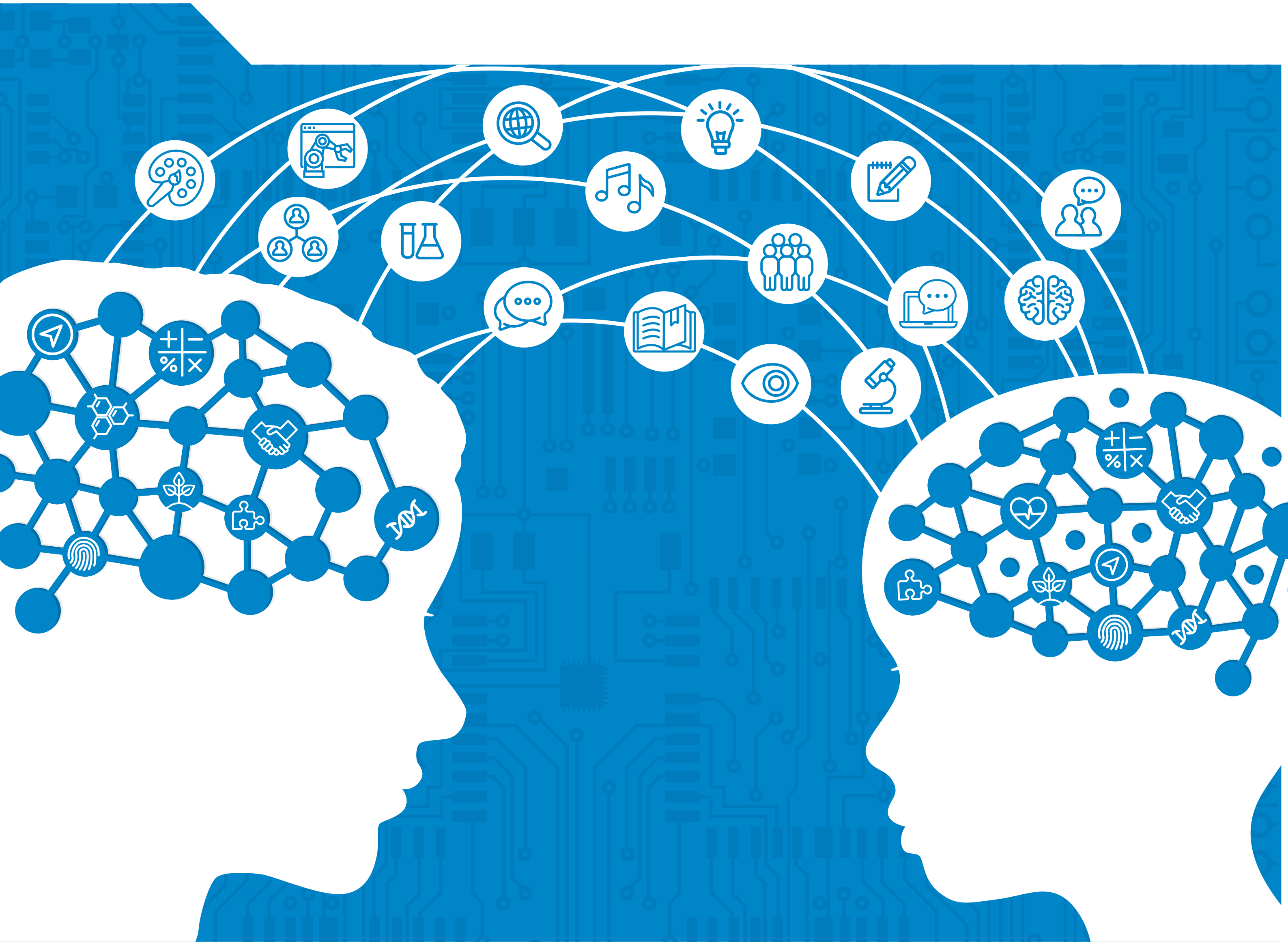
Educational Research and Innovation

Developing Minds in the Digital Age

TOWARDS A SCIENCE OF LEARNING FOR 21ST CENTURY EDUCATION

Patricia K. Kuhl, Soo-Siang Lim, Sonia Guerriero
and Dirk van Damme



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BETTER POLICIES FOR BETTER LIVES

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Foreword

In the first decades of the 21st century, many actors and stakeholders have urgently argued that education needs to be transformed in order to meet the demands of rapidly changing technologies, new skill demands in the workplace, and to foster equity, social cohesion and global citizenship. Implicit in these demands and expectations is the aim to realise every individual's potential. Twenty-first century education requires teachers, environments, technologies, educational content and pedagogical practices that can help learners attain that goal.

In order to realise this ambition, 21st-century education needs to be underpinned by the best available research evidence on human learning and how to improve it. Knowledge is one of the most important raw materials of education; yet education is not particularly good at updating its own scientific knowledge base. A lot of the knowledge at work in education practices and transmitted in teacher education and professional development activities is outdated and sometimes contradicts more recent research. Education seems to be vulnerable to myths and erroneous ideas, born out of romantic ideals, wishful thinking or love for children. Sometimes science tells us something different from what educators wish to hear.

Constantly updating its own knowledge base is one of the most needed but also most difficult tasks in moving education forward. In many countries, the mechanisms and practices used to translate and transmit scientific evidence into education policy and practice are missing. Compare this with, for example, the health sector, which has effective mechanisms for constantly updating the medical knowledge in the system and among medical professionals.

But things have started to change in recent years, most importantly in the field of scientific research itself. Human learning became the object of research in many more scientific disciplines than pedagogy or education science. Well-established disciplines, such as cognitive psychology, and social and behavioural sciences, and also neuroscience, brain research, computer science and even engineering, are amplifying efforts to better understand human learning and the conditions needed to nurture it. As an interdisciplinary effort, a new "science of learning" is in the making, with enormous potential for improving teaching and learning practices. These developments offer fascinating new perspectives, based on technological advances, that enable a re-examination of longstanding problems in learning, raise new questions, and offer new approaches to the study of learning.

To translate, transmit and inject the new "science of learning" into education will not be easy. The distance between what happens in a research lab and in a classroom is huge, and there are both institutional obstacles and barriers of mindset that need to be overcome to bridge these two worlds.

We prepared this book with that in mind. Researchers and scientists have done their best to make their research findings accessible to education policy makers and practitioners. I hope it will inspire many. This is not the end of a process though; the science of learning is only in its infancy. Thus this book is also a call for more research, and more communication and interaction between the world of science and the worlds of policy and practice.

Andreas Schleicher

Andreas Schleicher

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Executive Summary

Powerful trends are reshaping the context for education. They accompany calls for change and innovation to meet the demands of rapidly changing technology, new skills in the workplace, and the need to foster equity, social cohesion and global citizenship. Central to success in meeting these demands and expectations is the development of an individual's full capacities to learn throughout his/her life span. Only then can education produce individuals who are productive in, and can successfully navigate an increasingly knowledge-intensive and technology-driven 21st century. A key pathway to realising this ambition is to use the best available research evidence on human learning to inform educational practice and policy.

Recent years have spawned technology advances and new research methods that enable the study of learning in ways that were previously not possible. Significant insights have been achieved into the complex, dynamic processes and mechanisms that underlie how people learn, and how environmental factors affect learning. Important glimpses into the proverbial "black box" between input to and output from the learner have come from diverse disciplinary experts working together, including: neuroscientists, social, behavioural and cognitive scientists, mathematicians, computer scientists, engineers and education researchers. This is an opportune time for researchers, education practitioners and policy makers to collaborate more closely to examine the implications of new findings about human learning, and propose science-based actions to address the learning and educational challenges before us.

In the spirit of the translational mission of the OECD Centre for Educational Research and Innovation between research and education policy and practice, this book aims to contribute to this much-needed effort. The book is not intended to be a comprehensive treatise of all topics central to learning, and does not presume to prescribe solutions to the myriad of complex educational dilemmas. It seeks to catalyse discussions on the implications of research findings for education practice and policy, and in turn, on how knowledge and experience from real-world education practice and policy could challenge and inform research agendas and theory building.

The book has three parts, with chapters by leading researchers presenting recent research and discussing its implications for educational policy and practice.

Interplay between the learner and the environment

The chapters here underscore the dynamic and interactive elements of biological, behavioural and cognitive development across the life span, and the interplay of the learner with his/her environment. The importance of the early years as a foundation for later learning is featured for language learning, the development of numerical understanding and spatial learning. Another theme is the importance of social learning and social-emotional interactions in learning. Examples include: how gender and racial stereotypes can negatively affect career choices and academic performance, and how early and targeted interventions can mitigate the harmful consequences of negative role models; and how maths anxiety among parents and teachers can negatively affect children's maths learning.

Science of learning in design and use of technology for learning

Integrating principles of how people learn into the design of technology is essential for its use to effectively support and enrich learning. Some examples include: incorporation of cognitive models of human visual, spatial, conceptual representations and processes in spatial learning to improve communication via sketching; use of collaborative capabilities of digital technologies to foster the creation of social relationships in learning; use of intelligent, computer-based tutors to adapt instruction to individual students based on assessments of their knowledge and ability; and the use of Big Data, Artificial Intelligence algorithms, education data mining and learning analytics to choose among the trillions of instructional strategies to improve learning and education. Additional chapters give a sense of the enormous potential of digital technologies and Artificial Intelligence in innovating learning environments and at scale.

Implications for research, education practice and policy: Opportunities and challenges

The third part of the book explores what needs to be done in order to facilitate the use of research from the science of learning for more innovations in teaching, learning and education. The application of laboratory-derived scientific principles of learning to "messy" classroom practice remains challenging. To bridge these two worlds, more interaction, communication and collaboration between the communities of researchers and practitioners is necessary. Discussion in this section includes specific attention to training and up-skilling of both researchers and teachers. For the researcher, training is needed to work with big data in order to reap its benefits; for the teacher, education and training need to keep pace with developments in the science of learning and more in-depth understanding of learning processes. This is vital because the teacher is a critical partner in the implementation of science-based interventions to improve learning. Additionally, teacher training and technical support of teachers are needed for timely and effective incorporation of learning technologies for pedagogical purposes.

The book is also illustrative of the role government can play, and the emerging global networking around a more integrative and interdisciplinary science of learning. For example, funding by the US National Science Foundation has fostered an interdisciplinary and networked community in the United States, focused on the study of learning. Perhaps the largest single investment in research centres for large-scale, interdisciplinary study of learning, the US Science of Learning Centers have also helped catalyse science of learning efforts in Hong Kong, Australia and Brazil. Many other groups beyond those mentioned in this book exist as well, raising the need for exploring socio-technical infrastructure that supports networked knowledge and resources. By leveraging economies of scale and the collective engagement of researchers, practitioners and policy makers, new paths can be forged for transformative advances in learning and education.

Chapter 1. Introduction

By

Soo-Siang Lim
National Science Foundation
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This chapter presents an overview of the book's organisation and the events that led to its publication. It introduces an interdisciplinary Science of Learning that integrates across levels of analysis and disciplinary perspectives to provide new advances in the study of learning. It argues for renewed efforts to make use of scientific findings of how people learn, in order to advance education goals, human development and 21st century workforce preparation. It also calls for the science of learning to inform the design of technology that more effectively support and enrich learning in this digital age. The chapter ends with implications for research, education policy, and practice and presents the potential of international networking for collaborative action to make transformative advances in learning and education.

Why science of learning? Why now?

Learning is a sine qua non of effective education and human accomplishment. It encompasses complex changes in the learner from his/her dynamic engagement with an equally ever-changing environment. At best, the interplay of the biological, physiological, cognitive and behavioural processes supporting the learner in interactions with the environment remain robust and resilient over a life-time of positive and negative experiences – at home, in school, at the workplace and in old-age. The key in the journey through this increasingly knowledge-intensive and fast-changing society is life-long learning.

Learning is an important research topic in many disciplines, but much knowledge is confined within disciplinary boundaries and practices. To address these challenges, the US National Science Foundation established the Science of Learning Centers (SLC) programme in 2003. Significantly larger than usual awards, the SLCs afforded large-scale, convergent and interdisciplinary efforts that integrate across levels of analysis and disciplinary perspectives – from molecular/cellular mechanisms of circuits and brain systems that underlie cognitive and behavioural processes, to social/cultural influences that affect learning – in individuals and in groups. The launch of this programme was timely, taking advantage of technological advances, particularly in neuroscience, engineering, and computer and information sciences, which enabled a re-examination of longstanding problems in learning, raised new questions and offered new approaches to the study of learning previously not possible. It fostered interdisciplinary team science and expanded the range of expertise traditionally identified with the study of learning in the context of education goals.

The premise was that new insights would be found through convergent, integrative knowledge at the interfaces of many disciplines, and that advances in our understanding of learning would have wide ranging societal impacts. The new insights were expected to not only transform how we learn and teach, but also lead to innovations in diverse technologies (e.g. in health and national security) that permeate 21st Century work and work-force preparation.

Overview of book organisation:

The idea for this book stemmed from a 2012 Conference, “Connecting How We Learn to Educational Practice and Policy; Research Evidence and Implications”. Focused on the science of learning, this conference was jointly organised by awardees of the US Science of Learning Centers programme and the Centre for Educational Research and Innovation at the OECD. In response to interest from researchers and educators in Australia, China and South America, a series of additional conferences followed in Brisbane, Shanghai and Rio de Janeiro, respectively.

This book highlights some of the increasing bounty of scientific findings about how people learn from participants in these conferences, who represented multiple disciplinary perspectives including neuroscience, social, cognitive and behavioural sciences, education, computer and information sciences, artificial intelligence/machine learning, and engineering. It seeks to catalyse discussions that examine the implications of these research findings for education practice and policy, and in turn, examine how knowledge and experience from real-world education practice and policy could challenge and inform research agendas and theory building. This book is not intended to be a comprehensive treatise of all topics central to learning, and does not presume to prescribe solutions to the myriad of complex educational dilemmas.

Nonetheless, taken in total, the Key Themes and Findings illustrate the diverse disciplinary and expanding scientific groundwork in the study of learning, explain the implications of research findings for educational practice and policy and present some cases of successful models for bridging basic research and education practice through interventions that improve learning and education.

Chapters 2 to 7 underscore the dynamic and interactive elements of biological, behavioural and cognitive development across the life-span, and the interplay of the learner with his/her environment. Just as technology increasingly pervades every human endeavour, the confluence of technology affordances in service of learning and education has been inevitable. Chapters 8 to 18 provide examples of technologies that promote spatial learning and others that create new learning opportunities; and how learning can be tracked, assessed and shaped at scale.

The aspirations of interdisciplinary research to make transformative advances in educational practice and policy are shared by other countries. Chapters 19 to 22 are examples of like-minded efforts in Australia, Hong Kong and Brazil that grew out of mutual support and collaborations with the US Science of Learning community. Each is a story about local motivators and grass roots organisation to create a national/regional core of experts, inspired by the use of scientific understanding of how people learn to make a difference in education outcomes. These and many other groups around the world represent the potential building blocks to realise the full power of networked knowledge and resources needed for transformations in learning and education.

Key themes and findings

Interplay between the learner and the environment

- **Learning is life-long, starting with the important early years and the interplay of learner and environment.**

Chapter 2 (Kuhl and Ferjan Ramírez) links neuroscience to behaviour to demonstrate the importance of social interactions and sensitive periods in early childhood that impact early language learning. The quantity and quality of early input also matters in how children master basic understanding of numbers. In **Chapter 6** (Gibson, Berkowitz and Levine), cognitive science-based interventions based on better understanding of sources of variability in children's understanding of number, factors that make learning about numbers challenging, and characteristics of effective number input were used successfully in promoting early number knowledge and reducing achievement gaps. Spatial skills are important foundational skills for science, technology, engineering and mathematics (STEM) learning. **Chapter 16** (Toub, Verdine, Golinkoff and Hirsh-Pasek) demonstrates how everyday activities can create spatial learning opportunities through play with shapes, blocks, puzzles and origami. Utilizing these ways to develop spatial skills early in childhood will help scaffold formal learning later on. Across age, methods for training broad cognitive, social and communicative skills are critical. **Chapter 7** (Congdon, Novack, Wakefield and Goldin-Meadow) shows that modifying everyday actions produced as gestures can causally improve learning outcomes. Gestures facilitate learning through its capacity to engage the motor system, be integrated with speech, and can be used as a spatial tool to reflect and to communicate thinking not apparent in spoken explanations. **Chapter 15** (Khalil, Minces, Iversen, Musacchia, Zhao and Chiba) describes other enriching experiences that support learning, including music as a stimulant for learning that transfers to attentional behaviour, language, literacy and the ability to integrate easily into a social-cultural environment. **Chapter 17** (Suarez, Samano, Yu, Snyder and Chukoskie) explores STEM learning opportunities that are facilitated by engagement of researchers with community educators and the general public

- **Social identity and socio-emotional interactions matter in learning and STEM engagement**

Underrepresentation of women and minority populations in STEM are existent inequalities in education and opportunity that are of a global concern. **Chapter 3** (Meltzoff and Cvencek) combines psychology and education research to demonstrate how the gender stereotypes in girls develop from early social experiences that shape identity and self-concepts to negatively impact later academic performance and choices. Science-based interventions designed to strengthen children's resistance to STEM stereotypes are described that help spark children's continued engagement in and success in STEM disciplines. In **Chapter 4** (Nasir), the intertwining of racial identity and learning is explored in the construct of Racialized Learning Pathways, and points of intervention that break the negative cycle between racialization and learning are highlighted. **Chapter 5** (Rozek, Levine and Beilock) reveals that young children are sensitive to the maths anxiety experienced by adult role models, such as teachers and parents. Children with maths-anxious parents or teachers tend to show less growth in their maths knowledge than those without a maths-anxious role model. Home and classroom interventions that were effective in mitigating harmful learning consequences of negative affect are highlighted.

Science of learning in design and use of technology for learning

Technological affordances create significant possibilities for supporting learners and teachers. Aligned and combined with principles of how people learn, they provide novel avenues for enhanced learning through new ways of presenting the curriculum, adaptivity in how information is presented, and the provision of feedback contingent on learner needs, knowledge and behaviour. Technology presents new avenues and scales of access for the learner, as well as new ways for learners to express themselves through natural language and sketching to communicate, interact and collaborate with other. These new technologies promote learning through argumentation and develop learners' identities as reasoners and problem solvers.

Chapter 8 (Forbus and Uttal) describes how modern digital technology provides new options for enriching spatial learning with a focus on technologies for: 1) improving communication via sketching where the software incorporates cognitive models of human visual, spatial, and conceptual representations and processes; and 2) Geographic Information Systems (GIS), computer-based mapping systems that facilitate spatial data analysis and visualization, leading to improved spatial reasoning in high school students. Recognizing that digital technologies have become an integral part of children's lives, **Chapter 9** (Barron and Levinson) urges us to consider not only the content children use, but how families can engage collaboratively in technologies through joint attention to support development in and out of school. This brings to the fore the need for programmes and policies to support equitable learning opportunities for parents and educators, in order to avoid exacerbating the digital gap. **Chapter 10** (Llorente, Moorthy and Dominguez) shows how Designed Joint Engagement with Media (DIEM) can promote co-reviewing and joint attention which in turn improves children's development of early science literacy.

In **Chapter 11** (Okita), the use of programmable robotic systems, virtual avatars and computer agents have revealed new insights into the role of social relationships in learning. For example, the mere "belief" that an avatar was human (vs. a computer agent) promoted significant learning gains and higher arousal measures. Incorporation of well-grounded theories of learning, such as Learning-by-Teaching and Recursive Feedback into technology design optimizes the learning relationship between learner and technology. **Chapter 12** (Klahr and Siler) introduces the TED tutor, an intelligent computer-based tutor that adapts instruction to individual students based on its assessment of their knowledge and ability. The tutor is used to address children's difficulty in acquiring an understanding of basic experimental design known as Control of Variables Strategy (CVS). This essential component of STEM education all too often receives inadequate instruction; the TED tutor can be used as an online instruction to augment classroom instruction.

