Daniel L. Schwartz
Stanford University / Stanford, CA

2021 Klaus J. Jacobs Research Prize
“New insights about how children learn will improve the way we teach“

Daniel Schwartz uses creative designs and experiments to bridge the gap between basic research on human cognition and STEM learning, improving educational success at all ages.

How did you come to be interested in this work?
I taught middle school for many years before undertaking a Ph.D. in human learning and cognition at Columbia University. Perhaps because of my undergraduate philosophy degree or my many years as a public-school teacher, my research has been driven by the basic and ancient question, “How can people learn and generate new ideas?” As a rough statement, a “new idea” means something that a person would not naturally recognize and that has generative properties such that it can help explain and organize the world. One of my favorite examples of a new idea is negative numbers, which are neither innate nor given by experience.

Your research specialty involves addressing cognitive questions through innovative learning experiments. How did you apply this to the question of learning negative numbers?
In a set of experiments bringing together fMRI [functional magnetic resonance imaging], reaction times, innovative teaching technologies, and classroom interventions and data, we discovered that the brain learns the concept of negative numbers through association with the perception of symmetry. We then showed the effectiveness of a symmetry-based curriculum in teaching negative numbers. If we help students recruit their native abilities at perceiving symmetry and coordinate them with magnitude and verbal systems, they can better learn the concepts of negative numbers. Many people think of learning as strengthening a brain muscle, but when it comes to gaining new ideas, a better analogy might be teaching the brain to dance.

How does early learning impact subsequent learning?
My research shows that that early learning or instruction can help or hurt subsequent learning, and that the impacts of learning experiences are not finished once a person has mastered something, as previously believed.

If people get locked into their initial realization of a problem, they might not think beyond that in solving new problems. In the end, one fundamental realization has been that much of school-based learning depends on coordinating different brain systems with the support of the right learning environment. One of the most important contributions of this work is the demonstration that we have different modes of reasoning and learning, such as verbal and non-verbal, and they can collide if poorly sequenced. Verbal and procedural instruction thinking can undermine non-verbal reasoning and learning. This is one of the reasons people learn more by first working on problems before they are told how to do them.

What does your research tell you about the process of transfer in education?
Transfer is how people generalize their learning to new contexts, for example, from class to home, from class to job, from class to class. Much of the research on transfer has examined sequestered problem solving, in contexts that require the ability to directly apply old knowledge to solve new instances of problems. This is very different from asking if people have been prepared to learn to solve novel problems and engage in other kinds of productive activities, which is what educators say they want for their students.
We have demonstrated that certain methods of learning do a better job of preparing students to be flexible and to transfer their learning to support future learning. For instance, in one of our studies of teaching physics to adolescents, we found that being told procedures and concepts before problem solving can inadvertently undermine the learning of deep structures in physics. If students do not learn the underlying structure of physical phenomena, they will exhibit poor transfer. In a world where jobs and knowledge bases change regularly, preparation for future learning should be a significant goal of education. Our research suggests that a framework for thinking about this problem should consider a balance of innovation and efficiency in the transfer of learning.

You invented a technology called a Teachable Agent. Can you explain what that is, and how it works?
A Teachable Agent or TA is a graphical computer character that students teach. The TA uses artificial intelligence to learn and reason about what it has been taught. They reflect their teacher’s knowledge but have minds of their own. One of the concepts we have studied with TAs is the protégé effect. In our Betty’s Brain study, 8th grade students worked with Betty’s Brain software to learn biology, but some of the students believed they were teaching the TA, while others believed they were learning for themselves with the use of an avatar. We found that students in the TA condition experienced a protégé effect, in that they made a greater effort to learn for their TA than for themselves. These students learned more and spent more time on learning activities.

In the second part of the study, 5th grade students were asked to think aloud while they worked, externalizing their thoughts and emotions, while they worked with either a TA or an avatar. These data begin to uncover the psychological machinery behind the TA students' increased motivation to learn, as the children treated their TAs socially by attributing mental states and responsibility to them.

Why are Teachable Agents effective, and what kinds of learning can they impact?
Teaching Agents may invoke a sense of responsibility that motivates learning, provide an environment in which knowledge can be improved through revision, and protect students' egos from the psychological ramifications of failure. We have found that students transfer the form of reasoning to learn about new topics, even when they are no longer using the agent. We have found evidence for the transfer of causal reasoning for 6th-graders and propositional logic for high-schoolers. We will soon experimentally test a new hypothesis for why TAs appear to be effective tools for teaching reasoning.

What are some of the ways that you share your findings with a wider public and education audience?
I co-host of the Stanford podcast and SiriusXM radio show "School's In," where we discuss current topics in teaching and learning with an aim of helping educators and parents understand and use the latest research. With two past doctoral students, I wrote a "trade book" for educators, researchers, and learning technologists called The ABCs of How We Learn that has sold over 30,000 copies. The book is also aimed at teachers and learners so they can apply the research on mechanisms of learning to their own educational activities. I serve on the expert groups responsible for two important U.S. National Academy of Science reports, How People Learn II, and Learning Science Through Computer Games and Simulations, and served on the working group of the President's Council on Science and Technology to create their influential 2010 report on improving the teaching in higher education. I have worked with the San Francisco city school district on the design of their new pre-kindergarten program and the American Society of Clinical Oncology on better professional training for their member physicians.

What are some of your future research goals?
Over the next five years, one of my broad research goals is to learn how to make online experiences that capture much of what is lost without an in-person learning experience. For instance, in one project, I am working with geologists to create virtual field trips that create a sense of shared adventure. The hypothesis is that shared adventures improve learning, create long-lasting friendships, and increase stewardship of the land.

As part of this, we want to determine how to enable children to create virtual field trips relevant to their own circumstances, which they can then share with other children around the world.
Another broad goal is to collaborate with colleagues in artificial intelligence to produce fundamentally new ways of teaching and learning. In one project, for example, we are developing ways to auto-generate contrasting and analogous cases that maximize student abilities to discover patterns and explanations.

How will the Klaus J. Jacobs Research Prize money be used?
We will take a new approach and create a Teachable Agent that supports learning to reason between data and claims. We will test general hypotheses about how to help people learn to reason, as well as the added value of the TA in supporting learning and transfer in classrooms and informal experiences. Here, the basic TA play pattern will be that students design experiments and collect data. They feed the data to the TA, which uses a visual interface to show its reasoning over the data and the valid conclusions it can reach. We have previously demonstrated different design elements for TAs, and we will conduct design-based research to determine the most successful ways to mix them together here. We will also experimentally test a new hypothesis for why TAs appear to be effective tools for teaching reasoning. The core hypothesis is that a powerful way to help people learn to reason occurs when person 1 sees person 2 reason with 1's ideas. An intuitive example involves the case of a graduate student presenting the results of a study. The student may hear a more advanced student or faculty member reason about the conclusions that are and are not supported by the evidence, and what further evidence is needed. This helps the student learn about considerations to make in future studies. We propose this recursive cycle of seeing another person reason with one's data or ideas is an especially effective way to support early learning of reasoning as compared, for example, to asking students to reason it out on their own, or by students listening to the teacher reason about someone else's data and claims. If our recursive hypothesis is true, it will have broad implications for cognitive models of learning and the design of effective learning experiences.
The work will also develop a publicly available database that captures common research designs, good and bad, produced by students of different ages, which can inform more precise instructional practices. Finally, if ultimately successful, the work will result in an engaging and effective way to increase scientific literacy, for example, for learning and reasoning about pandemics.