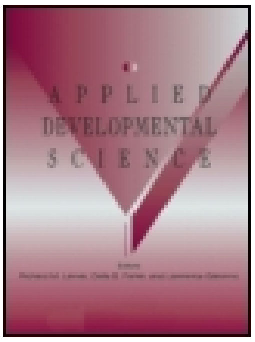

Routledge
Taylor & Francis Group

Applied Developmental Science

ISSN: 1088-8691 (Print) 1532-480X (Online) Journal homepage: http://www.tandfonline.com/loi/hads20

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Melina R. Uncapher

APPLIED DEVELOPMENTAL SCIENCE
https://doi.org/10.1080/10888691.2017.1421437

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Melina R. Uncapher

University of California

ABSTRACT

In this issue, Cantor and colleagues synthesize a broad representation of the literature on the science of learning, and how learning changes over the course of development. Their perspective highlights three important factors about the emerging field of *science of learning and development:* (1) that it draws insights from increasingly diverse fields of research inquiry, from neuroscience and social science to computer science and adversity science; (2) that it provides a means to understand principles that generalize across learners, and yet also allow individual differences in learning to emerge and inform; and (3) that it recognizes that learning occurs in context, and is thus a shared responsibility between the learner, the instructor, and the environment. Here I discuss how this complex systems dynamical perspective can be integrated with the emerging framework of 'learning engineering' to provide a blueprint for significant innovations in education.

What is learning, and how do we know it has occurred in another? This was the provocative question posed to me and my fellow Ph.D. littermates on our first day of grad school by Professor Norm Weinberger, founding faculty of the first center for neurobiological investigations of learning (University of California's Center for Neurobiology of Learning and Memory). Fifteen years later, I imagine Norm would be deeply gratified to see the growing convergence of fields attempting to answer that question from varied and diverse perspectives. These disparate fields are independently building toward a multi-dimensional understanding of what learning looks like, from cells to systems. Cantor, Osher, Berg, Steyer, and Rose (2018) synthesize findings from learning science, developmental science, neuroscience, adversity science, social science, computer science, and the science of the individual, to present a compelling case for how these fields may work together to generate a more whole-learner and systems-level approach to understanding and supporting learning. Here, I discuss how this perspective may be incorporated into an emerging framework that moves the science of learning toward the engineering of learning, to generate a roadmap for education innovation.

Importance of understanding the multi-dimensionality of learning and development

A central point raised by Cantor and colleagues is that scientists and educators are at a critical juncture where independent efforts to understand and intervene on learning will falter unless combined with complementary efforts. For instance, if a researcher is interested in understanding and intervening on how a child learns mathematics, it is important to not only understand how her numeracy skills are developing, but also how her sense of agency in math affects her ability to express those numeracy skills. Likewise, it is important to understand how her executive functioning is allocated in service of developing her numeracy skills, and what factors in her internal and external environment may be facilitating or hindering her skill development. This assessment will require integrated, trans-disciplinary scientific inquiry that moves beyond descriptions of isolated learning constructs and towards more integrative accounts of interrelationships and dynamics between learning constructs.

An advantage of pushing for integrated efforts in the educational climate current at this writing is that there now exist early technologies that may facilitate such multi-disciplinary integration. These technologies are beginning to capture various expressions of learning, in high dimensionality. Thus, Cantor and colleagues' highlighting of such integrated efforts is timely and important for innovative research and development efforts. For instance, intelligent tutoring systems are starting to assess where a student is on a learning trajectory and also can use that information to push the student towards accelerated learning or help remediate if the learner is off track (e.g., Open Learning

CONTACT Melina R. Uncapher melina.uncapher@ucsf.edu University of California, Sandler Neurosciences Center, 675 Nelson Rising Lane, MC 0444, Room 502, San Francisco, CA 94158, US.

Initiative; Enlearn). Other technologies are able to assess multi-dimensional components of learning, such as those involved in mathematics (e.g., math fluency, groupitizing/subitizing) and executive functioning (e.g., attention, inhibitory control, working memory) and how those components predict academic achievement (e.g., Rodondi et al., 2017; see Zelazo, Blair, & Willoughby, 2016 for review of relationships between executive functioning and academic achievement).

These technologies are allowing researchers to move their scientific inquiry out of the lab and into the "wild," by assessing learning in context. Whereas many tools are still constrained for use during separate assessment sessions, the goal is to move towards being able to assess learning in real-time, in real-world environments (i.e., while the student is learning). Future efforts will necessarily involve methods that integrate these various high-dimensional assessments of learning, to glean insights into how different components of the whole child coact dynamically across time, expertise, and context. These integration efforts will surely be facilitated by the growing movement toward open science and data sharing across many scientific disciplines (e.g., Nosek et al., 2015), as well as toward funding opportunities that encourage multi-disciplinary research (e.g., National Science Foundation's Science of Learning Collaborative Networks).

From research-research partnerships to research-practice/policy partnerships

Cantor and colleagues give voice to a growing contingent of stakeholders who are pushing a movement in education similar to that which occurred in medicine two centuries ago, when medical practitioners began to partner with scientists who studied the human body. Very rapidly after creating this research-practice partnership in medicine, the efficacy of medical practice improved dramatically. There is now an emerging discipline starting to foster analogous research-practice partnerships in education, with the understanding that education is one of our most important applied sciences and that the future of education will surely benefit from being grounded in a scientific understanding of how students learn, and how this learning develops over the course of the life span.