Chapters 13 (Koedinger) and **14** (Rosé, Clarke and Resnick) address technology-mediated possibilities of scale – and address issues for scaling iterative course improvements, learning research in classrooms that are practical and aligned with real-world contexts, and professional development in instructional practice. **Chapter 13** demonstrates how systematic and iterative use of intelligent tutoring systems in large-scale classroom experiments has led to the development of the Knowledge Learning Instruction (KLI) framework. This new learning theory is driven and fuelled by Big Data, AI algorithms, education data mining and learning analytics, and has provided important guidance and a "roadmap" in choosing among the trillions of instructional strategies to improve learning and education. **Chapter 14** provides another example of AI-enabled scaffolding of learning through collaborative and discussion-based strategies that benefit student learning and teacher professional training. It draws on classroom facilitation practices by teachers referred to as Accountable Talk (AT), and students' articulation of reasoning and transactive exchange. Findings derived from teacher-led classroom discussions and computer-supported collaborative learning (CSCL) were positive. For example, a district-wide professional development effort in promoting transactive exchange through automated AT facilitation in small groups led to enhanced learning, and greater uptake of AT facilitation practices among teachers; a second investigation leveraging the same concept of Transactivity in a crowdsourcing environment and then tested in a real MOOC deployment, yielded promising results as well. Mandated tests exert strong influence on what is taught in schools and how it is taught. **Chapter 18** (Means, Cheng and Harris) argues that rich technology-based environments will be necessary to assess the science proficiencies described in national standards, to capture students' ideas, concepts and practices simultaneously. Innovations in science and technology-based assessments have the potential to resolve the challenge that many countries face in trying to align and reconcile classroom-based and national learning assessments.

Implications for research, education practice and policy: Opportunities and challenges

- **The need for more effective communication and shared knowledge across research, education practice and policy communities**

Large disconnects exist among the diverse basic science disciplines and education research, and among researchers, education practitioners, policy makers and other stakeholder communities. Inadequate communication and sharing of knowledge have been among the varied reasons why longstanding, complex problems about learning continue to elude our understanding, and why research findings have not found traction and adoption in education practice and policy.

The good news is that for the most part, the need for and the importance of interdisciplinary approaches to study learning is recognized, and the availability of research funding opportunities have increased collaboration among the basic science disciplines. The gaps between basic science researchers and education researchers continue to be challenging, complicated in part by the inherently different contexts in which research are conducted: the "messy" classroom with difficult to control variables, and in contrast, the use of abstracted stimuli and highly controlled experimental conditions in the laboratory.

The application of laboratory-derived scientific principles of learning to classroom practice remains challenging. To date, there are varying models and outcomes, usually confined to a few classrooms, except in cases of technology-mediated interventions that are more scalable. While there is implicit acceptance that knowledge about how people learn should be the foundation for how we teach and educate, the reality is that researchers, education policymakers and education practitioners rarely have opportunities to examine and discuss the issues surrounding application of evidence-based learning practices. More accessible and active collaboration between researchers and practitioners are needed to affect the following: 1) ensure that the research conducted is relevant to practitioners; 2) engage practitioners in the research process, thereby building capacity for educators to become more knowledgeable about the science of learning; and 3) contribute to the building of a knowledge base and conceptual framework for translation of research to practice.

- **Renewed investment in preparing researchers to work in a data-driven society**

The continued development of new technologies will advance acquisition, sensing and processing capabilities of data collection in real-time during learning and in real-world contexts. This promises exciting possibilities to better understand the complex dynamics of the many factors that impinge upon the learner simultaneously, including the biological and physiological influences as well as those from the external, physical and social environment. Current capabilities have already raised concerns about workforce preparedness to harness the big data promise in ways that properly acquire, curate, analyse and share these data resources. There is urgent need to train researchers to effectively generate and use sensitive, public and private big data that is actionable and of value.

- **Renewed investment in teacher education and research about teaching**

Teacher education has traditionally focused primarily on subject content, classroom management, teaching methods and a rudimentary understanding of learning, child development and the use of assessment for diagnostic purposes. Teacher education has not kept pace with developments in the science of learning and more in-depth understanding of learning processes. This leads to a serious weak link as the teacher is a critical partner in the implementation of science-based interventions to improve learning. There is need for policy change to create incentives and new requirements in the reform of teacher education curricula and the qualifications of teacher educators to enable the incorporation of the new knowledge and practices. This is a complex issue because teacher education takes place in universities and universities have autonomy over their programmes and hiring practices.

There is also need to better understand the process of teaching and the underlying cognitive, behavioural and social processes. Teaching is a complex cognitive skill that requires real-time learning (e.g. of cues from the learner, class) for real-time decision-making involving many factors (the student, the task, the classroom environment, the teacher's expertise with the material, the teacher's cognitive processes). Currently there are few studies on how teacher decision-making affects student learning; such studies would also benefit from collaborations among basic science researchers, teachers and teacher educators.

New technologies with learning analytic functions can be used to support teaching and learning in the classroom by supporting teachers to adapt lessons for students of different abilities or as a teacher's aide with large or multi-grade classrooms. Teacher training and technical support of teachers are needed for timely incorporation of learning technologies for pedagogical purposes.

- **Investment in socio-technical infrastructure to facilitate knowledge convergence and collaboration among research, educator and policymaker communities**

Effective collaboration among disparate disciplines spurs innovation and is critical for solving society's complex problems. Investment in cyberinfrastructure for the Science of Learning community will take advantage of the affordances of technology to bridge disciplinary and geographical barriers so that researchers and stakeholders can better collaborate and converge their expertise and resources towards shared goals and problem-solving. Such investment in infrastructure will capitalise on the growing international expectations that the science of learning can play a vital role in training the research community to master the skills necessary to benefit from an increasingly data-intensive environment; to build a foundation of shared values and standards that facilitate transparent, high-quality science; and to foster a culture of ethical, responsible innovation that anticipates and addresses the threats and vulnerabilities accompanying the digital age.

The views expressed in this article are those of the authors. They do not necessarily represent the views of the United States National Science Foundation, UNESCO, nor the United States Government.

Part I. Interplay between the learner and the environment

Chapter 2. Neuroscience and education: How early brain development affects school

By

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Research on young children reveals their extraordinary ability to learn. Early learning prepares children to succeed in school and is a key factor in enhancing education worldwide. Regarding language and literacy, high quantity and quality of language addressed to young children, and parents' use of the speaking style called "parentese", are associated with advanced early language skills and reading readiness in children at the age of 5 years. Brain imaging on young infants demonstrates the importance of social interaction for the growth of language. Translational science on "parent coaching" for children's language skills resulted in significant increases in both parental language to infants and language skills in children. A method and curriculum created for teachers to enhance early bilingual language learning ignited dual-language learning in infants aged 7 months to 3 years with 1-hour per day of instruction. Scientific studies of children's minds and brains can positively affect education policy.

One of the transformative areas of discovery of the science of learning centres focused on the developing mind and brain of the child. Children's extraordinary learning during the period from birth to five years of age was shown to be far greater than scientists and educators previously thought. During this early period, scientists have shown that brain growth and behavioural advancements in learning can be directly linked to a child's opportunities to learn, and that reduced opportunities to learn can contribute to a lack of "preparation" for formal schooling. The "preparation gap" has been linked in numerous studies to a failure to succeed in school and in life.

The science of early childhood has shown not only that our youngest citizens learn more and learn earlier than previously thought, but also how they learn, and why they do or do not learn. These discoveries have produced a grand challenge for educators and policymakers, not only in the United States but all over the world as governments begin to understand the value of investing in young children's natural abilities to learn. Governments worldwide are now seeking science-based information about how children learn with the intention of using that information to affect policy.

The goal of this chapter is to briefly share some of the exciting basic science discoveries on early learning and brain development and to describe successful interventions that show promise for scalability in early education centres and with parents who want to understand how to best support their children's learning.

Integral to these discoveries is the work on the developing brain. My laboratory pioneered brain measures that are safe and non-invasive for use with young children. Our approach was to develop methods that allowed us to use sophisticated and safe brain imaging equipment (magnetoencephalography or MEG, see Figure 2.1) to record, for the first time, brain activity as infants listen to words or music, look at people or objects, or experience tactile stimulation. MEG analysis produces a movie that shows the baby brain at work and is helping us uncover the mechanisms underlying learning that can only be revealed by brain imaging infants as they engage in a task.

The discoveries discussed here use early language learning as a model system. Language learning provides an example in which brain imaging and behavioural studies reveal the impact of experience on learning and explore the brain mechanisms underlying young children's extraordinary neuroplasticity – the ability of the brain to change with experience. Language learning thus provides a window into the young child's brain. Basic science discoveries have elucidated how language learning works, what it requires, and guided us towards language interventions – with parents and in schools – that successfully improve children's language learning outcomes.

Figure 2.1. An 11-month-old infant being tested in the MEG machine

Source: Ferjan Ramírez, N. et al. (2017[1]), "Speech discrimination in 11-month-old bilingual and monolingual infants: A magnetoencephalography study", Developmental Science, Vol. 20/1, p. e12427, http://dx.doi.org/10.1111/desc.12427.

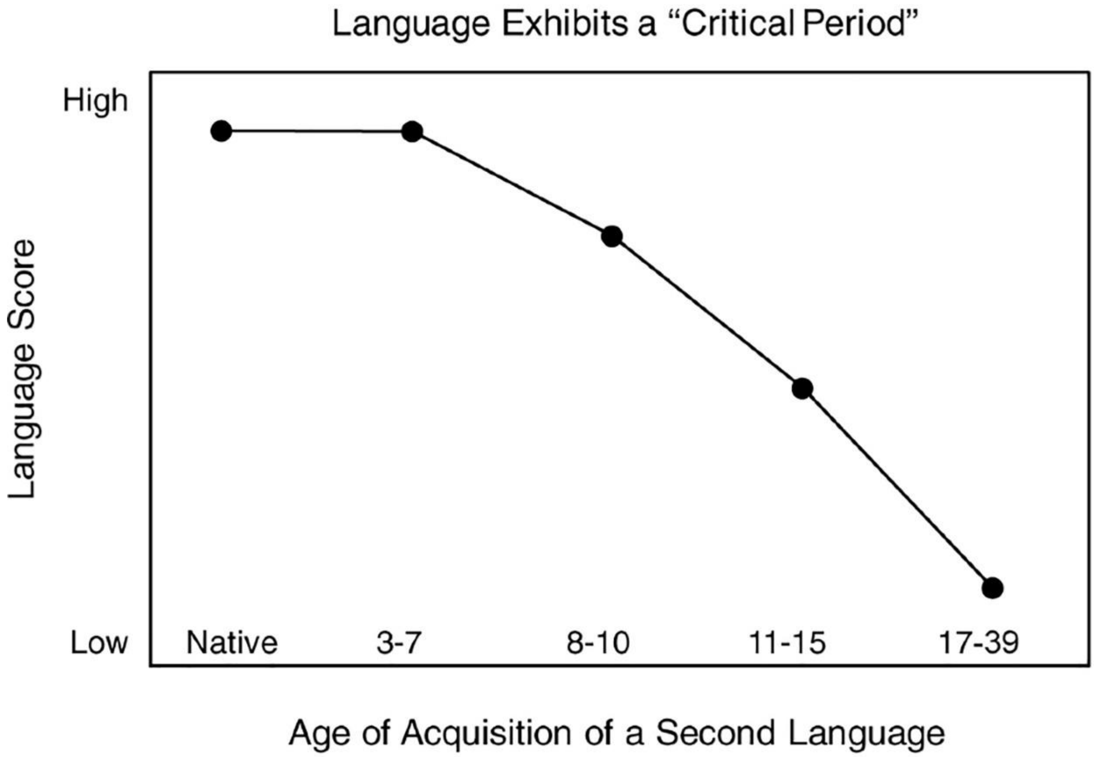
Basic science: Infants are linguistic geniuses

Infants begin life with brain systems that allow them to acquire any and all languages to which they are exposed. A stage-setting concept for human language learning is the graph shown in Figure 2.2 (Kuhl, 2011[2]). The graph shows a simplified schematic of second language learning as a function of age. It shows that infants and young children are superior learners when compared to adults, in spite of adults' cognitive superiority. Language is one of the classic examples of a "sensitive" period in neurobiology (Kuhl, 2017[3]). A sensitive period marks a time in development when experience easily alters brain development. It is a very important time for building the brain's foundation for strong language and literacy skills.

The earliest sensitive period for language learning happens during the first year of life. Between 6- and 12-months of age, infants learn the sounds that will be used to create words in their language. Each language uses about 40 phonetic units (consonants and vowels) to distinguish words, and the child's job is to discover the set of elemental units upon which words in their culture depend and do this before their first birthdays when initial word learning begins. Studies in my laboratory demonstrate that until about six months of age, infants from all nations are able to discern differences among the sound units that distinguish words in all of the world's languages. This "universal" ability is extraordinary, given that the infants' parents can only discriminate the sounds contained in languages they were exposed to as a child.

By 12 months of age infants' skills narrow – the ability to discern sound differences for languages the infant has no exposure to declines sharply during the period from 6- to 12-months, while their abilities to hear differences among native language sounds improves significantly (Kuhl et al., 2006[4]). The ability to learn during this sensitive window of opportunity predicts the speed at which a child's language will grow to the age of three (Kuhl et al., 2008[5]), and their reading readiness at the age of five. In other words, this initial stage of language learning is very important – it establishes the foundation for language learning and literacy.

Figure 2.2. The relationship between age of acquisition of a second language and language skill



Source: Kuhl, P. et al. (2008[5]), "Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e)", *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, Vol. 363/1493, pp. 979-1000, http://dx.doi.org/10.1098/rstb.2007.

Basic science: How infants learn language

What causes the transition from a "universal citizen of the world" to a "language-bound" listener? We found that two factors hold the key to infant learning during the sensitive period for language: one factor is computational and the other social. From a computational standpoint, an implicit form of learning referred to as "statistical learning" (Saffran, Aslin and Newport, 1996[6]) plays an important role in infants' phonetic learning. During the first year of life infants are highly sensitive to the frequency with which they hear speech sounds – the distribution of the sound types they hear matters. Infants focus on the sounds that occur with very high frequency. Languages such as English and Japanese, for example, differ in the sounds they contain and the sounds' distributional characteristics, and infants are sensitive to these distributional cues.

However, our studies further demonstrated that human infants' statistical learning skills require a social context. The impact of the social brain was shown in a study with infants at nine months of age, during the sensitive period for early phonetic learning. Infants experienced a foreign language for the first time (Kuhl, Tsao and Liu, 2003[7]), either from: 1) a live tutor; 2) a video; or 3) audio-only presentations. In all conditions, American infants listened to four different native speakers of Mandarin Chinese during 12 sessions scheduled over 4-5 weeks. The foreign language "tutors" read books and played with toys in sessions that were unscripted. A fourth group, our controls, also experienced 12 language sessions but heard only English from native English speakers. Infants in all four groups were subsequently tested with Mandarin Chinese sounds that do not occur in English using both behavioural and brain measures of learning.

The results indicated that infants learned only from the "live-person" sessions. Infants who heard the new language from live speakers performed as well on the Mandarin sounds as the infants in Taiwan who had been listening to these sounds for ten months. Infants exposed via video or audio-only performed at chance, just like the control group who heard only English. Using the same experimental design, we extended our studies to Spanish. These new studies demonstrated that infants not only learn Spanish sounds through social exposure (Conboy and Kuhl, 2011[8]) but also a set of Spanish words that were used during the language-exposure sessions (Conboy and Kuhl, 2010[9]). Moreover, our Spanish experiments demonstrated that infants' social behaviours – their eye-gaze shifts from the tutor's face to the objects the tutor held while naming them in the foreign language – predicted the degree to which infants learned both Spanish sounds and Spanish words (Conboy et al., 2015[10]).

These results were surprising. Scientists had underestimated the power and necessity of social interaction for learning. The study's result was reported widely by the press and it raised issues that are increasingly debated today about humans' need for a social context during the early period. In a world in which technology is ever present in adults' lives, and one in which even very young children are seen using smart phones and iPads, our finding raises issues about children's learning from technology. These and other findings led paediatricians in the United States to recommend that until two years of age, parents should not rely on screen technology for learning. The finding led us to argue that social interaction "gates" early language learning, that it is essential for infants to interact socially with people to learn (Kuhl, 2007[11]).

Basic science: Language input

Classic studies by Hart and Risley in the 1990s (Mabry, 1997[12]) in the United States demonstrated vast differences in the number of words children heard at home depending on whether they were growing up in families whose parents were on welfare as opposed to growing up in families whose parents were professionals. By age three, these data showed a 30-million-word gap for welfare children compared to children with professional parents. Brain (Raizada et al., 2008[13]) and behavioural (Fernald, Marchman and Weisleder, 2013[14]; Hirsh-Pasek et al., 2015[15]) studies confirm a pattern of association between brain function in five-year-old children and the socio-economic status (SES) of the child's family – when IQ, current cognitive skills and current language skills are measured in five-year-olds, the family's SES was the most powerful variable explaining differences in brain function in five-year-olds. Children need opportunities to learn in the early years of life for their brains to reach their full potential.

Human social interaction and language input from parents – talking and reading to children at an early age – are clearly important factors for successful language learning. But how much language do infants need to learn effectively, and does it matter how you talk to infants? My laboratory's studies have recently focused on the quality of language input. We have found that parents' use of the special speech register known as "parentese" predicts advanced future language development in children, regardless of SES. Parentese, which has a higher overall pitch, exaggerated pitch contours, a slower tempo and acoustically clearer phonetic units – is associated with advanced future language abilities in both monolingual (Ramírez-Esparza, García-Sierra and Kuhl, 2014[16]) and bilingual infants (Ramírez-Esparza, García-Sierra and Kuhl, 2017[17]). Parentese increases children's attention, engages them and exaggerates the acoustic differences between sounds (Kuhl et al., 1997[18]). Our brain studies show that when young infants hear speech we see brain activity not only in the auditory areas of the brain but also in the brain centres that are responsible for children's ability to respond to us verbally. Even before infants can speak, hearing adults talk to them prompts their motor brain centres to rehearse the motor movements necessary to allow them to join the social exchange (Kuhl et al., 2014[19]).

In the parentese studies, we recorded infants at home using small and highly accurate microphones made by LENA (LENA Research Foundation, 2015[20]) that infants wore in light-weight vests as they went about their daily lives. We analysed the number of words infants heard and measured "turn-taking" events when parents and children exhibit back and forth language interactions. The prevalence of "parentese" versus "standard" speech was also measured. In infants recorded at 11- and 14- months of age, the prevalence of parentese in the home predicted the number of words they had mastered by two years of age. Infants who heard the most parentese each day learned over twice as many words as those who heard standard speech most of the time.

Science of the bilingual brain

Parents and teachers in the United States often believe that bilingualism puts children at risk for academic failure, confusion or language delay, but the research does not support this belief (Ferjan Ramírez and Kuhl, 2017[21]; Hoff et al., 2012[22]). Instead, our MEG brain studies have shown that when infants are exposed to two languages, the infant brain is just as capable of learning two languages as it is of learning one. In fact, bilingual children's productive vocabulary skills, when combined across both languages, is equal to or exceeds that of their monolingual peers (Ferjan Ramírez et al., 2017[1]; Hoff et al., 2012[22]). Our MEG research and behavioural studies reveal that bilingual Spanish-English infants' brain responses are just as strong in response to English as those of monolingual children exposed only to English, and the bilingual infants' brains also respond to Spanish. In other words, there is no evidence that exposure to two languages is harmful to infants' development of either the primary language or the second language. Moreover, there are demonstrated cognitive benefits of bilingualism that include enhancements in executive functions and cognitive flexibility (Bialystok, Craik and Luk, 2012[23]).

