-stage analogical mapping. *Cognitive Science*, 33(7) 1192-1231.

Ping, R., Beilock, S. L., & Goldin-Meadow, S. (2014). Understanding gesture: Is the listener's motor system involved? *Journal of Experimental Psychology: General*, 143(1), 195-204.

Quandt, L. C., & Chatterjee, A. (2015). Rethinking actions: Implementation and association. *Wiley Interdisciplinary Reviews*: *Cognitive Science*, 6(6), 483-490.

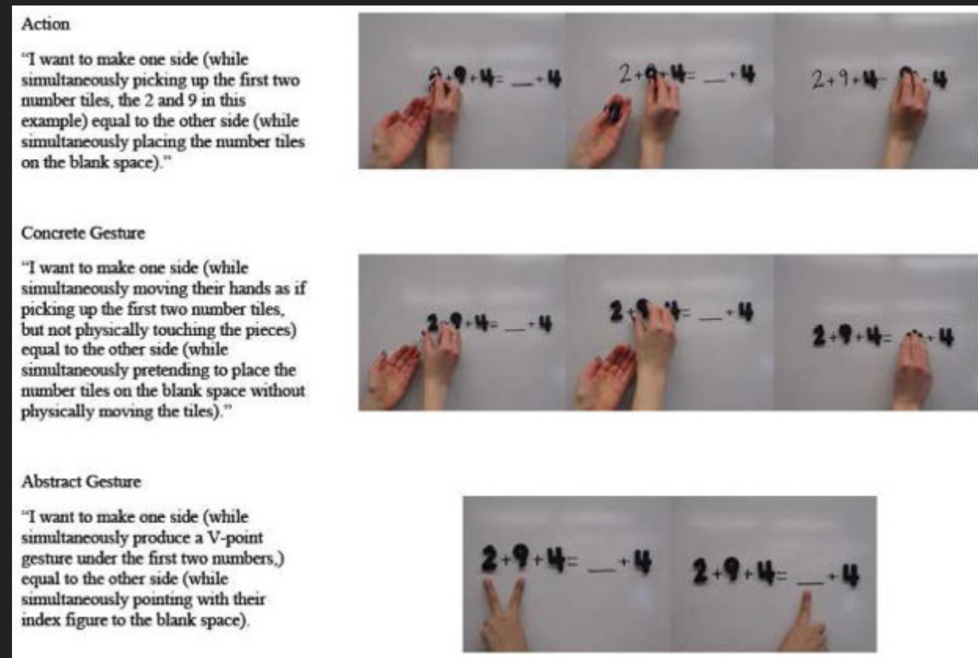
Solomon, T., Vasilyeva, M., Huttenlocher, J., & Levine, S.C. (2015). Minding the gap: Children's difficulty conceptualizing spatial intervals as linear units of measurement. *Developmental Psychology*, 51(11), 1564-1573.

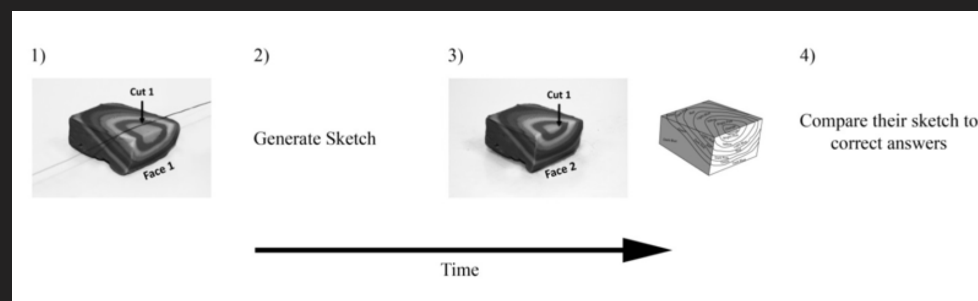
Yuan, L., Uttal, D., & Gentner, D. (2017). Analogical processes in children's understanding of spatial representations. *Developmental Psychology*, 1098-1114.