The first step in driving evidence–based and evidence-informed practices in education is certainly a more integrated research base that respects the contributions of all disciplines (from social science and affective science to neuroscience and cognitive science). The methods described in Cantor et al. will provide processes by which to further our scientific understanding of the multiple dimensions that interact to give rise to how people learn. It is critical that the researchers revealing insights in these various domains consider and integrate findings across multiple disciplines. However, it may be even more important that the integration extend beyond research-research partnerships, and into research-practice partnerships (with practitioners here being educators and policymakers).

The growing emergence of research-practice partnerships is a critical step in translating the science of learning into the art of teaching. By bringing research to bear on how people learn, from the various dimensions covered by Cantor et al., educators and policymakers can be guided by what works, for whom, when, and where (Bornstein, 2017). Such evidence-based and evidence-informed knowledge can protect against programs and tools that have not been shown to improve student outcomes (and may indeed be ineffective or even harmful), and can guide more effective decision-making.

Perhaps just as important, however, is the reverse relation: when researchers truly hear from and understand how students learn in real-world contexts, this information can refine and advance scientists' research questions. Cantor and colleagues make a cogent argument for why understanding how learning in context is important. When educators share their experience about the contextual, social, and systems-level variables that influence how people learn, researchers can design more effective research programs and can target their research to answer not just basic scientific questions of how people learn, but also questions that may have real-world utility (a "sweet spot" referred to as *Pasteur's Quadrant*; Stokes, 1997).

From science of learning to learning engineering

Cantor et al.'s comprehensive synthesis of key elements in the science of learning and development goes on to foreground a number of additional processes and methodologies that I suspect they would argue will move the field away from simply considering the science of learning, and toward an understanding of how to *engineer* learning. The field is now starting to appreciate that every scientific discipline that has made an impact on the real world has not done so only through its scientists, but rather through the associated engineers who translate the scientific insights into solving real world problems. When applied to the science of learning (and development), one can consider the engineering processes that can be brought to bear on the principles of learning, which can together be used to build effective learning environments and experiences.

This concept of "learning engineering" was first introduced 50 years ago by Nobel Laureate Herb Simon (Simon, 1967), and yet is only just recently starting to take root (e.g., Hess & Saxberg, 2014; Uncapher, 2016; Willcox, Sarma, & Lippel, 2016). As a strong advocate of learning engineering, the working definition I use with educators, policymakers, and developers of curricula and edtech is: How do we use promising *principles* from the science of learning, together with design *processes* from engineering, and the *platforms* of technology (where appropriate) to co-create and test rapid-cycle, iterative solutions to grand challenges in education? By this definition, learning engineering can be thought of as serving a "boundary agent" function (Beauchamp & Beauchamp, 2013), which moves us away from a one-sided, linear transfer of research into practice, and toward a more bidirectional, action-research based conversation between researchers and practitioners. Scalable, real-world impact will likely require a new job description: engineers who are skilled in understanding both the problems of practice and the insights of research and practice, and can apply scientific principles to planning, prototyping, deploying, and iterating sustainable solutions to practical real-world problems.

Missing link: The science of the individual

Cantor and colleagues describe many elements of a learning engineering approach: the trans-disciplinary basis of the science of learning and development; that learning is a shared responsibility between learner, instructor, and context; and more. Most importantly, however, they make a critical and novel contribution to the emerging field of learning engineering, in their focus on the *science of the individual*. As they explain: "The science of individuality … starts with the premises that individuals vary in how they learn, behave, and develop; that these processes vary according to context; and that there are patterns within that variability (Rose, Rouhani, & Fischer, 2013)" (Cantor et al., 2018). They go on to describe a methodological approach that may help crack one of the most vexing challenges in education: how to create effective educational experiences at scale, which support learning for every child and not just the average child. The "analyze then aggregate" approach of Rose and colleagues (2013) first identifies individual differences in learning—as well as how those differences vary according to where, when, and with whom learning is occurring—and then uses those individual differences as a foundation by which to model more generalizable principles that can be applied at scale. By recognizing the factors that contribute to individual differences in learning, and describing methods by which to understand and accommodate those individual differences, the authors are paving a way forward for how to truly bring the science of learning to scale in the form of learning engineering.

Conclusions

The way in which the human brain learns involves complex system dynamics, and the way in which we deliver educational experiences involves equally complex system dynamics. Any innovation that hopes to make a significant difference in teaching and learning will recognize the complex system dynamics and propose dynamic complex systems solutions. Cantor and colleagues nicely articulate the complexity of human learning, how it develops over time and with expertise, and how it varies with context. They do not artificially reduce down the problem into a silver bullet solution, but rather describe some critical factors that must be considered in any potential education innovation: the multi-dimensionality of learning and development, how learning varies with context (both internal context such as motivation and agency, and external context, such as social dynamics and teacher beliefs), and how individual differences in learning must be taken into account. By extending these factors into the framework of learning engineering—which allows for principles of learning science to be designed for individual learners and learning contexts utilizing a user-centered design approach—we may just have a possible blueprint for how to solve grand challenges in education.

Implementing this plan will not be simple, and will require highly siloed fields and calcified systems to re-engineer their dynamics. It will require, as well, changed incentive structures for researchers and practitioners that enable evidence-based and -informed practices to be co-developed, prototyped, tested, and iterated. It will require trust and respect between disciplines. This mutual trust and respect can allow for problems of practice and problems of research to be informed by the affordances of practice and the affordances of research. In this way, research-practice partnerships may build toward a larger research-practice ecosystem, supported perhaps by the boundary agents and processes of learning engineering.

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