With roughly two thirds of the world's population estimated to understand or speak at least two languages, bilingualism has become the norm in many parts of the world. In the United States, the rate of bilingualism is lower than the world's average. Nevertheless, census data indicate that 27% of US children under the age of six come from families where languages other than English are spoken, (Capps et al., 2004[24]) and this number is projected to grow as a result of continued migration and births to immigrant parents. Data indicate that US children who are simultaneously learning two languages (typically referred to as Dual Language Learners, DLLs) often lag behind their monolingual English-speaking peers in academic achievement and also lack a strong foundation in either language due to the low quantity and quality of input in both languages. In 2016, the White House released a policy statement (DHSS, 2016[25]) noting a substantial mismatch between the learning experiences that DLL children need to reach their full potential, and the quality of experiences that they are currently receiving.

Interventions that utilise evidence-based practices to enhance early language learning

My laboratory has developed two language interventions that have been shown to be successful in randomised control trials. One focuses on parent "coaching" to increase parents' use of speaking styles and social exchanges that foster language, and the other is a programme that is successful in creating bilingual infants in early education centres in only one hour per day. These two interventions have the potential to be scaled-up worldwide.

Intervention Science: Parent "Coaching" to Enhance Language Learning

It is not a given that one can "coach" parents to change their behaviour and that this will in turn improve children's developing language skills. To test this idea, we conducted an intervention that involved coaching parents by providing them with information about brain development, language learning and their language input to their children (Ferjan Ramírez et al., 2018[26]). Infants wore LENA recorders over two weekend days at home when they were 6-, 10- and 14-months of age. After the data from the recordings were analysed, we met with parents and shared information and data from their recordings. We discussed the power of the infant brain and the need for parents to talk and read to their children to give them ample opportunities to learn. Data shared with parents included measures of their own language input quantity and quality (parentese) when speaking to their children and were compared to the average data from comparable parents with children of the same age. Parents from a wide range of SES families were involved and they were randomly assigned to either the parent coaching group or a parent control group whose children were recorded in the same way at home but whose parents were not coached.

Parent coaching was very effective. By 14 months of age, parents who were coached showed significant increases in both the quantity and quality of language input and had children who produced significantly more language than comparable parents and children in the control group. Moreover, at 14 months of age our data show that children's language outcomes are significantly higher in the parent-coached versus control children. No differences with the SES of the family were observed. Apparently, when given relevant information about what they can do to enhance their children's language abilities, parents act on that information. They respond by increasing the language-input factors known to be associated with improved language outcomes, and their children's language skills improve. We are now continuing the study to examine the longevity of the effects in parents and children. We also plan to create software that would provide all parents with these tools to improve language outcomes in their children.

Intervention science: Creating bilingual children during the sensitive period

The documented advantages of bilingualism have dramatically increased the demand for bilingual education around the world. Given that research shows that the infant brain is much more adept at learning multiple languages than the adult brain, the demand for bilingual learning programmes for young children is especially strong. In the United States, the growing need to serve DLL children has led to increased interest in evidenced-based methods of teaching, and proven curricula. Research shows that, for infants and young children, social interaction is critical for language learning, and therefore technology is not a viable approach for teaching a second language to this age group. Private schools teaching second languages to infants and young children are very expensive and thus out of reach for many families, and public educational settings lack the resources and curricula to teach second languages to young children as part of their educational experience.

Based on our 30-year history of brain and behavioural laboratory research, we asked ourselves a simple question: If we designed a curriculum and method of teaching based on our research on early language learning, could we successfully teach a foreign language in early educational settings and create truly bilingual minds? Could we ignite foreign language learning in infancy? We designed an intervention called SparkLing™ and conducted a randomised control study in four Bilingual Infant Education Centres in Madrid, Spain (Ferjan Ramírez and Kuhl, 2017[27]) involving over 300 children ranging in age from 7-33.5 months. Children were assigned to Intervention vs. Control groups; Intervention children received 18 weeks of daily one-hour English play-based instruction, using a specially designed evidence-based method and curriculum, while Control infants in the same schools received Madrid's standard method of bilingual instruction. The four Infant Education Centres were neighbourhood schools, and these neighbourhoods differed in SES. Two of the schools served low-income neighbourhoods, and two served middle-income neighbourhoods.

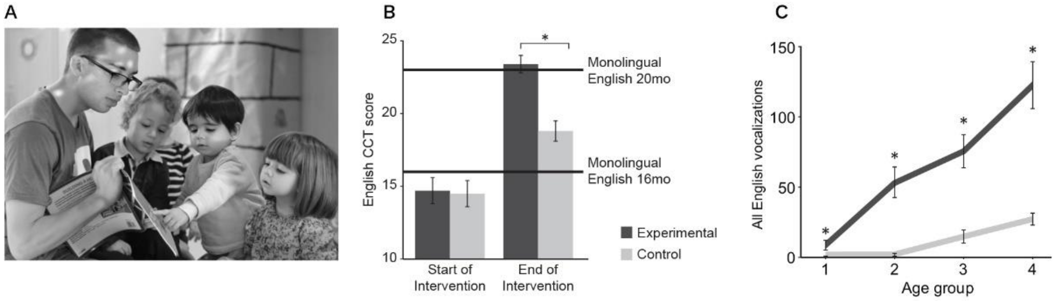
Intervention sessions followed six SparkLing™ principles, each backed by research results: 1) The learning context was highly social and interactive; 2) tutors used a high quantity of English speech in the classroom and all language input to children used "parentese" speech; 3) tutors were native speakers of English; 4) children heard English from multiple talkers; 5) children were encouraged to talk, even if babies were only babbling, and interact from the first session; and 6) the curriculum was play based, with activities adapted for age and children's language levels (Figure 2.3A). Control children participated in the Community of Madrid's standard bilingual programme, which consisted of approximately two hours of weekly instruction through typical nursery school activities such as book reading, nursery rhymes and singing.

Our results demonstrated clear and significant effects of the Intervention at each of the four Early Education Centres in Madrid, for the whole age range tested. We used standardised measures of English and Spanish comprehension at the beginning and end of the Intervention to document learning. We also measured English production, recording infants using LENA recorders. Importantly, the results did not differ by the social-economic status of the neighbourhoods. At the beginning of the 18-week Intervention period (Figure 2.3B), comprehension of English and Spanish was equivalent in Intervention and Control children. At the end of the 18-week period, Intervention children were significantly better at English comprehension than Controls, who also showed gains. Spanish comprehension showed equivalent and significant gains in both Intervention and Control children, as expected, over the 18-week period. English speech production was measured in Intervention children every two weeks, and in Control children at the end of the 18-week period (Figure 2.3).

Intervention children produced significantly more English vocalisations at each age when compared to Controls. Our results suggest that all infants, regardless of socio-economic background, are capable of acquiring a second language through high quality playful social interactions (Ferjan Ramírez and Kuhl, 2017[27]).

Figure 2.3. Randomised control Language Intervention in Madrid Bilingual Infant Education Centres

A: English session at one of the participating schools. B: English CCT scores at the start and at the end of Intervention, for Intervention (black) and Control (grey) participants. C: English vocalisations per child per hour at the end of the 18-week period, for the Intervention (black) and Control (grey) children by age group. Age groups (in months): 1 = 7-14, 2 = 14-20.5, 3 = 20.5-27, 4 = 27-33.5.



Source: Ferjan Ramírez, N. and P. Kuhl (2017[27]), "Bilingual baby: Foreign language intervention in Madrid's Infant Education Centers", *Mind, Brain, and Education*, Vol. 11/3, pp. 133-143, http://dx.doi.org/10.1111/mbe.12144.

Policy implications and the future success of our children

Our results have two significant broader impacts for education and society worldwide. First, investments in early childhood learning can produce profound results, a conclusion supported both by the basic laboratory research on language learning in early childhood and by the translational research we conducted with parents and in Early Education Centres in Madrid. Research can now connect the dots from early childhood to kindergarten readiness in children from all socio-economic backgrounds.

The Obama administration held a White House conference in 2014 that calculated the benefits of investing in children's learning in the first five years of life, concluding that early investments produce large dividends. An analysis by the President's Council of Economic Advisers described specific economic returns to investments in childhood development and early education with roughly USD 8.60 in benefits to society for every USD 1 spent. About half of this return comes from increased earnings for children when they enter the workforce (data from the Bill & Melinda Gates Foundation, as well as the data of Nobel Laureate and economist James Heckman, support this view).

The scientific findings, along with the economic arguments, suggest that governments seeking to enhance K-12 learning consider investing in children before they get to school. Young children have an enormous capacity to learn, and both brain and behavioural science reveals how an enriched environment changes the brain and supports its growth at critical times in development. In many countries around the world, governments and education ministries are discussing strategic plans that include an emphasis on early learning and preparation for school. The science of early learning, including both brain and behavioural studies, has advanced this cause.

Second, the basic science on language learning has led to two evidence-based interventions (SparkLing™ and Parent Coaching) that are effective in children aged zero to three years. Our findings underscore an important point about the human ability to acquire language: Children's language learning is experience dependent, and early learning is potent. All children have the capacity to develop strong language skills not only in a single language but in a second language early in infancy (Kuhl, 2010[28]). Moreover, infants and toddlers can benefit from enhanced language input in a social context both at home and in a school setting. Given the many advantages offered by excellent language skills, and the additional benefits of bilingual language skills, policymakers can affect change that supports learning in families and educational systems worldwide. Basic neuroscience showing how the human brain learns is now reaching out from basic science laboratories to affect the homes and nursery schools of the future and this holds promise in preparing all our children for success in school and in life.

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Chapter 3. How stereotypes shape children’s STEM identity and learning

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The scarcity of women who pursue careers in science, technology, engineering and mathematics (STEM) is of global concern. What are the origins of this gender gap and what can we do about it? To make progress, we need to recognise that the problem starts early in development. In early elementary school, children are already sensitive to cultural stereotypes about “who does mathematics”. This begins to influence their own emerging self-concepts about mathematics. We show that children’s stereotypes and self-concepts have a far-reaching impact on children’s achievement in school. Science-based interventions can be designed to strengthen children’s resistance to STEM stereotypes and to enhance their self-concepts. We discuss the promise of these interventions for sparking children’s engagement, enjoyment and success in STEM.

The scarcity of women who pursue careers in science, technology, engineering and mathematics (STEM) is a concern for educators and policymakers worldwide (OECD, 2014[1]). In the United States, the White House is consulting scientists for advice about how to increase the number of females in the STEM workforce (Rodriguez and Garg, 2016[2]). What are the origins of this societal issue? We believe that the roots of the gender disparity in STEM start early in development.

Our hypothesis is that pervasive societal stereotypes about academic subjects are registered by children at surprisingly early ages. Children come to believe the cultural message that "mathematics is for boys" and this, in turn, influences children's emerging beliefs about themselves. We found a developmental trajectory progresses from: "I am a girl", (gender identity), to "girls don't do mathematics" (stereotype adoption), to "I don't do mathematics" (self-concept). More succinctly: *me = girl, girl ≠ mathematics*, therefore *me ≠ mathematics* (Cvencek, Meltzoff and Greenwald, 2011[3]).

This developmental trajectory has implications for society and helps build a bridge between experimental psychology and education, often called "convergence research". Children's identity – what they believe about themselves and their futures – influences their interests, choices and motivation to learn in formal and informal learning environments. One goal of this chapter is to document when psychological factors, such as stereotypes, begin to take hold in the mind of the child and how these eventually influence children's actual academic achievement. We will show that stereotypes and self-concepts play a powerful and measurable role in academic learning. A related goal is to speculate about what we can do to help children resist stereotypes and increase children's engagement, enjoyment and interest in mathematics. The design and implementation of practical intervention programmes, and their adoption by educators and policymakers, will be enhanced by using the evidence from the science of learning (Master, Cheryan and Meltzoff, 2017[4]; Meltzoff et al., 2009[5]; Newcombe and Frick, 2010[6]).

Establishing a conceptual framework

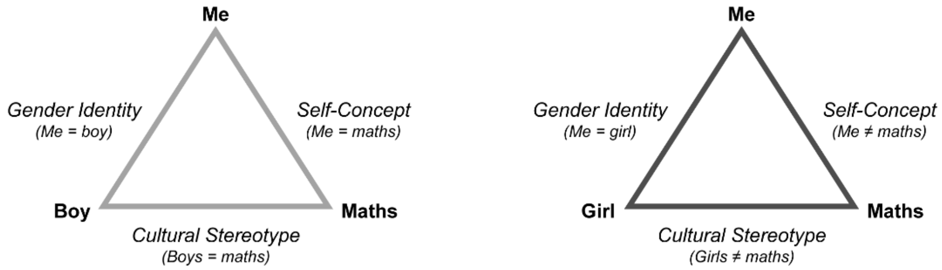
In order to make progress in understanding and ameliorating the gender gaps in STEM, it is helpful to distinguish interrelated concepts that are sometimes confused with each other. We differentiate between children's developing stereotypes and self-concepts; and also draw distinctions between children's explicit (slow, deliberate, conscious) and implicit (fast, automatic, unconscious) cognitive processes. These distinctions are useful for establishing a common interdisciplinary language and for designing more precise measurement tools. Common language and new tools, in turn, lay the groundwork for a convergence between scientific research, educational applications, and policy.

Stereotypes and self-concepts

Studies in social psychology in adults (Greenwald et al., 2002[7]) distinguish stereotypes from self-concepts, but these constructs are often confused in child development and education literature. In this chapter we distinguish these aspects of children's developing social cognition. The stereotype that we focus on pertains to a social group and what academic activities are believed to go with this social category, for example "mathematics is for boys". We refer to this as a maths–gender stereotype. The self-concept does not apply to a social group but to the self, such as "I am a maths person", which we refer to as a maths self-concept. A third related construct pertains to the child's identification with being a boy or girl, their gender identity.

The interrelation among these three constructs is illustrated in a triangle diagram shown as Figure 3.1. The base of the triangle shows the pervasive cultural stereotype that mathematics is associated more strongly with boys than with girls. This stereotype is widely held in the United States and other OECD countries (Leslie et al., 2015[8]; Nosek et al., 2009[9]). Because this is a generalised belief about a social group (based on gender), it is termed a stereotype. The right leg of the triangle shows the link between the self and mathematics, how much an individual identifies with maths. If the individual child thinks "I am a maths person", or "*me = maths*", he or she has a positive maths self-concept. The remaining leg of the triangle captures the idea that many individuals identify with their own gender, which is termed their gender identity. Social psychologists have made these distinctions, and the new aspect added by the work with children has been to empirically determine the developmental order of emergence of these three aspects of social cognition and how they related to actual maths achievement in school.

Figure 3.1. Children's mental network about mathematics, self and gender



Note: The interrelation between self, gender and an academic subject (in this case, mathematics) yields three constructs. The developmental ordering of these constructs and their relation to school achievement is of interest to theory and practice. The left panel depicts the triangle for boys; the right panel depicts the corresponding triangle for girls. (It incorporates the cultural stereotype that maths ≠ girls.)

Explicit and implicit cognition

In examining children's maths stereotypes and self-concepts and the role they play in maths outcomes, it is useful to assess both explicit and implicit cognition in the same children. Explicit processes are typically measured in children by asking them verbal self-report questions (or having them fill out a checklist, scale or bubble sheet). These are traditional measures used with children and adults, and are characterised as being accessible to introspection. By contrast, there has been recent attention to measuring implicit processes, which are usually characterised as being unconscious, non-deliberate responses (Greenwald and Banaji, 1995[10]). During the administration of explicit measures, the participant is aware of what is being tested; but implicit measures do not involve the participant being informed about what is being assessed. Young children may hold stereotypes but may not be able to introspect and articulate them. Even adults sometimes hold unconscious stereotypes that they cannot – or are not willing to – express. Studies show that implicit stereotypes and beliefs exert a powerful influence on people's behaviour, and we have capitalised on new tools to measure children's implicit beliefs in the maths domain.

Each type of measure, implicit and explicit, has advantages and disadvantages (Olson and Dunham, 2010[11]). There are two reasons why we put special weight on developmental studies using both types of measures in the same children. First, children may not be able to fully describe or reflect upon their beliefs about society and themselves, in which case, using both implicit and explicit measures will provide us with a more comprehensive evaluation of the child's mind. Second, new empirical research shows implicit measures are linked to children's actual maths achievement and account for additional variance over and above explicit self-report measures. We obtain a less complete picture of the children if we restrict ourselves to one type of measurement alone. We want to know both what children verbally express and also what they implicitly believe.

Beliefs and attitudes

Here we focus on maths–gender stereotypes and maths self-concepts but in so doing we do not mean to discount the role of other factors related to maths outcomes (e.g. maths anxiety, see (Beilock et al., 2010[12])). We believe, however, that it is useful to distinguish between children's cognitive orientations towards maths (e.g. stereotypes and self-concepts) and their attitudes about maths. Children's emotions and attitudes about maths, for example their "maths anxiety", are certainly important, but we focus on maths stereotypes and self-concepts for two reasons. First, a study using the Programme for International Student Assessment (PISA) database found that the best non-academic predictors of these standardised test results were maths self-concept and maths self-efficacy (Lee, 2009[13]). Second, maths attitudes and anxiety may form relatively quickly, whereas maths–gender stereotypes and self-concepts form more gradually and maybe more malleable to targeted interventions (Gonzalez, Dunlop and Baron, 2017[14]). We take up the issue of how to design effective interventions about maths stereotypes and self-concepts in the last section of this chapter.

Development of maths stereotypes and self-concepts in elementary school children

Rationale

Research with adults shows that there are pervasive societal stereotypes about STEM. There is a stereotype that males, more than females, are linked to maths (and other STEM disciplines) which is held in varying degrees by adults in most OECD countries, including the United States (Leslie et al., 2015[8]; Nosek et al., 2009[9]). When do children acquire this societal stereotype?

Evidence

We assessed a large sample of elementary school children (N = 247 participants, approximately 6.5-10.5 years of age) using both implicit and explicit tests. To obtain the implicit measures we used a new assessment tool, which is a child-friendly version of the adult Implicit Association Test (IAT). The Child IAT is an easy-to-administer sorting task in which stimuli are presented on a screen (Baron and Banaji, 2006[15]; Cvencek, Meltzoff and Greenwald, 2011[3]). Children are asked to rapidly sort the stimuli belonging to four categories by using two response keys. The Child IAT is based on the principle that it is easier to give the same response to items that are associated than if they are not.

Children with a strong maths–gender stereotype (*maths = boys*) should respond faster when maths words and boy names share a response key ("congruent task") than when maths words and boy names are mapped on different response keys ("incongruent task"). Details about the particular variant of the Child IAT used in this study are provided elsewhere (Cvencek, Meltzoff and Greenwald, 2011[3]).

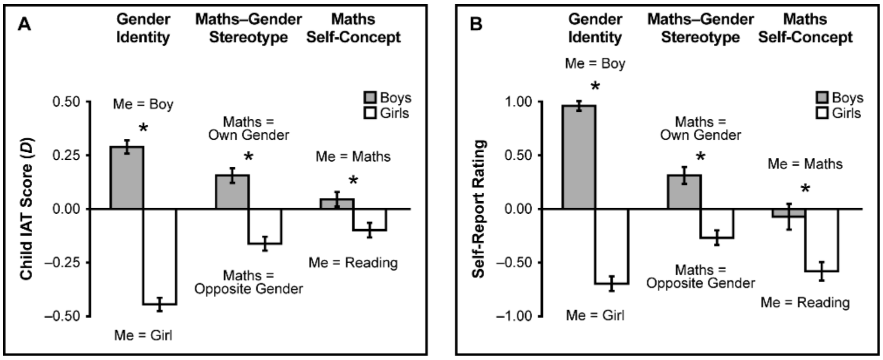
Figure 3.2 displays the results for both the implicit (Child IAT) and explicit (self-report) measures separately for boys and girls, combined over the five elementary school grades.

The left-most pair of bars show, as expected, that boys strongly associated *me* with *boy* and girls strongly associated *me* with *girl*. This is not a surprise. It is known from other tests that gender identity develops quite early – obtaining these results with the Child IAT helps to validate the child implicit measure.

The new findings pertain to maths stereotypes and self-concepts. Both boys and girls associated maths more strongly with boys than with girls (Figure 3.2). There were also differences between the maths self-concepts of boys and girls. Boys associated *me* with *maths*, and girls associated *me* with *reading*. Further probing of the data suggests that the stereotype begins to emerge by 2nd or 3rd grade in this US sample, and the maths self-concepts emerged later.