INITIATIVE 3:

IMPROVE SPATIAL SKILLS, SPATIAL LEARNING AND STEM EDUCATION.

The goal of Initiative 3 was to examine how to improve spatial skills and how to use spatial tools. We conducted controlled studies of malleability in STEM learning and in STEM-related skills.





SAMPLE PUBLICATIONS

Fisher, K.R., Hirsh-Pasek, K., Newcombe, N.S. & Golinkoff, R.M. (2013). Taking shape: Supporting preschoolers' acquisition of geometric knowledge through guided play. *Child Development*, 84, 1872-1878.

Gagnier, K. M., Atit, K., Ormand, C. J., & Shipley, T. F. (2016). Comprehending 3D diagrams: Sketching to support spatial reasoning. *Topics in Cognitive Science*, 1-19.

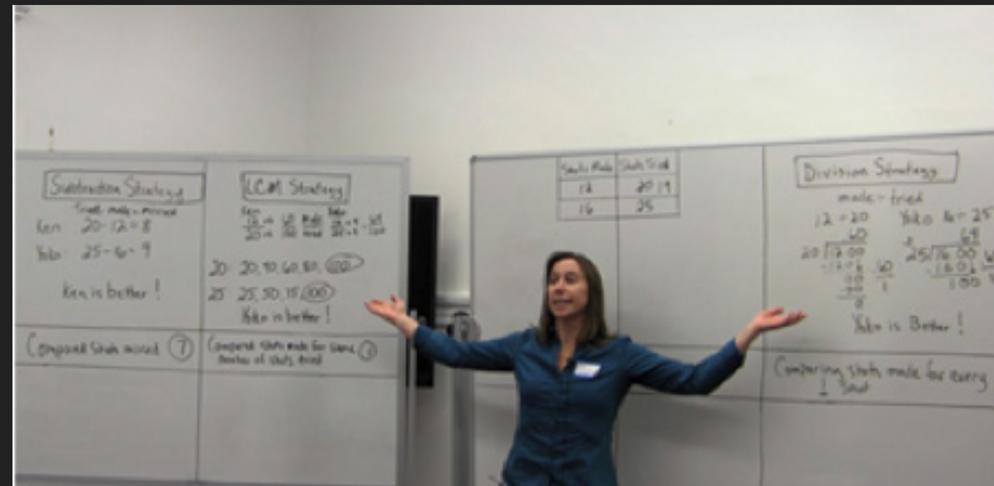
Gibson, D.J., Congdon, E.L. & Levine, S.C. (2015). The effects of word-learning biases on children's concept of angle. *Child Development*, 86(1), 319-326.

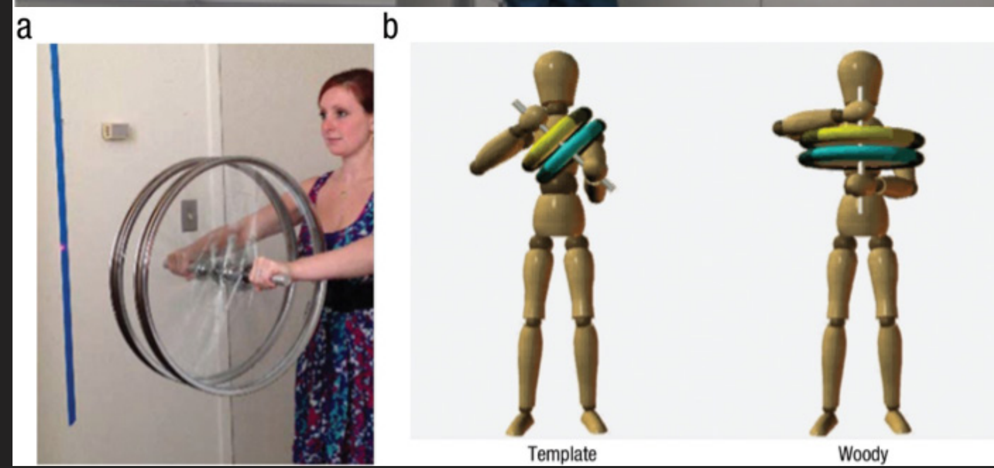
Goldwater, M.B., & Gentner, D. (2015). On the acquisition of abstract knowledge: Structural alignment and explication in learning causal system categories. *Cognition*, 137, 137-153.