Figure 3.2. Results of (A) implicit tests and (B) explicit tests of elementary school children

* indicates statistically significant effects; error bars indicate ±1 *SE*.



Source: Cvencek, D., A. Meltzoff and A. Greenwald (2011[3]), “Math–gender stereotypes in elementary school children”, http://dx.doi.org/10.1111/j.1467-8624.2010.01529.x.

Why it matters

The results suggest that the maths–gender stereotype is acquired early. Interestingly, this stereotype is acquired prior to the age that self-concepts about mathematics emerge (Del Rio et al., 2018[16]). Moreover, girls in this age range receive equal or higher school grades in maths than boys (Hyde et al., 2008[17]), and they do equally well on standardised maths tests (Mullis, Martin and Foy, 2008[18]). Thus, the adoption of the maths stereotype and the gender-related differences in maths self-concepts precede actual differences in maths achievement. This has societal and educational implications, as discussed in the final section.

Cross-cultural studies on children’s maths stereotypes and self-concepts: Singapore

Rationale

Singaporean children excel in maths, consistently ranking in the top two or three top countries in the world on standardised tests, ahead of the United States and other OECD countries (Mullis, Martin and Foy, 2008[18]). We conducted cross-cultural work in Singapore to: 1) examine maths stereotypes and self-concepts in high-achieving children; and 2) assess children’s actual maths achievement and its relation to our psychological factors.

Evidence

An interesting developmental picture has emerged from our research with four key points (Cvencek, Meltzoff and Kapur, 2014[19]; Cvencek, Kapur and Meltzoff, 2015[20]). First, the Singaporean children exhibited a maths–gender stereotype, but did so at a slightly weaker level than their same-age US counterparts. Second, Singaporean children's maths–gender stereotypes increased as a function of age. Although the younger Singaporean children did not show significant evidence of the stereotype (whereas US children did), the older Singaporean children began to exhibit the stereotype. Third, there was a significant relation between children's implicit maths self-concepts and their actual maths achievement. There was no such correlation between the explicit self-report measure and actual maths achievement, underscoring the value of implicit measures. Fourth, we found mathematical evidence for "cognitive consistency", that is, we found that the strength of children's maths–gender stereotypes, together with their gender identity, significantly predicted their maths self-concepts. That is, the psychological constructs were related in a consistent and balanced way. Those particular boys who strongly identified with being a boy, and thought that *maths = boys*, also tended to have strong maths self-concepts (which significantly predicted actual maths achievement).

Why it matters

Even in Singapore, where boys and girls both excel in this domain compared to their peers in other cultures, children tend to have stereotypes linking maths with boys. Based on what is known about school grades and performance on standardised tests of maths achievement, both within this study and on TIMSS (Trends in International Mathematics and Science Study) (Cvencek, Kapur and Meltzoff, 2015[20]; Mullis, Martin and Foy, 2008[18]). Singaporean boys and girls are not developing maths–gender stereotypes based on differences in actual achievement (because boys do not outperform the girls on these measures of achievement). Why would Singaporean children hold the stereotype that "maths is for boys"?

Possible sources of the stereotype include parents/family members, peers, teachers, the worldwide web, and media messages. American print media and television programmes are freely available in Singapore. Fully 98% of children aged 7 to 14 have accessed the Internet in the past 12 months, and 76% of Singapore households have regular access to the Internet. It is possible that Western cultural stereotypes reach Singaporean children through the web and other electronic and print media. Also, many Singaporean adults espouse stereotypical views about gender and academic subjects (Nosek et al., 2009[9]), and children may be likely to adopt the stereotypes of their grandparents and parents. In current studies we are investigating whether children pay particular attention to the maths stereotypes of their own father and mother and the degree to which this interacts with the child's own gender (Del Rio et al., 2018[16]). Finally, Singapore is a collectivist culture that values traditionally masculine gender roles. It also prides itself on its educational system, especially the world-famous "Singapore maths" programmes. Because children seek a consistent and balanced organisation of their beliefs, they may come to associate two highly valued categories (i.e. maths and males) with each other.

What can be done? Bridging between psychological science and education

Children are extremely social and pay special attention to others who they judge to be "like me". Meltzoff (Meltzoff, 2007[21]; Meltzoff, 2013[22]), has argued that this drive to identify with others "like me" and to form social groups begins in infancy. This is a fundamental social drive before language and formal schooling and indeed may have neuroscience correlates (Meltzoff and Marshall, 2018[23]). There are benefits of this deep-seated sociality, but it also has costs. One cost is that it leaves our human young vulnerable to the pervasive and sometimes pernicious stereotypes about their own social group.

By preschool or earlier, children develop a sense of gender identity. Many children identify with being a boy or a girl, and feel a sense of belonging to their own gender group. Meltzoff's "like-me" social developmental theory (Meltzoff, 2007[21]; Meltzoff, 2013[22]), proposes that children have heightened attention to how society treats others of their own gender – others identified as "like me". Children's sense of belonging to a social group (based on gender) makes them vulnerable to rapidly acquiring cultural stereotypes about their gender. Children apply the cultural stereotypes about their social group to their own emerging individual identities (self-concepts). On top of this, children seek consistency or "balance" between societal expectations about how people "like me" can and should act and their own sense of self. Thus, when adults in the culture hold strong stereotypes about gender, young girls (similarly to adults) may experience: *me = girl*, *girl ≠ maths*, therefore *me ≠ maths*. Research with adults demonstrates that college age (and older) women sometimes feel conflicts between being a female and identifying with STEM disciplines that are not stereotypically associated with women in their society (Master, Cheryan and Meltzoff, 2016[24]; Nosek, Banaji and Greenwald, 2002[25]). Obviously, women may also excel in stereotypically male disciplines, but such success may be accompanied by extra psychological pressures that are not experienced by their male counterparts.

Our central thesis is that these psychological pressures begin to exert themselves early in development. Once stereotypes are internalised, students may begin to devalue particular school subjects, not because they have experienced difficulties with those subjects in the past, but because the stereotypes connote that they may experience difficulties in the future. A tendency to organise social knowledge in a way that is cognitively consistent or balanced implicates maths–gender stereotypes as an early developing "mental filter" that differentially influences boys' versus girls' developing maths self-concepts. This can, in turn, influence their maths achievement and aspirations for the future. Cultural stereotypes block or dissuade many young girls from engaging in certain maths and STEM-related activities, with the cost that society misses out on the potential contributions of large numbers of our youth. This also squarely raises issues about gender equity.

Translational impact

The scientific findings provide information that may be of practical use to teachers. For example, Carol Dweck (Dweck, 2006[26]) has shown that "mindsets" influence learning, and this has been extended to learning about STEM (Master, Cheryan and Meltzoff, 2016[24]). It is likely that cultural stereotypes about maths contribute to some girls' belief that they lack maths ability and perhaps nudges them towards a mindset that this is an inherent state (linked to their gender), which may prompt them to put less effort into mathematics. This immediately suggests "convergence research" in which scientists and practitioners co-operate to design valid and reliable ways to both 1) identify such beliefs early in development (when they may be malleable) and also 2) to design intervention tools to change this trajectory.

Regarding the early identification issue, our child implicit measures are easily administered, psychometrically sound and extremely sensitive to individual differences. Implicit measures have the potential to be used, alongside other already existing batteries, as diagnostic, teacher-administered tools to identify students who are at risk for lower academic performance. Regarding the design of interventions for young students, one could seek to change their beliefs and motivation about maths (Master, Cheryan and Meltzoff, 2017[4]), their actual maths skills (Clements and Sarama, 2011[27]), or both. Interventions on maths skills are the most common approach, but we suggest that intervening to change young students' beliefs and motivation about maths might also be effective and cost-efficient. Of course, doing both in parallel would be ideal, because the two approaches probably interact with each other in positive ways. Below we offer some speculative ideas about how to use existing research to design interventions to help reduce the impact of cultural stereotypes and improve children's maths self-concepts. The ultimate goal is to have young children approach and enjoy maths and other STEM disciplines. By changing students' underlying beliefs and attitudes, we may in turn influence their behavioural choices and engagement with maths-related activities, and thereby contribute to enhancing skills and achievement.

Interventions targeting students' thoughts and feelings about school – rather than solely teaching children academic content – can have long-term effects on educational performance (Dweck, 2006[26]). Building on this work, we believe that interventions concerning children's maths stereotypes and self-concepts can be designed in an age-appropriate fashion for elementary school children. One possible way to strengthen young students' identification with maths is to have them "approach" maths. At the most basic level, approach behaviours can be conceptualised as pulling something or someone towards one's body. Work with adults found that training female college students – who initially had weak implicit maths self-concepts – to approach maths by pulling a joystick towards themselves increased their implicit maths self-concepts relative to those who were trained to avoid maths by pushing a joystick away (Kawakami et al., 2008[28]). We are working on designing a similar intervention for elementary school children.

Another possible intervention derives from providing young children with an opportunity to affirm their identity as a maths learner, along the lines that has been used with older students (Yeager and Walton, 2011[29]). It would be possible to have very young children reflect on how good they are at numbers or maths, and have them generate some reasons why it is important to be good at this activity, which could have longer-term benefits for children's motivation and learning in maths. Another promising direction is to re-design the classrooms and curricular resources to remove gender stereotyping and convey a broader diversity of people who are associated with and good at maths (and STEM more generally) (Cheryan, Master and Meltzoff, 2015[30]).

Designing early interventions can have cascading and cumulative effects as the child develops. Early interventions may be particularly effective due to the malleability of maths stereotypes and self-concepts during their embryonic stage, when first being acquired. Interventions involving the whole family – parents and siblings included – warrant special attention. The family is often the young child's first "culture;" parents/close-kin have a powerful influence of children's developing sense of identity, who they are and what they aspire to become.

Society will profit from a convergence of multiple scientific disciplines co-operating to address scientific puzzles that address societal concerns. In psychology and education, a goal is to develop and scale up interventions that help children reframe or resist the effects of stereotypes and increase their identification and joyful engagement with mathematics and other STEM disciplines. By investigating children's stereotypes, identity, and maths outcomes we can contribute evidence-based information that can help achieve this end.

This may provide a showcase example of how the science of learning can fulfil its potential for advancing practical responses to problems that matter to society.

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Chapter 4. Race and education: How inequality matters for learning

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This chapter highlights the importance of considering and addressing issues of race and inequality if one is concerned with improving learning and learning outcomes. I argue that the learning sciences creates a unique opening for theorising the ways that race and inequality impact learning, given its attention to the social context of learning. I then introduce the idea of racialised learning pathways, a construct that elucidates how processes of learning and processes of racialisation are intertwined. I examine possible points of disruption to racialised inequality, highlighting several points of intervention in the negative cycle between racialisation and learning. Finally, I consider policy implications.

Inequality in learning outcomes between students from privileged social groups and students from marginalised groups in society is a key issue in education. When education systems globally take up the explicit challenge of reducing inequalities, more learning occurs for more students, and societies are strengthened (Darling-Hammond, 2017[1]). Thus, there is no greater policy challenge than that of creating and leveraging policies and practices in the service of greater equity in learning outcomes. Policies at the national, state and local levels can be effectively targeted to produce greater equity and to disrupt disparities by race and social class.

The learning sciences, as an interdisciplinary field, has opened up new possibilities for taking up complex problems of learning and education, and has provided rich conceptual terrain for bringing new lenses to key issues in education. Perhaps no problem of education has been as intractable in the United States as the problem of educational inequality (Carter and Welner, 2013[2]). Traditionally, the field of education has treated educational inequality as a problem of access; that is, viewing educational inequality as being primarily about the way that we fail, in nations across the world, to provide equal access to high-quality teaching to children and adolescents from marginalised social groups. This is certainly true, but the problem may be even more complex than that when we consider what high-quality teaching actually is. Recent developments in the learning sciences, building on conceptual approaches to understanding the intertwining of identity and learning (see Meltzoff and Cvencek, this volume), have highlighted the multiple ways that race, inequality and systems of privilege matter for learning (Esmonde, 2011[3]; Gutiérrez and Rogoff, 2003[4]; Hand, Penuel and Gutiérrez, 2012[5]; Langer-Osuna, 2011[6]; Lee, 2007[7]), and how processes of identity are key in mediating who has access to learning, and who learns (Mahiri, 2017[8]). Scholars have used the term racialised learning pathways (Nasir and Vakil, 2017[9]) to articulate how race impacts access to learning and infuses the learning process. In this chapter, I centre the concept of racialised learning pathways, explain how these pathways play out in schools, and describe some of the mechanisms that can contribute to or disrupt troubling patterns of inequity. As I do so, I highlight implications both for teaching and for the design of learning environments.

In order to understand why issues of race are so pervasive in learning, it is critical to contextualise our analysis within the long and pervasive history of race and inequality in the United States and indeed internationally. The United States has long been identified as a society that is highly stratified by race, and despite the publicly held perception that the civil rights movement of the 1960’s solved the racial inequities in policy and public systems, the United States is a vastly unequal society, on just about every measurable dimension of social life, including housing, criminal justice, income, wealth, health outcomes and education (Carter, 2012[10]; Nasir, 2016[11]; Omi and Winant, 2014[12]). As one example, the inequities in policing practices and criminal justice outcomes have been hotly debated in recent years, and people have taken to the streets in protest, calling out specifically race-based discrimination against African Americans (Hill, 2016[13]). Schools are another site where inequities continue to persist. From the very beginning of the system of public schooling (Anderson, 1988[14]), to recent analyses of teacher quality and school funding (Darling-Hammond, 2010[15]), schools and schooling outcomes continue to be stratified by race.

These stratified outcomes are not limited to the United States. A recent report by OECD cites the 2015 Programme for International Student Assessment (PISA) study and asserts that “socio-economically disadvantaged students in OECD countries are almost three times more likely than advantaged students to perform below the baseline (Level 2) proficiency in science" (OECD, 2017[16]). Thus, social class and race predict educational outcomes in ways that are disconcerting.

Racial inequality in schools

I have argued that racial inequality in schools can be conceptualised as involving two key processes: 1) access to high-quality teaching, which has direct access on learning through providing unequal exposure to content, critical thinking skills and the opportunity to learn (Darling-Hammond, 2010[15]); and 2) access to identities as learners, which captures how racial stereotypes, processes of positioning in classrooms, and assumptions about which students can be strong learners have important impacts on the learning process (Nasir, 2011[17]; Nasir, 2012[18]; Nasir, 2016[11]). Both of these mechanisms comprise racialised learning pathways.

Defining racialised learning pathways

Building on the tradition of understanding learning as a social and cultural process (Rogoff, 1990[19]; Vygotskiĭ and Cole, 1978[20]), the notion of racialised learning pathways conceptualises learning as occurring along culturally organised pathways of learning and participation. These are constituted by learning activities that move (or do not move) one towards greater engagement and social recognition as competent in learning domains and situations (Nasir et al., 2015[21]). This framework draws attention to the specific resources that learners have access to over time, the ways that learners are positioned within learning the settings in which they participate, and the roles that identity and race play in learning. It also calls out the need for explicit attention to the institutional and societal level influences that provide or constrain access to particular learning environments in ways that marginalise, or push some learners off of pathways. Learning pathways, as a frame, can "deepen our analyses of learning to attend to the ways that learning is fundamentally shaped by issues of culture and by structures that can empower or marginalise" (Nasir and Vakil, 2017[9]).

The notion of learning pathways ties moment-to-moment instructional analyses to the broader set of social, political and socio-economic framings of experiences in classrooms. In other words, it allows us to jointly analyse the opportunities for learning and identity on a micro-genetic time scale in classroom interactions (Gutiérrez and Rogoff, 2003[4]; Saxe, 1999[22]), with the way that these micro-environments are part and parcel of socio-political, social, and political trends and patterns (Nasir et al., 2016[23]). While the concept of learning pathways captures the deeply contextual, interpersonal and even cultural aspects of learning pathways, it also attends to the specific issues of racialisation within and between learning pathways. Thus, we use the term racialised learning pathways to highlight how race frames access to learning pathways and defines interactions within them.

We view race, drawing on Omi and Winant (2014[12]), as "a concept which signifies and symbolises social conflicts and interests by referring to different types of human bodies". Thus, race refers not only to membership in racial groups, but also to a tradition that uses racial categorisation to justify stratification and unequal distribution of societal resources. Racialised learning pathways highlights how learning pathways are profoundly connected to the racial stratification and sense-making about that stratification that pervades our society. To attend to racialised learning pathways is to attend to several interconnected aspects of learning environments, including a concern for the identities students do and do not have the opportunity to develop in a learning setting, the ways that power, privilege and marginalisation play out in relation to race in learning settings, how students are positioned through micro-interactions in learning settings, and how access to learning settings is structured and enacted.

One way that race operates as a discourse in development and learning is through racial 'storylines,' or stereotypical artefacts (e.g. "Asians are good at maths") that mediate how individuals make sense of themselves and how they position one another through their actions and interactions (Nasir, 2012[18]). Storylines are often pervasive, unspoken and unconscious ways of thinking that are assumed to be deterministic of individuals' or groups' abilities and ways of knowing. Racial storylines have distinct implications for students' perceptions of themselves as individuals and as learners, especially in domains like mathematics where race stereotypes are especially pronounced and long-standing (Nasir and Shah, 2011[24]). While some storylines are explicit, often racial storylines are implicit, rarely spoken beliefs and values that constitute our social imagination. As such, racial storylines are an undeniable aspect of life in schools and serve to racially and academically socialise students in ways that make available or close down certain identities that may be critical for engagement in learning settings, and ultimately for learning.

An example from research

To better understand the nature of racialised learning pathways, and their connection to learning, an example is in order. In a recent paper a colleague and I describe the racialised learning pathways at a high school that we studied (Nasir and Vakil, 2017[9]). The high school, Bay View High, was one of the highest performing high schools in a city that is highly stratified by race and social class, in the context of a district that has been plagued with frequent leadership changes and financial challenges. The neighbourhood in which Bay View High was set had historically been a high-poverty African American neighbourhood, but in recent years has been increasingly gentrified, whereby young white and multi-ethnic families purchased homes, the nearby restaurant and business district was revitalised, and several high-process high-rise condominium and apartment buildings were constructed nearby. In an effort to recapture a more diverse student population, Bay View started several learning academy programmes, geared towards the humanities and science, technology, engineering and mathematics (STEM) learning, creating rigorous programmes of study, recruiting highly qualified teachers and conducting a separate admissions process for the academies, which start in the 10th grade year. Other learning pathways and a "general population" also existed at Bay View. These included an academy focused on health, one focused on fashion and a green academy. When we entered the school as researchers, it was immediately apparent that these academies were vastly unequal, serving very different student populations. For instance, while the school as a whole is 37% African American, 18% Latino 23% white and 20% Asian and Pacific Islander, the highly prestigious Mathematical Sciences Academy enrols 5% African American, 5% Latino, 28% Asian and Pacific Islander and 38% white. Clearly, the demographics of this rigorous learning academy is not representative of the school. And because the academies determine the exposure to content, high-quality teaching and rigor, these learning academies and pathways are themselves racialised learning pathways.

Importantly, these are not simply different academic tracks. Each of these racialised learning pathways constitutes a 'default' pathway by virtue of race and social class. They are not entirely determined by race or social class, however, the identity processes that take place in the different learning academies further reify notions of who 'belongs' in these academic spaces. In fact, teachers and students that we interviewed were very clear with us that the academies were racially stratified. For instance, consider this quote by a teacher:

> *But this is important, that's why there's the big division. People say, "well Bay Prep is really two different schools", but you know the reality is, it is two different schools. There's kids who are prepared for high school, there are kids who are not prepared for high school. That's the big problem with what you see the demographics of this programme...I know [that] might be a question.*

However, while teachers made sense of this stratification by arguing that students were not "prepared" for the rigors of the work, and that preparation differences accounted for the under-representation of Black and Latino students in the rigorous academies, students pointed to the identity issues and the challenges with being in culturally white learning spaces. One African American student reported:

> *Last year was stressful 'cause I did not know how to relate to others. It wasn't the same as if there were, you know, if was talking to a Black person, I feel like they can relate to me more 'cause they have the same experiences. I would really relate easier. Yeah. So I felt kind of ostracised when I was in [the Academy]. Like it was just, yeah…I guess it was the simple things like talking, not everyone laughs at the same jokes, not everyone knew about the same stuff, when I talked about movies or music.*

This student comment highlights the significant identity challenges that this student faced within the academy whereby they felt disconnected culturally and socially, which resulted in the student deciding to leave the academy the following year. This example illustrates how students can be placed on pathways where they have greater or lesser access to learning content, but also importance of not only access to the physical learning space, but the important of access to the identity space as well. Learning pathways then are constructed in both real ways and in symbolic ways.

Mechanisms that contribute to and disrupt unequal racialised learning pathways

I have described the nature of racialised learning pathways, and provided an empirical example of how these played out in one high school. These pathways are actively maintained through several key mechanisms at multiple levels that operate to keep these structures in place. However, it is also possible to disrupt these racialised learning pathways; that is, they are not set in stone, and the possibility for equity does exist. In this section I highlight both the mechanisms that keep these pathways in place, and those that disrupt them in the service of greater equity.

Mechanisms that contribute

Unequal learning pathways, as is illustrated in the case presented, are connected to the broader contexts within which schools are set. This includes norms of neighbourhood segregation, which then get reflected in segregation both within and between schools. Segregation allows for inequity to persist (Orfield, 2001[25]), which was one of the reasons the civil rights movement focused so fervently on school integration as a mechanism for societal change. Neighbourhood segregation then, and the ways it gets reproduced within and between schools is a mechanism that contributes to the presence of unequal learning pathways.

Pervasive racial stereotypes about learners also contribute to the perpetuation of unequal learning pathways (Nasir, 2012[18]). This occurs both because stereotypes contribute to the negative self-perceptions of students from marginalised groups, and because stereotypes (operating through implicit bias) frame how students are positioned and treated as learners in learning spaces. These stereotypes often inform how unequal access is perceived and responded to, making it seem "natural" that students of colour would not be in the most prestigious schools or academies within schools, thus making it difficult for such norms to be challenged.

Mechanisms that disrupt

As I have noted, while these default racialised learning pathways are powerful, they are not impervious to change. In this section, I draw on lessons gleaned from studying classrooms where unequal racialised learning pathways have been disrupted. I highlight two approaches to creating more expansive and equitable learning pathways; one where identity work was from and centre in supporting students in countering long-standing racial stereotypes, and another where students were positioned in powerful ways in relation to the content (in this case mathematics) thus providing access to a rigorous maths learning pathway.

One important mechanism to disrupt unequal learning pathways is to consciously address the identity issues related to racial stereotypes that hinder learners from marginalised groups. This often takes the form of explicitly addressing racial stereotypes and their implications as a part of classroom life. In one series of studies, I, along with my colleagues, examined the learning processes and social environment in classrooms that were targeted towards supporting the achievement and engagement of African American male students through a district-wide Manhood Development programme. One key finding was that instructors in these classes, targeted towards African American male middle and high school students, were intentional about disrupting the pervasive negative stereotypes about African American males. They utilised classroom discourse, fieldtrips, guest lectures and implicit and explicit modelling to both critique prevailing stereotypes of Black males as anti-intellectual, unemotional and unproductive and to provide counter-examples to model for young people the range of possibility for their identities that moved beyond negative racial-academic stereotypes (Givens et al., 2016[26]). This explicit treatment of harmful racial stereotypes provided a space where young people could redefine their identities, learn to challenge prevailing stereotypes, and connect more deeply with school. This then allowed them to expand their own learning pathways, and access a wider range of academic opportunities at the school.

Another key mechanism is to create pathways of access to important intellectual content and to position learners from marginalised groups in powerful ways in relation to that content. While the Manhood Development programme took up issues of students identity explicitly, in a study of a successful equity pedagogy in an urban high school, teachers created expanded learning pathways by positioning students as capable learners of mathematics, and creating learning experiences in the classroom that allowed them to master difficult mathematical content successfully (Nasir, 2014[27]). Key in this effort was the use of challenging group tasks that provided students with the opportunity to work on difficult maths problems together, and a course-taking structure which valued heterogenous classrooms (and did not engage in tracking by ability). These classes provided students the opportunity to become powerful mathematical thinkers, and supported them in achievement in mathematics and in persisting in taking high-level mathematics courses.

Importantly, both of the mechanisms described above – making identities available and positioning students in relation to intellectual content – need to occur as an intentional effort on the part of the institution, be it a school, classroom or school district. In other words, these efforts are strongest when not executed as isolated strategies, but when designed as aspects of a holistic system with clear and shared equity goals. It is then that new kinds of learning pathways can be created, and expanded opportunities for learning can begin to blossom.

Conclusion

In this chapter, I have highlighted the multiple ways that access to education and to learning are racialised, and have articulated a way of understanding the connection between race and learning. I have also described some key mechanisms that perpetuate or disrupt current racialised learning pathways. This thinking, in many ways, is a part of a new turn in learning sciences research. Learning science is increasingly taking up concerns with conceptualising the relation between power, privilege and learning, and is viewing race as a key aspect of systems of power (Esmonde, 2017[28]; Hand, Penuel and Gutiérrez, 2012[5]; Langer-Osuna, 2011[6]). In doing so, a deeper understanding of how race, power, and privilege operate in learning settings is taking shape.

Policy implications

- Inequality in schooling outcomes is deeply tied to unequal access to high-quality teaching; creating greater equity and access should be a key goal for education systems and school districts globally.
- Inequality is perpetuated at both the school and classroom levels; policy solutions should attend to both.
- At the school and district level, state and local policy-makers and school district leaders should discontinue tracking practices in all forms and attend to creating access to rich curriculum and deep learning for all students, especially those from marginalised groups that tend to have less robust access to such learning environments.
- At the classroom level, teachers need to provide opportunities to explicitly support students in building strong academic identities by challenging students with rich curriculum and high expectations.
- Teachers should also explicitly attend to supporting students from marginalised groups in resisting racial stereotypes and storylines and should create classrooms and learning environments that disrupt such storylines.

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Chapter 5. The role of anxiety and motivation in students’ maths and science achievement

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Ensuring that all students can perform up to their potential in school is a central goal in education. As such, improving students’ ability and skill is often the main focus of educational interventions. However, psychological factors such as anxiety and motivation are also important for student learning and success. Those students with high levels of anxiety and low levels of motivation tend perform below their capabilities – even when they have high levels of skill and ability. We review recent work showing the importance of parents and teachers in shaping students’ attitudes, interest and persistence in maths and science. We also highlight classroom and home interventions shown to be effective in combating high levels of student anxiety and low levels of student motivation and reducing the harmful learning consequences of negative affect.

There is no doubt that students' ability and knowledge are important predictors of their advancement in school and beyond. However, it is also the case that students' attitudes and beliefs about school play a large part in their academic success. In this chapter, we focus on recent research around the world demonstrating the important role of academic attitudes (specifically anxiety about performing at a high level and motivation to exert effort in order to learn) in academic achievement. First, we define key attitudes that are implicated in students' academic performance. Second, we discuss the growing evidence about the influence of caregivers in the development of students' academic attitudes. Third, we review emerging research on interventions to improve academic achievement by changing students' anxiety and motivation as well as the attitudes of the adults who interact with students. This research demonstrates that efficacious low-cost and light touch interventions are available to put into educational practice to help students learn and achieve. Finally, we point to future directions for research in this area.

Performance anxiety

Imagine two middle school students, Jason and Tracy, who have equivalent maths knowledge and are about to take a test on algebra. Jason always gets anxious when doing maths, and as he begins the test, he starts thinking negative thoughts (e.g. "I can't do this! I'm just not a maths person") and his heart starts racing. The worries he experiences make it hard for him to concentrate while calculating answers to the maths problems. Tracy, on the other hand, is not anxious about maths at all and experiences none of these anxious responses. Thus, she can more easily concentrate on the maths problems and receives a higher test score.

Performance anxiety is defined as the worries and fears students have about performing well on a certain task or in a certain domain (Beilock, Schaeffer and Rozek, 2017[1]). Maths anxiety, or fears and apprehension about doing maths, is the most highly researched subject-specific type of performance anxiety in school, so we focus our discussion on that topic, even though students can suffer from performance anxiety in other subjects as well (e.g. anxiety about reading or about taking tests generally). Maths anxiety can be expressed as negative thoughts and emotions about doing maths as well as increased physiological arousal, which can include an elevated heart rate, dry mouth and sweaty palms (Dowker, Sarkar and Looi, 2016[2]).

Maths anxiety has been consistently shown to be associated with worse maths performance for students (Dowker, Sarkar and Looi, 2016[2]). Recent findings from international assessments of adolescents' support that this is truly a global phenomenon (Foley et al., 2017[3]). In a report on data from the Programme for International Student Assessment (PISA), high maths anxious students performed worse than low maths anxious students in 63 out of the 64 countries examined. Not only was that the case, but countries with higher levels of maths anxiety (high maths anxious countries) tended to perform more poorly than countries with lower levels of maths anxiety. This effect was reliable for high ability, middle ability and low ability students and was even descriptively stronger for high ability students. Other studies, mainly carried out in the United States, show that maths anxiety arises early in development – by first grade, students who report feeling anxious about maths perform worse at maths (Ramirez et al., 2016[4]). These findings are concerning, given that more than 50% of people suffer from some level of maths anxiety by adulthood (Dowker, Sarkar and Looi, 2016[2]).

Why does maths anxiety undermine students' academic achievement? Although various types of performance anxiety are topic-specific (e.g. maths anxiety) or task-specific (e.g. test anxiety), all types of performance anxiety are theorised to work through similar mechanisms (Beilock, Schaeffer and Rozek, 2017[1]). In particular, working memory, or our limited capacity system used for temporarily storing information, is implicated in the deleterious effects of performance anxiety (Beilock, Schaeffer and Rozek, 2017[1]). Individuals differ in their natural working memory capacities, with some having higher working memory (HWM) capacities and others having relatively lower working memory (LWM) capacities. Students with higher levels of working memory tend to do better on academic tasks, likely because they can store information to use while doing, for example, different parts of a maths problem. Counterintuitively, individuals with higher levels of working memory have been shown to be most hurt by performance anxiety (Beilock, Schaeffer and Rozek, 2017[1]; Ramirez et al., 2016[4]). For example, those students would otherwise be able to use highly efficient problem-solving strategies that make use of their HWM, but maths anxiety reduces the availability of cognitive resources, leading to underperformance compared to HWM students who are low in maths anxiety (Ramirez et al., 2016[4]).

Recent neuroscientific work has also shed light on the mechanisms underlying the effects of maths anxiety on maths performance. In the first study on the neural basis of maths anxiety, 7- to 9-year-old children were asked to complete maths tasks while having their brains scanned in a magnetic resonance imaging (MRI) machine (Young, Wu and Menon, 2012[5]), allowing researchers to see which parts of the brain are being used during the task. Results showed that higher maths anxious children, as compared to lower maths anxious children, had increased activation in areas of the brain related to negative emotions as well as those involved in controlling negative emotions (i.e. hyperactivity in right amygdala and increased connectivity between the amygdala and the ventromedial prefrontal cortex). This pattern of activation suggests that high maths anxious children had to expend mental effort to regulate their anxiety. Other brain imaging studies on adults have supported these findings by showing that even anticipating doing maths activates threat and pain areas of the brain (Lyons and Beilock, 2012[6]).

Motivation

In addition to performance anxiety (and specifically as outlined above regarding maths anxiety), students' motivation to perform well is implicated in maths and science achievement. Consider two high school students: Myeshia and Kenny. Myeshia is very confident in her maths ability. She also views maths as important to her future because she plans to become an engineer, which requires a strong maths background. Thus, she enrols in all of her high school's advanced and optional maths courses, including statistics and calculus. Kenny, on the other hand, is also confident about his maths ability, but he is always asking his maths teachers, "When will I ever use this in real life?" Because he does not see the value of maths, he decides to take additional elective language classes instead of optional maths courses. Inevitably, when taking college entrance exams, Kenny scores lower on the maths section than Myeshia because he was exposed to less maths during high school.

Although there are a variety of theories of motivation relevant to educational achievement, here we focus on expectancy-value theory. Eccles and colleagues have proposed that students' achievement and achievement-related choices, such as being engaged in school and enrolling in elective maths classes, are the result of their expectations to succeed in a particular domain (can I do this?) and how much they value a certain domain (why do I care about this?) (Eccles and Wigfield, 2002[7]). Based on the above examples, it is easy to see how students need to expect to succeed in a topic and to value a topic to be optimally motivated. Both Myeshia and Kenny had high expectations for success in maths, but only Myeshia highly valued maths. This difference in their motivational attitudes led to different choices and to differential maths learning.

Decades of correlational research supports this finding: Both students' expectations for success and how much they value a subject contribute to their academic performance and choices, such as course-taking (Eccles and Wigfield, 2002[7]). These effects appear to replicate internationally with studies on adolescents. Using PISA data from nearly 400 000 students across 57 countries, researchers showed that students' expectations and values in science were associated with a variety of student outcomes, including participation in science-related extracurricular activities and science career pursuit (Nagengast et al., 2011[8]). This pattern of results largely generalised across the various countries in the study. Higher expectations and value promote optimal performance in school through a variety of mechanisms, especially through students' choices to invest in increased effort, engagement and persistence on school-related tasks, such as persisting longer during maths activities like homework and studying (Durik et al., 2015[9]) or choosing to enrol in optional maths courses in high school (Rozek et al., 2017[10]).

The role of teachers and parents in students' attitudes and performance

Having established that individuals' maths and science attitudes can affect their performance, we next ask how these attitudes develop. It turns out that the attitudes of caregivers can influence the attitudes and performance of students. Specifically, teachers' and parents' anxiety and motivational attitudes are associated with students' attitudes and performance.

Teachers

One study of first and second grade teachers investigated whether teachers' maths anxiety was associated with students' attitudes about maths and their maths learning during the school year (Beilock et al., 2010[11]). Results showed that students of maths anxious teachers learned less maths over the course of the school year; however, this finding was only significant for female students. Given that gender is salient even at early ages and elementary school teachers are overwhelmingly female, female students might be more likely to pick up on their teachers' negative attitudes about maths and look to them as role models (Dasgupta, 2011[12]). Female students also developed negative stereotypes about females and maths when they had a maths anxious teacher, which other research has shown is harmful for their attitudes about maths (Cvencek, Meltzoff and Greenwald, 2011[13]). Finally, the analyses suggested that young girls were underperforming in classrooms with maths anxious teachers due to their increased negative attitudes about maths that developed over the school year, suggesting that teachers' attitudes about maths might affect students' maths performance by changing their attitudes about maths.

In addition to teachers' maths anxiety, several studies have shown that teachers' expectations about their students' success in class are associated with their students' own expectations for their success as well as their performance in class. In two studies of elementary school students, teachers' expectations for each student were associated with students' future performance, even after controlling for students' prior performance (Friedrich et al., 2015[14]; Upadyaya and Eccles, 2015[15]). Furthermore, the association between teachers' expectations and students' achievement was partially accounted for by the association between teachers' and students' expectations for success. That is, when teachers viewed a student as more likely to succeed in class, that student viewed himself or herself as more likely to succeed in class, and because of that, students performed better in class.

Parents

Research also supports the role of parents' attitudes in students' academic achievement. Parents' maths anxiety has been shown to be negatively associated with elementary school students' maths learning (Berkowitz et al., 2015[16]; Maloney et al., 2015[17]), such that students learn less maths if their parents are more highly maths anxious. This lower performance, might in turn, contribute to students' maths anxiety (Gunderson et al., 2018[18]). Further, parents' maths anxiety may directly lead to students' maths anxiety (Soni and Kumari, 2015[19]), which may undermine children's maths achievement.

Parents' expectations for their children in school and how much they value maths and science for their children have both been shown to be associated with student attitudes and outcomes (Jacobs and Eccles, 2000[20]). Parents' expectations seem to act as a filter through which children understand their abilities, such that the feedback that children receive in school (e.g. grades) affects their expectations for success to the extent that the feedback affects their parents' expectations for their success in school. This is because children look to their parents to interpret the meaning of feedback (Jacobs and Eccles, 2000[20]). Likewise, parents who value maths and science for their children tend to have children who value these domains and enrol in additional relevant courses in high school (Svoboda et al., 2016[21]).

Interventions to reduce performance anxiety and increase motivation

Recent research in psychology has focused on improving students' performance by reducing negative attitudes or promoting their positive attitudes about learning. Often, these interventions involve activities that students complete in school to change their attitudes about learning in beneficial ways. Though many interventions are student-centred, other interventions focus on parents to help improve students' attitudes and performance.

Student-centred attitude interventions

Targeting students' attitudes with interventions in the classroom has shown much promise as one route to improving students' performance in school. Performance anxiety interventions typically involve students expressing, re-evaluating and/or normalising their worries. Motivational interventions focus on raising students' expectations for success or increasing their perceived value of a subject, such as maths.

One type of performance anxiety intervention, expressive writing, involves having students write about their anxiety before taking a test in order to offload their worries. By doing this, it is thought that students can free up their cognitive resources to use on the test, which would otherwise be consumed by their worries. Indeed, this kind of intervention has been found to improve maths problem-solving performance for maths anxious individuals (Park, Ramirez and Beilock, 2014[22]) and final exam performance for high school biology students (Ramirez and Beilock, 2011[23]).

A second type of performance anxiety intervention focuses on helping students reappraise or normalise their performance anxiety. Reappraisal interventions improve performance by teaching students that the anxious arousal (e.g. fast heart rate) they feel during a test is actually beneficial (e.g. because it means more blood flow and energy in the brain).

Jamieson and colleagues (Jamieson et al., 2016[24]) found that giving community college maths students this information directly before a test improved their exam scores and helped them feel more capable of performing well in the class. Another study found that normalising performance anxiety improved women's performance in college engineering classes and helped them feel more capable of academic success and managing stress in school (Walton et al., 2015[25]), a finding that replicates across several age groups. Interventions that normalise performance anxiety involve teaching students that encountering difficulty in school, on a particular task or in a particular class is an experience common to many students, which helps them attribute low performance to temporary causes (e.g. this happens to everyone at first) instead of unchangeable low ability (e.g. this just happens to me because I am stupid).

A frequently used motivational intervention aims to change students' expectations by teaching them a growth mind-set, which is the idea that their intelligence is malleable and can grow (as opposed to being fixed). Believing that intelligence can grow and change helps students persevere through difficulty and is associated with many positive self-beliefs, which is a finding that replicates in international settings (Claro, Paunesku and Dweck, 2016[26]). In one study, Blackwell and colleagues (Blackwell, Trzesniewski and Dweck, 2007[27]) found that middle school maths students given a growth mind-set intervention, as compared to students in a control group, showed improved motivation and higher grades.

A second type of motivational intervention is used to increase students' value in a topic. These relevance interventions involve asking students to write brief essays to explore the utility of what they are learning by making connections between the material and their lives. In a study of high school students in science courses, results showed that the relevance intervention was particularly effective for students who lacked confidence in their ability to perform well in the class – exactly the students who needed a boost (Hulleman and Harackiewicz, 2009[28]). Students in the relevance condition who lacked confidence in their abilities reported valuing science more and performed nearly three-quarters of a grade point better in terms of their course grade than low confidence control group students. These findings show that relevance interventions hold promise for improving students' attitudes and performance in class.

Parent-centred attitude interventions

The interventions described in the previous section were all directed at students. Another type of intervention focuses on improving students' attitudes and performance by engaging their parents. For example, one parent-centred intervention focused on reversing the negative effects of parents' anxiety on their children's performance (Berkowitz et al., 2015[16]). In this study, intervention group parents were asked to use a maths intervention, delivered via an electronic app on tablet devices, with their children that was designed to provide structured, fun parent-child maths interactions. Control group parents were asked to use a reading app with their children, similar to what many parents already do with their children. Results showed that in the control group, children of maths anxious parents learned less maths during first grade, consistent with prior findings (Maloney et al., 2015[17]). In contrast, in the intervention group, children of maths anxious parents learned as much maths during first grade as children of less maths anxious parents. Thus, providing a way to support positive parent-child maths interactions eliminated the negative relation between parents' maths anxiety and children's maths learning.