Novack, M. A., Congdon, E., Hemani-Lopez, N., & Goldin-Meadow, S. (2014). From action to abstraction: Using the hands to learn math. *Psychological Science*, 25(4), 903-910.

INITIATIVE 4:

EDUCATE USING SPATIAL LEARNING AT HOME AND AT SCHOOL





The aim of Initiative 4 was to take what we learned and use it in real-world learning settings such as the home, museums, and the classroom. We also sought to identify phenomena needing more focused study in controlled laboratory settings.

SAMPLE PUBLICATIONS

Congdon, E. L., Novack, M. A., Brooks, N., Hemani-Lopez, N., O'Keefe, L., & Goldin-Meadow, S. (2017). Better together: Simultaneous presentation of speech and gesture in math instruction supports generalization and retention. *Learning and Instruction*, 50, 65-74.

Forbus, K. D., Chang, M., McLure, M. & Usher, M. (2017). The cognitive science of sketch worksheets. *Topics in Cognitive Science*, 9(4), 921-942.

Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical experience enhances science learning. *Psychological Science*, 26(6), 737-749.

Resnick, I., Newcombe, N.S. & Shipley, T.F. (2017). Dealing with big numbers: Representation and understanding of magnitudes outside of human experience. *Cognitive Science*, 41,1020-1041.

Richland, L. E., Begolli, K.N., Simms, N., Frausel, R. & Lyons, E. A. (2016). Supporting mathematical discussions: The roles of comparison and cognitive load. *Educational Psychology Review*, 29(1), 41-53.

CORE FACULTY

Nora S. Newcombe (PI), Laura H. Carnell Professor, James H. Glackin Distinguished Faculty Fellow—Department of Psychology, Temple University
Dr. Newcombe's research concentrates on spatial cognition and its development, mainly using behavioral techniques, as well as collaborating on studies using fMRI, non-human animals, and computational modeling to study phenomena of interest.

Dedre Gentner (Co-PI), Alice Gabrielle Twight Professor —Department of Psychology, Northwestern University
Dr. Gentner's research interests focus on learning and thinking; analogy, similarity and metaphor; concepts and conceptual structure; language and cognition; language acquisition; cross-linguistic studies.

Susan Goldin-Meadow (Co-PI), Bearsdley Ruml Distinguished Service Professor—Department of Psychology, University of Chicago
Dr. Goldin-Meadow's research interests include language development and creation and gesture's role in communicating, thinking and learning.

Susan C. Levine (Co-PI), Rebecca Anne Boylan Professor of Education and Society—Department of Psychology, University of Chicago
Dr. Levine's research focuses on the development of early mathematical thinking, including numerical and spatial aspects of math, and how variations in home and school input relate to children's learning in this domain.

Sian Beilock, President, Barnard College
Dr. Beilock's research focuses on girls' and women's success in math and science and how performance anxiety can either be exacerbated or alleviated by teachers, parents and peers.

Anjan Chatterjee, Elliott Professor—Department of Neruology, University of Pennsylvania
Dr. Chatterjee's research interests include the cognitive neuroscience of spatial attention and representation, the neural basis of language, and the relationship of space and language, neuro-ethics, neuro-aesthetics

Jason Chein, Professor—Department of Psychology, Temple University
Dr. Chein's research employs a cognitive neuroscientific approach to evaluate alternative theoretical claims surrounding the basic mechanisms of cognition, the relationship among these mechanisms, and the contribution each makes to high-level cognitive function.

CORE FACULTY

Jennifer Cromley, Associate Professor, Educational Psychology, University of Illinois at Champaign-Urbana
Dr. Cromley's research focuses on reading comprehension of illustrated scientific text and cognitive and motivational predictors of STEM students' achievement and retention.