Similar benefits have been shown with interventions that target parents' motivational attitudes. In one study, parents of second grade students in Denmark in an intervention group were taught about having a growth mind-set for their children's intelligence (i.e. that their children's intelligence can grow with effort; (Andersen and Nielsen, 2016[29])). Compared to children of parents in the control group, children of parents in the intervention group showed greater improvement in their academic achievement over the school year. In another study, parents of high school students were either assigned to an intervention group that asked them to talk about the relevance of maths and science with their children or a business-as-usual control group (Rozek et al., 2017[10]). The intervention increased the value parents placed on maths and science for their children. Moreover, children of intervention group parents benefitted – they enrolled in more maths and science courses in high school, performed 12-percentile points better on their maths and science subsections of their college entrance exams and reported improved motivational attitudes about maths and science.

Future directions

Although the current state of knowledge has allowed for many important advances, future research is still needed in many areas. Here, we discuss four promising future directions. First, more studies are needed to understand how anxiety and motivational interventions may need to differ to be developmentally appropriate for students of different ages and cultural backgrounds. To date, many interventions have focused on students who already exhibit performance anxiety or are beginning to show declines in motivation rather than on preventing anxiety from arising in the first place or maintaining the higher levels of motivation seen for students in elementary school. Further, current instantiations of some of the interventions that have been studied with middle school and high school students may not to work with very young students. For example, expressive writing interventions with adolescents typically involve a reading and writing activity. However, with elementary school students, it might be more feasible to ask students to talk about their worries or to create drawings about their worries instead, given age-related differences in students' abilities to express themselves in writing.

Second, although some interventions are beginning to incorporate technology (Berkowitz et al., 2015[16]; Paunesku et al., 2015[30]; Rozek et al., 2017[10]), it will be advantageous to utilise technology in the development of anxiety and motivation interventions. Technology can help make learning exciting (e.g. more game-like), which could be appealing and motivating for children. Computer adaptive technology also allows for greater customisation for scaffolding to children's specific abilities, which could help with providing more personalised support for each student.

Third, the majority of the anxiety and motivation intervention research focuses on student-centred interventions. However, given the large role that caregivers play in the development of children's academic attitudes, it is important to consider caregiver-focused interventions as well. Parents, in particular, are a relatively untapped resource and can be engaged to help students perform up to their potential in school. Although research is just beginning on parent attitude interventions, three recent studies (Andersen and Nielsen, 2016[29]; Berkowitz et al., 2015[16]; Rozek et al., 2017[10]), suggest that parents can improve their children's performance in school with the help of interventions that change parents' attitudes and the ways they interact with their children. Natural advantages of parent-centred interventions include that students spend more time at home than they do in school, and students keep their parents year after year, as compared to teachers who typically change each year. Given the great potential of parent-focused efforts to improve children's achievement, research should continue to explore the myriad ways that parents can support their children's learning.

Finally, researchers should develop interventions for teachers in order to positively impact their students (e.g. reducing teachers' maths anxiety to help improve their students' maths achievement). The research on parent interventions provides a starting point for thinking about how to create supports for teachers, but teachers work with many students and have different relationships with them than parents, which might require different types of interventions than what is used with parents. Although it might be complicated, intervening to change teachers' attitudes is another promising avenue for improving students' attitudes and performance.

Of course, as described in the intervention section, it is possible to deploy interventions that target students themselves as well as their teachers and parents. A co-ordinated effort that focuses on intervening at all levels (i.e. parents, teachers and students) may lead to the greatest positive impacts on student learning outcomes.

Policy implications

Ensuring that all students can perform up to their potential in school is a central goal in education. As such, improving students' ability and skill is often the main focus of educational interventions and policy. However, psychological factors, such as anxiety and motivation, are also important for student learning and success. Those students with high levels of anxiety and low levels of motivation tend to perform below their capabilities – even when they have high levels of skill and ability. In response to these findings, researchers have developed an emerging group of low-cost and light touch home and classroom interventions to promote student learning by decreasing anxiety and improving motivation for students. Policymakers could make use of this research in two main ways. First, schools may benefit from assessing students' anxiety and motivation in addition to academic performance in order to identify when students across the ability spectrum might be suffering from high anxiety or low motivation. Second, policymakers should work with researchers to integrate anxiety and motivation interventions and supports into students' classrooms and home environments in order to enhance student achievement in mathematics, science and other domains.

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Chapter 6. Designing effective number input: Lessons from cognitive science

By

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Mastering a basic understanding of numbers is critically important for children's future success in school, the workplace and everyday life. Unfortunately, individual differences in children's understanding of basic number concepts arise early in development and gaps in number knowledge are particularly apparent amongst children of varying socioeconomic statuses. Research in home and school environments suggests that much of the variability in children's number knowledge can be attributed to differences in quantity and quality of the number-related input that children receive from parents, teachers and caregivers. The present chapter explores sources of variability in children's understanding of numbers, factors that make learning about numbers challenging, and characteristics of effective number input. Finally, we discuss how previous and ongoing research can be useful in informing policies aimed at promoting early number knowledge and reducing achievement gaps.

Whether faced with the task of determining the trajectory of a satellite, developing plans for a new skyscraper, calculating a tip, or doubling a recipe, it is clear that developing a firm competency in mathematics is a crucial component of being successful in school, the workplace and everyday life. Mathematical achievement is a cornerstone of the science, technology, engineering and mathematics (STEM) domains, and as countries around the world recognise the need for a robust STEM workforce to fuel economic growth and foster innovation (Lacey and Wright, 2009[1]), it becomes increasingly important to improve students' STEM achievement in school. Basic maths skills are a necessity for the 21st century workplace (e.g. the logic and reasoning skills acquired through maths are essential to lawyers) and everyday life (e.g. cooking, calculating tips). Moreover, maths achievement levels are associated with other important life outcomes including earnings and contributions to society (Rivera-Batiz, 1992[2]).

A critical piece to improving the quality of mathematics education and STEM attainment in the United States and elsewhere is understanding the development of mathematical concepts in children. Individual differences in mathematical abilities emerge as early as the age of four, prior to the beginning of formal schooling, and these differences are predictive of later achievement gaps (MacDonald and Carmichael, 2017[3]). Additionally, these differences are especially apparent between children from lower and higher SES groups (Jordan, Huttenlocher and Levine, 1992[4]). Understanding how and why these differences emerge will enable us to work towards bridging the gap in maths achievement and encouraging a diverse group of students to pursue careers in STEM related fields.

One foundational area where individual differences are stark, is the understanding of the cardinal meaning of the number words. Although number development begins in early childhood, it progresses slowly and presents a challenge to young children. Children often learn to recite a portion of the count list, like the number words "one" through "ten", by their second birthday, but it typically takes around two additional years to learn what these words actually mean (Wynn, 1990[5]). Moreover, children learn each of the first three or four number words one at a time and in order over a period of 18 months or longer. Only then do children come to understand the cardinal principle, that the last number reached when counting a set represents the value of that set.

Although "number" may appear to adults as a single, unified concept, in reality there are many aspects of number and children do not appear to grasp these all at once (Wynn, 1990[5]). Children must learn that number words describe sets of objects (e.g. "three" tables) and do not label objects themselves (like "table") or even a property of an individual object (e.g. wooden) (Bloom and Wynn, 1997[6]). Some researchers have even proposed that children initially lack the concept of "set" and must develop it in the process of learning the meanings of number words (Carey, 2000[7]). Moreover, learning the meanings of number words requires that children learn numbers that refer to exact sets (e.g. "seven") as opposed to approximate sets (e.g. "some" or "few") (Barner and Bachrach, 2010[8]). Even still, children need to learn how to count as well as how the process of counting is related to individual quantities within the count list (Gelman and Gallistel, 1978[9]).

Related to the issue of why number words are challenging but also important in its own right is the question of how we can intervene to improve children's early number knowledge. The characteristics of number words that make them challenging provide insight into the types of input that may be helpful to teach children the meanings of number words. However, further research is necessary in order to translate the problems of learning number words into potential solutions. One body of research that we will review in this chapter are correlational studies that relate the quantity and qualities of number-related input that children receive to their subsequent understanding of number. Although such work is an important first step towards improving early maths education, even this research must be interpreted carefully given its correlational nature. Therefore, we will also review a growing body of research that is testing many of our theories about what constitutes effective number input by measuring the effectiveness of carefully designed number interventions. Such interventions allow researchers to make causal arguments about what types of number input are effective in promoting number development and are therefore the most direct path towards translating cognitive science to educational interventions.

The role of early input

Research examining children's early experiences shows that variations in children's language input has an impact on their language development and later literacy skills (Huttenlocher et al., 1991[10]). For example, early language input is related to variations in children's vocabulary growth and is responsible for strengthening the processing skills that facilitate language growth (Weisleder and Fernald, 2013[11]). Moreover, the richness of parental vocabulary and the overall quantity of parent talk accounted for differences in children's vocabulary growth both within and between SES groups (Hart and Risley, 2003[12]; Huttenlocher et al., 1991[10]). Based on these findings, interventions efforts have encouraged parents to engage their children in literacy related activities (e.g. Reach Out and Read; Too Small To Fail; Reading is Fundamental).

While there is much focus on the role of parental input on children's developing language skills, less attention is often paid to the importance of early input for the development of children's maths skills. Parents often believe that reading and social skills are more important for their preschool-aged children to learn than maths (Musun-Miller and Blevins-Knabe, 1998[13]) and that maths instruction is best left in the hands of teachers (Cannon and Ginsburg, 2008[14]). There has been pressure on schools and teachers to improve the maths performance of students, ignoring the fact that parents are the also teachers of their children. While a significant source of early number input may in fact be from day care and preschools, parental maths input also plays a critical role in the development of their children's mathematical knowledge (Bhanot and Jovanovic, 2005[15]; Gunderson and Levine, 2011[16]; Levine, Gunderson and Huttenlocher, 2011[17]). Understanding the role of early maths input on children's academic achievement, and assisting parents and caregivers in providing early maths input to children that is both frequent and qualitatively rich may help close the maths knowledge gap that emerges even before children enter kindergarten.

In fact, parents do engage their children in a wide variety of number activities (Blevins-Knabe and Musun-Miller, 1996[18]). Durkin et al. (1986[19]) conducted a longitudinal observation of ten mother-child dyads, and found that parents commonly used number words when their children were between the ages of 9 to 36 months. Further, the frequency of parents' use of smaller number words, that is "one" through "four", increased between the ages of 9 to 27 months, overlapping with the period when pre-schoolers' counting skills are developing (Gelman and Gallistel, 1978[9]). These naturally occurring maths interactions may provide natural leverage points to increase the quantity and quality of "maths talk".

Importantly, parental maths input varies by SES; when low- and middle-SES parents were asked about the types and frequency of maths activities their children engaged in at home, middle-SES parents reported engaging their children in a wider variety of maths-related activities and provided more support than did lower-SES parents (Starkey et al., 1999[20]). Middle-SES mothers also report engaging their children in more complex mathematical activities than low-SES mothers and these differences were correlated with children's performance on complex mathematical problems (Saxe et al., 1987[21]). It is possible that these SES differences are related to parents' varying education levels, differences in their exposure to mathematics courses, their own maths anxiety, and/or the value they place on their children's mathematical ability (Starkey et al., 1999[20]).

Not only do parents engage their children in maths talk to varying degrees, these differences predict children's later success in mathematics in the United States and elsewhere (Blevins-Knabe and Musun-Miller, 1996[18]; Huang et al., 2017[22]; LeFevre et al., 2009[23]). For example, Levine et al. (2010[24]) found large differences in the amount of number talk that parents engaged in with their children, and these differences related to children's later maths knowledge. They videotaped natural interactions of 44 parent-child dyads in their homes, visiting every 4 months for 9 visits starting at the age of 14 months. In their videos, Levine et al. (2010) found that the number input children received ranged from a low of 4 number words to a high of 257 number words across five 90-minute sessions – extrapolating this 60-fold difference would amount to a range of 28 to 1799 number words over the course of a week. Additionally, this variation in number input was related to children's own talk about numbers and their later understanding of the cardinal values of number words, even when controlling for overall parent talk to the child and SES, suggesting that it was specifically talk about numbers, and not talk in general, that is connected to later number knowledge. Interestingly, in a follow up to this study, Gunderson and Levine (2011[16]) found that parent number talk that referred to visible sets of objects was a significant predictor of cardinal number knowledge at 46 months of age, whereas number talk with no visible sets present did not predict cardinal number knowledge. Furthermore, parental talk that referenced larger sets (e.g. 4-10) was a better predictor of cardinal knowledge than was talk about smaller sets (e.g. 1-3). This suggests that the quality, and not only the quantity, of number input is related to children's mathematical development.

One pitfall of relying on parental report and observations to assess the connection of maths input to children's maths knowledge is that it does not allow us to draw strong conclusions about the causal nature of the relationship between number input and maths skill. Parents who talk more about number may be responding to their children's interest in number, for example. Or parents who provide more input may be better at maths than those who do not, and may be contributing to later variations in their children's maths ability through biological transmission of higher maths-related skills (Braham and Libertus, 2017[25]). Only experimental studies that manipulate the quantity and quality of maths input parents provide can provide the causal evidence needed to link parent maths talk to children's maths knowledge. Further, by manipulating the kinds of maths input provided, we can begin to test the effectiveness of particular kinds of input for children who differ in age and prior knowledge. Below we review the few existing studies that have taken this approach, often drawing on lessons learned from cognitive science research.

Interventions

Insights from how children learn relational language broadly, as well as analyses of children's errors when learning maths terms specifically, suggest that children may have difficulty attending to the features of a scene that are labelled by relational terms, including maths terms (Bloom and Wynn, 1997[6]). Therefore, maths instruction may be most effective when it clearly draws children's attention to features of children's experience that are relevant to maths vocabulary and concepts. In this vein, researchers have developed interventions that draw on principles from cognitive science to better support the development of mathematical concepts.

Efficacy studies: Interventions in controlled laboratory settings

Analogical reasoning is a powerful tool for teaching children about abstract properties. For instance, previous studies have shown that giving children multiple examples of a concept can help highlight a key similarity or difference and prevent children from focusing on erroneous features of the objects that do not correspond to the target concept but that are particular salient to children (Christie and Gentner, 2010[26]). Interestingly, commercially available tools for teaching children about number such as picture books often use a different strategy – mainly, pairing examples of sets that differ on multiple dimensions (e.g. two houses versus three dogs). To explore whether structural alignment could be a useful resource in teaching children about number, we provided children with evidence designed to either broaden their understanding of a given number word by comparing sets of multiple kinds (low aligned) or to narrow children's definition by contrasting multiple sets of only one kind (high aligned). Findings suggest that children may initially benefit more from a situation which limits the context in which they learn a new number word (e.g. holding the types of objects that comprise different sets constant) before broadening their definition of new number words to include sets of unfamiliar objects (Gibson, Congdon and Levine, 2015[27]).

There are numerous other ways that the context in which a child hears a number word can help children develop an understanding of number. There is evidence that labelling the objects within a set prior to labelling the number of items in the set can help children learn the meanings of number words (Ramscar et al., 2011[28]). In other words, saying, "balls, there are three" was more effective than "there are three balls", perhaps because by labelling "balls" first, children are less likely to assume that "three" means "balls" and more likely to focus on the number of items.

Mix et al. (2012[29]) looked at the relative benefits of four training approaches that manipulated the context in which number words were embedded: counting sets only, labelling cardinal values of sets only, labelling cardinal values of each set and then immediately counting, and alternating between counting and labelling cardinal values at each session. Children were trained once a week for six weeks and then tested on their understanding of the cardinal principle. They found that children only showed significant improvements in their understanding of the cardinal principle in the combined counting and cardinal labelling training condition, demonstrating that providing a clear link between counting and cardinality provides better information for children to learn the number words than either piece of input individually.

Other research has also started to examine how the types of objects used to teach children number words might be differentially beneficial to children as they attempt to break into an understanding of number. Petersen and McNeil (2013[30]) compared performance in counting tasks that used either perceptually rich or simple objects, and varied by whether children had prior established knowledge of the objects or not. They found that using perceptually rich objects was only beneficial to children's performance when children did not have established knowledge of the objects. In fact, perceptually rich objects hindered performance on the counting tasks when children were familiar with the objects, likely because children were focused on the objects themselves rather than on the set size. In a related study, Petersen et al. (2014[31]) trained children on number words using either pictures of sets or three-dimensional objects and found that practicing counting with pictures helped improve children's understanding of cardinality while practicing counting with objects did not. They suggest that the high representational status of the pictures makes them less distracting than the objects, and that the objects might have afforded more off-task distractions than did the pictures.

Finally, manipulating the type of maths input children receive is not only important early on, before formal schooling begins, but can be beneficial to children once they are in school and dealing with more formal mathematics. For example, children's numerical magnitude estimation abilities are related to later mathematical abilities, but children from low-SES backgrounds tend to have poorer knowledge of numerical magnitudes (Siegler and Ramani, 2008[32]). To address this inequality, Siegler and Ramani (2008[32]) had low-SES preschool-aged children play a simple numerical board game in four 15-minute sessions over the course of two weeks. Playing this simple game drastically boosted the accuracy of children's number line estimations, suggesting that exposure to linear numerical board games helps build children's intuitive understanding of numbers.

All of these findings highlight the importance of considering the quantity and quality of exposure to mathematical concepts that parents and teachers provide. Yet, many of these interventions are only first steps towards developing more effective maths interventions that can be implemented in schools and homes. The interventions we have just described took place under semi-controlled conditions, conducted by trained researchers. However, it is important to take into account that it may not be possible for homes to reflect the best practices discerned in the lab (e.g. Mix et al. (2012[29]) found that parents rarely provide cardinal labels immediately followed by counting). To develop effective ways to support children as they learn challenging mathematical words and concepts, we need to have a better idea of what it looks like when parents, or teachers, implement the kinds of interventions that have been designed and tested in laboratory studies. Recently, researchers have started to think about how we can encourage and support parents to provide better quality input to their children, by focusing on interventions that target parent/child interactions rather than solely focusing on content provided to the child alone.

Effectiveness studies: Interventions in the wild

One such intervention focused on exploring how providing children with greater exposure to talk about the numbers 4 through 6 might promote an understanding of cardinality above and beyond exposure to talk about the numbers 1-3. As previously mentioned, in a correlational study, Gunderson and Levine (2011[16]) found that parents' labelling and counting of larger sets (4-10) of present objects was a better predictor of children's later cardinality scores than was talk about smaller sets (1-3). To test this finding, we created two different versions of a number book – one that contained only the numbers 1-3 and the other than focused on the numbers 4-6 – to look at which book promoted greater gains in children's cardinal understanding of the values of numbers, and whether this might vary depending on children's pre-existing number understanding as assessed by their "knower level" on the Give-N task. Following a brief pre-test, children were randomly assigned, within knower level, to one of three conditions (small number, large number, and a control, adjective book), where parents were asked to read these books to their children frequently over the course of a month. After the month-long period, children were invited back to the lab and again tested on their understanding of the cardinal values of numbers. Findings showed that children who were 1 and 2 knowers benefited more from the 1 to 3 books than from either the 4 to 6 books or the control adjective books. In contrast, children who were

3 or 4 knowers benefited from both the 1 to 3 books and the 4 to 6 books, compared to children in the control adjective condition.

In somewhat older children, we assessed the effectiveness of a maths app in promoting 1st grade children's maths knowledge. By this age, we know there is a negative relationship between parent maths anxiety and children's performance, where students with high-maths-anxious parents learn less maths over the school year than students with a low-maths-anxious parent. Moreover, when high-maths-anxious parents help their children more often with homework, the children learn less over the school year, controlling for parents' education and classroom level variables (Maloney et al., 2015[33]). Therefore, in a recent study, we asked whether engaging parents and children in scripted, high-quality maths interactions might help ameliorate the negative effects of being a maths-anxious parents. Indeed, we found that when first-grade children in households with a high-maths-anxious parent used a maths-related iPad app as little as one or two times per week, they made gains in maths equal to those of their peers with low-maths-anxious parents (Berkowitz et al., 2015[34]). Moreover, these benefits persisted: being assigned to the maths group continued to have beneficial effects for children of higher maths-anxious parents well into second grade, when the children were rarely using the app, if at all (Schaeffer et al., 1999[35]). Creating a context for parents and children to have positive maths interactions led to significant gains for those children who might not otherwise have received high-quality maths input at home, partly because parents in the intervention group began to increase their value of maths achievement for their children, as well as their expectations of their children's achievement in maths. These few studies demonstrate how the lessons learned from cognitive science can be applied and tested in real world settings. Findings suggest that research-based interventions can lead to positive maths learning gains. There are of course many remaining questions having to do with the mechanisms that undergird these gains, and whether or not the interventions lead to long-term benefits in achievement.

Policy implications

Evidence that gaps in maths achievement are already apparent as early as kindergarten drive home the need for early interventions that reach homes as well as schools. In creating these interventions, it is important to consider the obstacles that parents and teachers face in talking effectively about numbers with young children. Maths anxiety and SES are just two factors that we know are related to parent-child maths interactions, and so interventions should be designed to provide adequate support to adults from a variety of backgrounds and with a variety of their own feelings about maths. By ensuring that students are better prepared for maths at the time of school entry, we can improve students' academic outcomes. Given the growing body of research on the factors that are important for developing children's early mathematical thinking, researchers and policymakers should work to develop effective ways of broadening the reach of research-based mathematics interventions.

The research discussed above suggests that technology can be a useful tool to improve parent-child interactions around maths. As computers and smartphones with internet access become a staple in every household, websites can be an increasingly effective way to demonstrate positive ways to incorporate maths into the home and classroom. Parents can look to websites such as Maths 4 Mums and Dads (maths4mumsanddads.co.uk) and Becoming a Maths Family (becomingamathsfamily.uchicago.edu) for ideas of how to talk to their children about maths and use numbers in everyday activities. Similar resources are being developed to support teachers as well. For example, DREME TE (http://prek-maths-te.stanford.edu) provides early maths resources for teacher educators to use in their classrooms. As research on effective early maths input grows, and technological advances make it increasingly possible to reach people in their homes, we are excited about the potential impact research can have on early mathematics education and the benefits this can reap over time in terms of STEM outcomes.

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Chapter 7. Gesture as a window onto the science of learning

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The actions we produce and observe every day can help us learn new ideas or change the way we think. One type of action – the gestures we produce when we talk – has been shown to support learning when incorporated into instructional contexts. Unlike other forms of action, gestures are not used to physically change the world. Instead, they are movements of the hand that can represent and manipulate ideas. Here we review literature demonstrating the powerful effects that gesture can have on learning, and we discuss findings that explore the mechanisms by which these effects occur. Specifically, we explore whether gesture facilitates learning through its capacity to be integrated with speech, its ability to engage the motor system and its role as a spatial tool. Finally, we discuss implications of these scientific findings for educational practice and policy.

Context

To understand how to optimise learning, researchers often focus on the language of learning – what teachers or students are saying in an instructional setting. But spoken language is only part of the story. Indeed, when we communicate with one another, we spontaneously and prolifically produce hand movements, or gestures, along with spoken language. These gestures are produced by both instructors and learners, and are ubiquitous around the world. And, these gestures have an impact: they can shape the outcome of learning situations. In this chapter, we review how a learner's own gestures reflect thinking and learning processes not apparent in their spoken explanations, and we show that modifying either a learner's or an instructor's gesture production can causally improve learning outcomes. We end by proposing some reasons why gesture is so powerful, and we discuss implications for policy and practice, including specific ways to encourage active learning by increasing children's gesture production in a classroom setting. The research presented throughout this chapter underscores the idea that gesture compliments spoken instruction and promotes learning across age groups, academic content areas and cultures.

Part I: Gesture and learning

Gestures have been categorised by scholars into several broad, descriptive classes (Kendon, 2004[1]). Here we define gestures as meaningful hand movements that are produced off-objects (i.e. in the air) and accompany speech. We focus on the gestures that have been most studied in instructional contexts – deictic gestures, which identify objects or locations in the world (e.g. pointing to the edge of a triangle drawn on the chalkboard), iconic gestures, which convey information through the similarity between their form and their referent (e.g. using ones hands as the edges of a triangle to talk about the angles of the triangle), and metaphoric gestures, which represent ideas through a metaphoric relation between their form and their meaning (e.g. making one's hands into a triangle shape to talk about the components of a mediation analysis).

Gestures differ from other types of movement that we see in learning or instructional contexts, such as classroom demonstrations, because they do not create lasting change in the external world. For example, a teacher gestures a rotating motion next to a model of a molecule to indicate that the molecule needs to be mentally rotated to correctly think about it. This instructor is representing the idea of rotation without physically rotating the molecule. Gestures, as representational actions, are construed by both teachers and students as being categorically different from other kinds of object-directed actions (Novack, Wakefield and Goldin-Meadow, 2016[2]; Wakefield, Novack and Goldin-Meadow, 2018[3]), and this construal has crucial implications for thinking and learning. For example, in one study, children who learned a novel maths concept through gesturing towards objects were able to generalise that concept to novel problem types better than children who learned through directly acting on the objects (Novack et al., 2014[4]). This type of research suggests that it is important to consider gesture as distinct from other types of actions, as they can have unique effects on learning outcomes.

Gesture is produced spontaneously by both teachers and students across a wide variety of academic domains, including mathematics, (Goldin-Meadow and Singer, 2003[5]), geoscience (Atit, Shipley and Tikoff, 2014[6]), conservation of mass problems (Church and Goldin-Meadow, 1986[7]), chemistry (Stieff, 2011[8]) and physics (Roth, 2000[9]). The prevalence of gesture in instructional contexts has led researchers to ask whether these spontaneous hand movements, particularly those produced by learners, can give us insight into learning processes.

As it turns out, the gestures that students produce while thinking through difficult problems do convey important information about their state of conceptual understanding information that is often absent from their verbal explanations. For example, a toddler still in the process of learning her numbers says the wrong number when asked how many buttons are shown (e.g. she says “two” when the correct answer is three). Yet, that same child can use her hands to show the correct number of buttons (i.e. holding up three fingers) (Gunderson et al., 2015[10]). Similarly, a third grader solving a missing addend equivalence problem (e.g. 4+6+9 =__+9) says that she solved the problem by adding up all of the numbers (e.g. “I added the 4, 6, 9, and 9, and got 28”, an incorrect solution), while producing gestures that highlight the two sides of the equation, a subtle demonstration that she is beginning to notice that the equation has two parts, a step towards understanding equivalence (Perry, Breckinridge Church and Goldin-Meadow, 1988[11]). Children can thus gesture about ideas that they cannot yet verbalise.

When a learner expresses different (but relevant) information in gesture than in speech, we call this a speech-gesture mismatch (Church and Goldin-Meadow, 1986[7]). Importantly, learners who produce these mismatches on a task are more likely to learn from instruction on that task than learners who do not (Alibali and Goldin-Meadow, 1993[12]). In addition to the domain of mathematics, speech-gesture mismatches have been documented among toddlers on the cusp of producing two word utterances (Iverson and Goldin-Meadow, 2005[13]), 5- to 7-year-olds learning about conservation of mass (Church and Goldin-Meadow, 1986[7]) and even 9-year-olds discussing moral reasoning dilemmas (Beaudoin-Ryan and Goldin-Meadow, 2014[14]). Across all of these instances, the learner’s spontaneous gestures on a task, and the manner in which that gesture relates to the spoken explanation, serve as a marker that a student is “ready to learn” the task.

Although gesture may seem like a subtle cue, all of us, not just trained laboratory researchers, are sensitive to its presence. Without any specific gesture training, both college undergraduates and experienced elementary school teachers can glean information from children’s gestures. After watching a video of a child describing his reasoning to a math problem, adults often mentioned ideas expressed uniquely in gesture (and not in speech) when describing the child’s reasoning (Alibali, Flevares and Goldin-Meadow, 1997[15]). Even more importantly, when teachers were asked to instruct children in solving mathematical equivalence problems after watching them explain their initial (incorrect) reasoning, teachers adapted their instruction in reaction to children’s verbal and gestured explanations. Children who produced speech-gesture mismatches, signalling that they were ready to learn the task, were given more extensive instruction, containing more different types of strategies, than children whose gestures matched their speech (Goldin-Meadow and Singer, 2003[5]).

Part II: Experimental manipulation of gesture

Spontaneously produced gesture can help experimenters and instructors identify students on the brink of conceptual change. This fascinating observation has led researchers to ask whether gesture simply reflects cognitive change, or whether it also plays an active role in creating or causing that change. In this section, we review studies in which gesture is experimentally manipulated in instructional settings, revealing that gesture not only reflects what learners think, but also affects the learning process.

There is some research showing that simply encouraging learners to move their hands when explaining a problem (i.e. increasing spontaneous gesture production) can lead to improved learning outcomes. In a maths instruction paradigm, children who were encouraged to gesture while explaining their solutions produced significantly more different kinds of problem-solving strategies during their explanations than children who were not told anything about gesture, or who were told specifically not to move their hands (Broaders et al., 2007[16]). Those same children then learned more from subsequent instruction than the children in the other two groups. Similarly, in another study with fifth grade students, children who were told to gesture during a moral dilemma reasoning task showed a willingness to consider issues from multiple perspectives, more so than their peers who were not told to gesture or were not given any instructions about hand movements (Beaudoin-Ryan and Goldin-Meadow, 2014[14]). Thus, experimentally increasing children's gesture production increases the likelihood that they will explore undiscovered implicit ideas via their own gestures, a process that then boosts their ability to gain further insights from instruction.

Researchers have also been able to improve learning outcomes by asking children to produce specific gestures. For example, asking children to produce a gesture highlighting the two sides of an equivalence problem helped them retain what they had learned about mathematical equivalence four weeks later (Cook, Mitchell and Goldin-Meadow, 2008[17]). In another example, children were more likely to learn how to correctly produce palindromes, words or phrases that read the same forwards and backwards (e.g. "kayak"), if they were taught to produce symmetry gestures along with a speech strategy than if they were taught the symmetry strategy only in speech (Wakefield and James, 2015[18]). The effects of this type of "trained" gesture instruction extend even to very young children. Eighteen-month-old toddlers who were taught to point, (i.e. taught to put their finger on a picture of an object as it was verbally labelled) learned to point more in naturalistic interactions with their parents, which also led to greater increases in their spoken vocabulary, compared to children who were not taught to point (LeBarton, Goldin-Meadow and Raudenbush, 2015[19]).

In addition to studies that manipulate child-produced gestures, studies that manipulate instructor-produced gestures can also positively influence learning. We review examples of these studies in more detail in the next section, as we address potential mechanisms through which gestures – both producing and observing – support learning.

Part III: Mechanisms of gesture

As we have established, gesture is a powerful tool for reflecting and promoting cognitive change, whether it is spontaneously produced or intentionally incorporated into instruction. In this section, we explore some of the specific mechanisms that may underlie gesture's wide-ranging effects on learning. Although these mechanisms are not yet fully understood, we believe that elucidating how gesture promotes learning will help us predict the situations in which gesture will be most effective, and create policy-level changes that reflect these findings. We review three potential mechanisms by which gesture may facilitate learning: its ability to spatialise information, its capacity to be integrated with speech and its ability to engage the motor system in the learning process.

Gesture as a spatial tool

One way in which gesture can be used as a spatial tool is by helping to direct a learner's visual attention to a certain location in the spatial environment. For example, children as young as 4.5 months will shift their visual attention following a dynamic, deictic or pointing gesture (Rohlfing, Longo and Bertenthal, 2012[20]). Adult learners also pay attention to gestures, particularly those that pause in space to emphasise the relevance of a particular spatial location (Gullberg and Holmqvist, 2006[21]). In a chaotic classroom setting with many competing sources of potential information, this ability to direct or capture students' visual attention has clear consequences for learning. For example, gesturing towards the referent for a new word can facilitate learning a label for that object (Rader and Zukow-Goldring, 2012[22]), tracing an outline of two symmetrical objects highlights the relation between the two objects and facilitates learning the concept of symmetry (Valenzeno, Alibali and Klatzky, 2003[23]) and gesturing towards two sides of a mathematical equivalence problem can clarify the role of the equals sign (Cook, Duffy and Fenn, 2013[24]).

Gesture can also represent spatial information or spatial relations through its form or motion. For example, when explaining mathematical equivalence, instructors often make a v-point gesture to the first two addends of the equation to represent the idea that those two addends should be combined into a single quantity. Or children who are reasoning through a mental transformation task may use their hands to represent the physical features of the to-be-rotated object, which facilitates their ability to solve these mental transformation problems (Ehrlich, Levine and Goldin-Meadow, 2006[25]). Finally, gestures can be used to represent objects when objects are altogether absent from the environment. Ping and Goldin-Meadow (2008[26]) taught children the concept of conservation, the idea that changing the shape of a substance does not change its mass, through speech alone, speech and gesture in the presence of objects, or speech and gesture in the absence of objects. Children learned more from instruction if presented with speech and gesture, regardless of whether the objects were present or absent. The gestures contained crucial spatial information that had the potential to help the children find meaning in the spoken instruction whether or not the objects themselves were present.

Gesture and speech integration

Gestures are predominately produced with spoken language, and it has been argued that these two streams of communication emerge from a single integrated system (Arnheim and McNeill, 1994[27]). Neuro-imaging data support this claim, finding that processing speech and gesture activates overlapping neural regions (Holle et al., 2010[28]). Furthermore, because speech and gesture occur in different modalities (oral and manual), they have the capacity to provide different, but complementary information at the same time. Singer and Goldin-Meadow (2005[29]) gave children instruction on a mathematical equivalence task containing either one or two problem-solving strategies, and varied whether these strategies were presented entirely through speech, through speech with 'matching' gesture (expressing the same information as speech), or through speech and 'mismatching' gesture (expressing two correct, but different strategies in speech and gesture). Children performed best on a post-test if they learned through gesture and speech that expressed different information, suggesting that the integration of the two complementary ideas provided the most comprehensive instruction. In a recent study, (Congdon et al., 2017[30]) expanded upon these findings by showing that the temporal simultaneity of the different pieces of information in the mismatching speech and gesture instruction was crucial for this integration effect. Future research will investigate whether simultaneity in speech and gesture production is as important, or perhaps more important, when it is being produced by the learner.

Gesture and the motor system

An obvious but often overlooked property of gesture is the fact that it is a type of action. Because gesture engages the motor system, it changes the way information learned through gesture is processed. For example, Alibali et al. (2011[31]) either allowed or prohibited the use of gesture when individuals solved a spatial gear-task. Those who were allowed to gesture, persisted in using a perceptual-motor based strategy, whereas those who were not allowed to gesture, used an abstract reasoning strategy. Neuro-imaging evidence has also demonstrated that the motor system is deeply involved in processing information learned through gesture. For example, after producing gestures while learning new information, such as musical melodies (Wakefield and James, 2011[32]) or new vocabulary words (Macedonia, Müller and Friederici, 2011[33]), motor areas are reactivated when these stimuli are subsequently encountered. Although it is obvious that producing gesture engages the motor system in the moment, these surprising neuro-imaging results suggest that motor system involvement continues after the participant has ceased gesture production. Gesture can provide learners with a robust representation of newly learned ideas that engages multiple neural systems, and this enrichment may, in part, underlie gesture's role in improving memory and recall after instruction. Furthermore, when watching co-speech gesture, adults show activation in motor planning regions (Wakefield, James and James, 2013[34]), suggesting that learners themselves need not be producing the gesture to meaningfully engage their motor system.

In sum, gesture's ability to direct visual attention and highlight spatial relations, integrate with speech, and engage the motor system each contributes to the role gesture plays in learning. Gesture is also produced spontaneously, can be manipulated experimentally, is a special kind of representational action, and is ever-present in educational contexts. So, which of these features is most important in making gesture an effective tool for teaching and learning? An open possibility, and the one we favour here, is that the real power of gesture does not come from any single property, but rather, from a combination of all of them. In other words, gesture may not have a unique, single characteristic that makes it good for learning. Instead, gesture may be a 'perfect storm' of properties that allow it have powerful and wide-ranging effects on cognition.

Part IV: Policy implications

The goal of this chapter has been to review the ways in which gestures can both reflect and change thinking during the learning process. We have explored some of the potential mechanisms driving these effects, and discussed instances in which gesture may be particularly powerful for promoting cognitive change. There is still much research to be done. Nevertheless, the work we have reviewed here provides solid evidence for incorporating gesture into the classroom, and carries with it implications for education practices.

One clear finding is that student-produced gesture supports learning. Yet, we know that gesture is very unlikely to occur in the absence of speech. That is, if students are not given opportunities to reason aloud through difficult problems or explain their solutions to others, they are unlikely to produce gestures that have the potential to unearth their own implicit ideas. Importantly, students should be given opportunities to produce gesture even before they have mastered a concept, as studies have shown that explanations need not be correct to be useful in promoting cognitive change. A simple way to create a gesture-friendly culture in the classroom is to ensure that students are regularly encouraged to talk aloud with one another and with the instructor in situations that are conducive to gesture production (i.e. with their hands free to move around).

Although it is important to give the learner opportunities to gesture, we also know that teacher-produced gesture can be a very effective instructional tool. In fact, cross-cultural research looking at gesture production in Hong Kong, Japan and the United States shows that teachers in the two higher achieving countries, Hong Kong and Japan, spontaneously use more instructional linking gestures, which help students make connections between various instructional elements, than teachers in the United States (Richland, 2015[35]). Studies like this suggest that teachers should generally be made aware of the power of gesture to direct and engage students' visual attention, highlight spatial relations and convey important semantic information. Many educators are naturally prolific gesturers; however, being explicitly aware of the power of gesture might further encourage teachers to create learning situations that are conducive to natural gesture. An instructor who is informed of gesture's potential can even integrate gesture in his or her lesson plans, designing their own hand movements to help students think through complex problems.

The integration of gesture into ever-evolving modern classrooms raises important questions about how this body-based learning tool interacts with technology-based learning interventions. Although there is much work to be done on this front, some recent research has found that integrating gesture into virtual learning environments improves student outcomes. For example, children who watched a maths lesson with a gesturing avatar, a computer-programmed instructor, learned more than the children who watched the same lesson from an avatar that did not gesture (Cook et al., 2017[36]). Other types of visuo-spatial learning technologies, like tablet-based virtual sketchpads, have affordances like touch-screen capabilities that could provide unique methods to promote student-produced gesture (see Chapter 8, by Forbus and Uttal, for examples of visuo-spatial learning technologies). Although these technologies have the potential for exciting revelations in gesture instruction, it should be noted that natural gesture is cost-effective, readily available at all times, and impervious to glitches, software updates and costly repairs.

Finally, to incorporate gestures into everyday classroom instruction, it may be necessary to directly affect policy. For example, standard teacher training and education could include information about the power of gesture, both as an index of a child's current stage of conceptual development, and as a tool for promoting further conceptual understanding. Teachers could also be given concrete tips on how to create a gesture-friendly classroom environment. In some cases, this type of information may challenge traditional notions of what kinds of behaviour are considered conducive to student learning. Many theories of classroom management, now widely adopted (especially among discipline-oriented charter schools), consider students cognitively "ready to learn" when they are sitting quiet and still with their hands folded across their desks and their feet on floor. The work we have summarised here provides powerful counter-evidence against this particular classroom culture – a quiet, motionless student is not necessarily the student who is most prepared to learn.