Alexandra Davatzes, Associate Professor—Department of Earth and Environmental Science, Temple University
Dr. Davatzes' research interests are in planetary geology, sedimentology, early Earth processes and geoscience education.

Russell Epstein, Professor—Department of Psychology, University of Pennsylvania
Dr. Epstein's research focuses on how do people perceive and recognize real-world visual scenes and how do people build up representations of their spatial environment in order to navigate from place to place?

Steven Franconeri, Professor—Department of Psychology, Northwestern University
Dr. Franconeri's research interest focus on studying visual thinking and communication: how it works, and how we can make it work better.

Kenneth Forbus, Walter P. Murphy Professor of Computer Science and Education Northwestern University
Dr. Forbus' research interest include artificial intelligence, cognitive science, education, human-computer interaction and computer game design.

Louis Gomez, Professor of Education and of Information Studies, University of California, Los Angeles
Dr. Gomez's research interests encompass the application of computing and networking technology to teaching and learning, applied cognitive science, human–computer interactions.

Elisabeth Gunderson, Assistant Professor—Department of Psychology, Temple University
Dr. Gunderson's research focuses on the cognitive and socio-emotional factors that affect young children's academic achievement, especially in the domain of mathematics.

CORE FACULTY

Larry Hedges, Professor Department of Statistics, Psychology, and Medical Social Science, Northwestern University
Dr. Hedges' work includes to develop statistical methods for meta-analysis in the social, medical, and biological sciences.

Kathy Hirsh-Pasek, Stanley and Debra Lefkowitz Faculty Fellow and Professor—Department of Psychology, Temple University
Dr. Hirsh-Pasek's research examines the development of early language and literacy as well as the role of play in learning. Her research also looks at bridging the gap between research and application.

Janellen Huttenlocher, William S. Gray Professor Emeritus—Department of Psychology University of Chicago
Dr. Huttenlocher's research focused on spatial coding and memory and the role of environment in the development of cognitive skills. (Deceased)

Cathy Manduca, Director of the Science Education Resource Center, Carleton College
Dr. Manduca's work focuses on supporting geoscience education through community vetted education resources and supporting professional development of teachers.

Peter Marshall, Professor and Chair—Department of Psychology, Temple University
Dr. Marshall's research concerns the linkages between self and other, how these linkages develop, and the neural processes involved in their instantiation.

Carol Ormand, Science Education and Research Associate, Science Education Resource Center—Carleton College
Dr. Ormand's research focuses on improving science education at the college and university level.

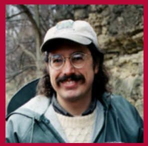
David Rapp, Professor—Department of Psychology, Northwestern University
Dr. Rapp's studies successful and unsuccessful comprehension, including the consequences of exposure to inaccurate information, and interventions designed to support learning through updating of knowledge.

CORE FACULTY

Terry Regier, Professor of Linguistics and Cognitive Science, University of California at Berkeley
Dr. Reiger's research investigates the relation of language and cognition, through computational methods, behavioral experiments, and cross-language semantic data.

Lindsey Richland, Associate Professor—School of Education, University of California, Irvine
Dr. Richland investigates children's memory and analytical reasoning development, exploring children's emergent ability to think about relationships and make inferences such as through metaphor and analogy.

Thomas F. Shipley, Professor of Psychology—Department of Psychology, Temple University
Dr. Shipley's research focuses on spatial cognition and learning. He applies formal methods from his previous research on object and event perception to understand the perceptual and cognitive processes supporting navigation and visualization.



Basil Tikoff, Professor of Structural Geology and Tectonics, University of Wisconsin-Madison
Dr. Tikoff's research focuses on field geology, geophysical methods, physical (analog) models, and numerical models to understand three-dimensional deformation.

David Uttal, Professor—Department of Psychology and Education, Northwestern University
Dr. Uttal's research interests include cognitive development; spatial cognition, symbolic development, mathematical thinking. Psychology and Education.

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