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Part II. Learning with technology

Chapter 8. Technologies for spatial learning

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Paper-based technologies, such as maps, diagrams and graphs, have been used to support spatial thinking and learning through the ages. Modern digital technology provides new options for enriching spatial learning with potentially transformative impacts. This chapter focuses on two such technologies. The first is sketch understanding, where software incorporates cognitive models of human visual, spatial and conceptual representations and processes in order to see a student's sketch as they do. We summarise CogSketch, a new platform that has been used to develop two novel kinds of educational software that have been successfully used in classroom experiments. The second technology are Geographic Information Systems (GIS), computer-based mapping systems that facilitate spatial data analysis and visualisation, e.g. the distribution of housing density, crime, school test scores, etc. in different neighbourhoods. We review evidence that using GIS can promote spatial reasoning in high school students.

Context statement

Spatial learning – learning to reason better about space and using space to learn about other subjects is critically important for science, technology, engineering and mathematics (STEM) education and practice. However, spatial learning has not been emphasised in education, in part because of the challenges of creating and assessing multiple representations of space. We show that new technologies can overcome these challenges. Modern digital technology provides new options for enriching spatial learning (Jee et al., 2014[1]). Here we focus on two technologies. The first is sketch understanding, where software incorporates cognitive models of human visual, spatial and conceptual representations and processes in order to see a student's sketch as they do, and thereby provide immediate feedback. We summarise research on CogSketch, a new platform for sketch-based educational software that has been used to develop two kinds of educational software that have been used in successful classroom experiments. The second is the use of Geographic Information Systems (GIS), computer-based mapping systems that allow the user to examine data in layers. We review evidence that using GIS can promote spatial reasoning in high school students.

Spatial technologies

People have been using external media to support spatial learning for millennia, going back to the construction of sketches in dirt and making models out of found materials. Today's digital technologies provide several key advantages for spatial learning:

1. Access to vast reference sources. The web, combined with open-source and open-data movements, has made a cornucopia of information widely and easily available for those with internet connectivity. The semantic web is adding a layer of metadata that further supports finding and using resources in novel ways.
2. Simplified sharing. Digital versions of maps, diagrams and sketches can be easily copied and distributed online, compared to copying and distribution of paper products. This facilitates students sharing work with each other and producing more complex materials for assignments. For example, digital sketches can include a complete history of a student's actions, which can be used for further assessment, which is impossible with paper sketches.
3. Intelligent software coaches and tutors. Rapid feedback is known to facilitate learning. With pencil and paper, feedback is delayed until a human instructor can look at it, and send it back to the student, often days, weeks or even months later. Digital media can have embedded software coaches and tutors, capable of providing helpful feedback immediately, anytime, anywhere (see also Chapter 12, by Klahr and Siler, and Chapter 13, by Koedinger).

There are many technologies that could have important impacts on spatial learning, including virtual reality, augmented reality and gesture understanding. Here we focus on two technologies that are now translation ready and have shown potential for improving spatial learning: Sketch understanding and GIS. We discuss each in turn.

Sketch understanding

Teachers and students sketch to communicate ideas to each other, and to think through problems. Creating software that can understand sketches in ways that people do is the goal of sketch understanding research. Recent progress in sketch understanding has enabled the construction of new kinds of intelligent software to support spatial learning.

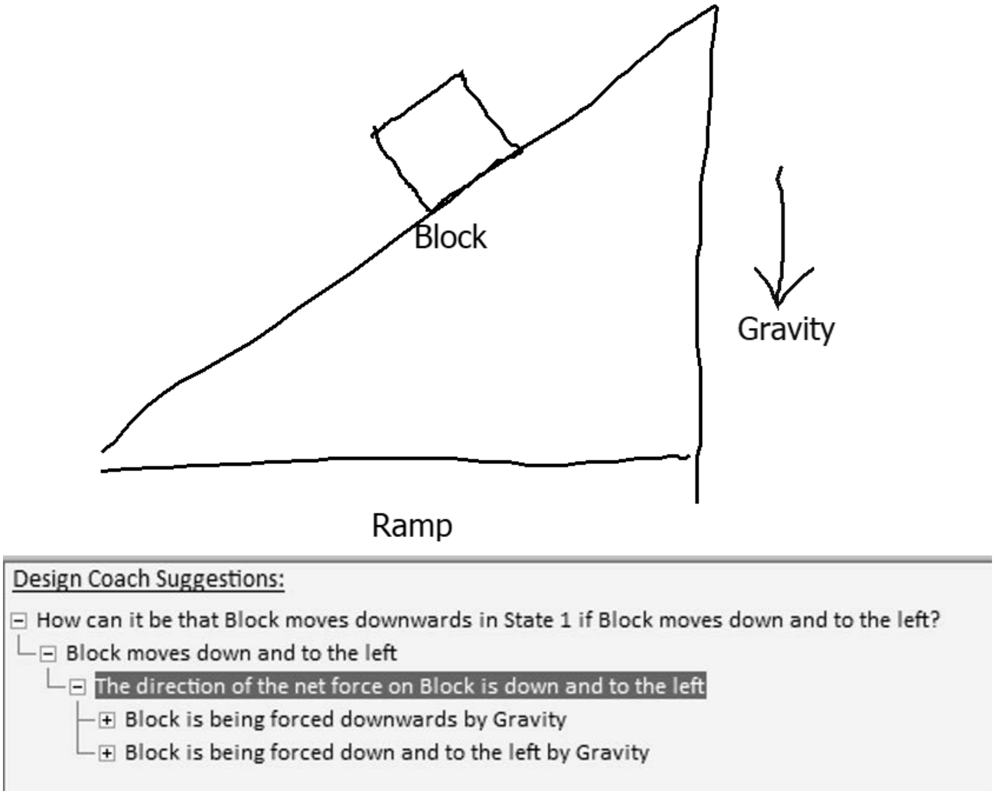
What is sketch understanding?

There is a common misconception that sketch understanding can be equated with sketch recognition. Sketch recognition has been used in domains where there is a vocabulary of abstract visual symbols that are part of domain practice, such as electronics (de Silva et al., 2007[2]), chemistry (Pargas et al., 2007[3]) and structural mechanics (Valentine et al., 2012[4]). However, there are two reasons why sketch understanding is more complicated than that. An analogy with speech recognition, which more people have experienced today, is helpful. Just because a system can transcribe spoken words into text does not mean it understands what those words convey (any user of Siri, Alexa or Cortana has experienced this). By contrast, people can solve complex visual problems, requiring rich representations and processing. Sketch understanding must investigate these visual and spatial representations and processes. The second reason is that most things that people sketch are not visual symbols. A speech recognition system produces garbage when fed music or street sounds – most of the sounds in the world are not human speech. And so it is with sketching: the spatial aspects of most things depicted in STEM domains are determined by the nature of the situation, not by symbolic conventions. The mapping between shapes and concepts is many to many, even within single domains. For example, circles in an Earth Science course can be used to depict the layers of the earth, planets and some orbits. Hence the goal of sketch understanding must include ascertaining what conceptual relationships follow from the visual and spatial relationships depicted within a sketch.

CogSketch

This insight that sketch understanding requires integrating conceptual, visual and spatial representations and reasoning has led to CogSketch (Forbus et al., 2011[5]), a software system that is both a computational model of aspects of human visual understanding and a platform for sketch-based educational software. Motivated by studies of human vision, CogSketch uses multiple, hierarchical levels of visual representations. Its initial descriptions are in terms of visual objects (called glyphs). Figure 8.1, for example, there are three glyphs, called Block, Ramp and Gravity. CogSketch can decompose glyphs into visual edges (e.g. four for the Block) and uses gestalt principles to flexibly break apart and combine visual materials. These capabilities have enabled CogSketch to model multiple visual tasks, including geometric analogies (Lovett et al., 2009[6]), an oddity task (Lovett and Forbus, 2011[7]), paper folding and mental rotation. Evidence of the fidelity of CogSketch's representations and reasoning can be seen in the ability of these models to provide explanations for human performance, including predictions of ordinal reaction times and variations in problem difficulty. For example, the performance of the CogSketch model of Ravens' Progressive Matrices (Lovett and Forbus, 2017[8]) places it in the 75th percentile, making it better than most adult Americans. These visual representations and reasoning capabilities are used in the educational software discussed next. In addition to visual representations, CogSketch uses the contents of Cycorp's OpenCyc knowledge base, which includes over 58 000 concepts, 8 000 relationships, whose meanings are specified by roughly 2.3 million facts. This background knowledge is augmented by qualitative representations for mechanics and other substrate capabilities needed to support STEM domains, although as discussed below, these capabilities will need to be built out considerably to handle STEM education more broadly.

Figure 8.1. A simple Design Coach example



Design Coach Suggestions:

- ⊟ How can it be that Block moves downwards in State 1 if Block moves down and to the left?
  - ⊟ Block moves down and to the left
    - ⊟ The direction of the net force on Block is down and to the left
      - ⊞ Block is being forced downwards by Gravity
      - ⊞ Block is being forced down and to the left by Gravity

Note: Given an explanation that does not fit with its conceptual understanding of mechanics, the system provides feedback about what parts of the explanation do not make sense.

To see how these kinds of knowledge interact, let us examine an example of an educational software system built on CogSketch, the Design Coach (Wetzel and Forbus, 2009[9]). The Design Coach attempts to address a problem that instructors in the Design Thinking and Communications class at Northwestern have with their students. While the instructors view sketching as a crucial way to think through new designs and communicate them to clients, they find that students are often afraid to sketch, and become embarrassed about their drawings. Design Coach provides a safe way for students to practice explaining designs through sketching. They use a combination of drawings and language-like input to explain their ideas. The Design Coach uses spatial reasoning and qualitative mechanics to look for problems or gaps in their explanations, and gives them feedback when it does not understand their design. Students can then change their explanation until the system understands it. Pilot data indicates that even doing a single Design Coach assignment can reduce student anxiety about communicating via sketching (Wetzel and Forbus, 2015[10]). Let us walk through a simple example. Suppose part of a student's design has a block sliding on a ramp (Figure 8.1). They draw the ramp, and give it a conceptual label of Fixed Object, indicating that this is something that cannot move. The conceptual label is applied by a simple menu interface, thereby sidestepping all issues with sketch recognition. The glyph for the block is labelled as a Rigid Object (by contrast with a cord or spring). The visual overlap between the two glyphs means, given their conceptual interpretations, that the two objects have a surface contact. Visual processing on the student's ink automatically identifies this region of the sketch. This visual analysis, combined with its conceptual knowledge, enables the Design Coach to reason through, in a human-like way, what might happen next. Using the qualitative orientation of the surface and the direction of gravity, as depicted by the arrow the student drew, CogSketch determines that the block will slide to the left and down. If this is what the students said in their explanation, the Coach tells them that it understands their explanation. If instead they said that the block would move in a different direction, it would point out the difference between what they said and its understanding of what might happen, as Figure 8.1 illustrates. Using qualitative, conceptual reasoning to check student reasoning instead of, say, numerical simulation, is important because it enables the Design Coach to explain its reasoning to students.

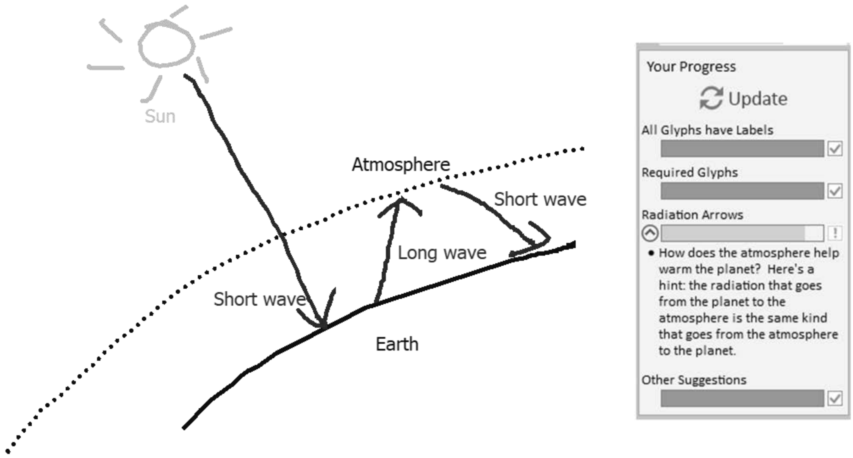
Sketch Worksheets

The Design Coach was targeted for a specific problem within a particular area. The second kind of educational software built on top of CogSketch are Sketch Worksheets (Forbus et al., 2017[11]; Yin et al., 2010[12]). Sketch Worksheets are domain-general. Their goal is to help students learn spatial layouts or domain information that can be communicated via visual representations, such as concept maps. To achieve generality, tutoring in Sketch Worksheets only relies on analogical matching between an instructor's solution and a student's solution. Each Sketch Worksheet is focused on a specific problem. The instructors (or curriculum designer), who sets the problem uses, CogSketch to draw their solution to that problem. They select which concepts and relationships from the knowledge base will be available to the student doing that exercise, and control how those concepts are displayed to the student. This enables the worksheet author to keep the student focused on the key concepts (plus distractors, typically) relevant to the exercise at hand, and tailor the description of the contents to be age and topic appropriate, as well as in the student's native language. CogSketch's visual system automatically analyses their solution, and authors browse through natural language depictions of the facts it derived. They can select some of these facts as important, i.e. if they are not true of a student's sketch, then there is something wrong with it. They can supply feedback to give to students in that case, as well as provide rubrics specifying how many points each important fact is worth. When students tackle a worksheet, they draw their sketch, using the set of concepts and relationships specified by the teacher to label their ink. When asked for feedback, CogSketch analyses the student sketch, and compares this analysis with its analysis of the solution sketch (to do this comparison, it uses a computational model of analogical comparison, the same model of analogy used in the visual reasoning models outlined earlier). The text associated with any differences found are provided to the student for feedback, highlighting the involved glyphs to help students see how the feedback applies to their sketch. If there is no feedback, the worksheet tutor congratulates the students on their sketch and they are finished. Students sometimes do stop early, but the ability to provide rapid feedback anywhere at any time is one of the valuable aspects of this model. Instructors can also provide misconception sketches that highlight common problems with student mental models, and give feedback based on the comparison with those sketches instead, when they match. CogSketch maintains a complete history of student actions, including what the sketch looked like every time a student asked for feedback, which can be used for additional assessment and data-mining (Chang and Forbus, 2014[13]).

Sketch Worksheets have been used in a variety of laboratory and classroom experiments. For example, students in a fifth-grade biology class showed gains in two out of three pre-test/post-test pairs after doing three worksheets on the human circulatory system (Miller, Cromley and Newcombe, 2013[14]). A set of worksheets for introductory geoscience courses were developed by researchers at the Spatial Intelligence and Learning

Center of the University of Wisconsin, Madison and used in classes there and at Northwestern University. While geoscience instructors think sketching is important, they do not give frequent sketching assignments due to the burden of grading paper-based sketches. The Madison experiment did not find differences in learning between paper-based and CogSketch-based worksheets, while CogSketch-based worksheets are far easier to grade (Garnier et al., 2017[15]). The geoscientist-authored worksheets from Madison were subsequently deployed in Northwestern classes, and are now available on line from the NSF-funded Software Engineering Research Center (SERC). Moreover, Sketch Worksheets have also been used in other Northwestern classes, in Knowledge Representation and Introduction to Cognitive Modeling (Forbus et al., 2018[16]). These experiments and deployments suggest that Sketch Worksheets could potentially be valuable across a wide range of STEM topics and age ranges.

Figure 8.2. An example of a Sketch Worksheet about the greenhouse effect, with feedback



- How does the atmosphere help warm the planet? Here's a hint: the radiation that goes from the planet to the atmosphere is the same kind that goes from the atmosphere to the planet.

Geographic information systems (GIS)

GIS technology has transformed the presentation of spatial information in many fields, ranging from marketing to architecture. A GIS is a database of spatial information, where entities in the world, or conceptual entities computed about the world (e.g. population density) are represented by polygons. These polygons are organised into layers, much like acetate overlays are used with maps. Defining and manipulating layers provides a valuable tool for spatial thinking. For example, a user can represent the locations of parks, businesses and schools within a particular city. Each layer can be added or subtracted as desired, allowing the user to see, and to think about, relations both within individual layers and among different layers. One use of GIS is to ascertain good locations for specific purposes, e.g. where to put a new fire station. The invention and popularisation of GIS led to substantial growth in the availability and sharing of spatially-coded data. For example, many US cities now make available GIS data concerning zoning, school catchment areas, and crime distributions.

There are many forms of GIS. Professional GIS, such as ArcGIS for Desktop (ESRI, 2014) are extremely powerful, providing numerous tools for representation, animation, and transformation of images. Such systems can be hard for novices to learn. Many simpler tools now provide some of the same services in a more approachable form, such as Google Maps and Google Earth.

GIS in education

A GIS supports students defining and solving spatial problems by gathering relevant data, decomposing it into layers, and manipulating them. This makes it especially effective for emphasising relations, patterns, and distributions (Sinton et al., 2013[17]). This approach to teaching and learning is consistent with recent approaches to science education that emphasises science as a set of practices. These practices include collecting data, representing and forming models, iterating, etc. (NGSS Lead States, 2013[18]). We suggest that GIS facilitates many of these processes, as it encourages thinking about data, representing and modelling, and combining representations to solve spatial problems.

Here we highlight two approaches that we believe illustrate 1) the unique affordances and instructional advantages of using a GIS-based approach to teach spatial problems; and 2) two different models for GIS use. One approach uses free tools (e.g. Google Earth) to teach a particular unit within Earth Science, while the other (the Geospatial Semester) uses a professional GIS to emphasise a problem-solving approach. We discuss each in turn.

The first approach uses GIS within specific topics or units within courses, such as Earth Science. A good example of this approach is (Bodzin, 2008[19]; Bodzin and Cirucci, 2009[20]), use of Google Earth to teach a variety of environmental science topics. For example, in one study (Bodzin and Cirucci, 2009[20]), students used Google Earth to investigate land use and how changes in land use affect the local environment. For example, students investigated how the building of a local shopping mall affected the pattern of land use around the mall. They then investigated how, and why, the presence of the mall led to heat islands, which are concentrated areas of relatively high temperature. The loss of plant cover, and its replacement with concrete, asphalt, etc., led to greater accumulation of heat and slower loss of heat after dark. This helped students learn how to think about complex, real-world spatial problems.

The second approach uses a more intensive approach to learning through GIS usage, working on more open-ended problems. For example, the Geospatial Semester (GSS) (Jant, Uttal and Kolvoord, under review[21]; Kolvoord et al., 2012[22]), is a semester or year-long class designed primarily for high school seniors. It emphasises a spatially-based approach to real-world problem solving. In contrast to the more specific curricula discussed above, the GSS emphasises a more holistic approach to learning and problem solving. Students learn to use the inexpensive educational version of ArcGIS for Desktop, a full GIS that allows flexible representations of spatially-coded data. The first portion of the course is devoted to learning the mechanics of ArcGIS and using it to solve specific problems. But as the course progresses, students begin to think about new problems that can be solved with GIS. The course culminates with an intensive, multi-week final project. Students must identify a significant problem that can be solved using GIS technologies. The students work to identify the problem, constrain possible solutions, identify relevant data, and propose a solution. The problems often involve engineering, in that they are forced to make compromises and offer working solutions rather than a perfect solution.

Some examples of final projects provide illustrations of the approach. One project, Bearly Relocated, was completed in a rural high school located near Shenandoah National Park in Northeast Virginia. The problem begins with the geography of the park itself; it is relatively easy for bears to leave the park in search of food. The bears have learned that it is easy to obtain food by venturing out of the park (where they are safe and protected) and enter a residential or farm area (where they put both themselves and the local human population at risk). It is not uncommon to find a bear in one's backyard. Thus, students were motivated to find a way to solve the problem. Working with a GIS allowed the students to come up with possible solutions. The basic idea was to identify areas of the park in which the bears could be relocated to decrease the chances of them leaving the safety of the park again. This requires evaluating trade-offs among a variety of variables: The locations where the bears are found out of the park, the presence of access roads, etc. The students use ArcGIS to define optimal areas within the park and shared these recommendations with the park rangers.

Another example of a compelling final project was investigating how to increase internet access in Africa. Lack of infrastructure and vast distances between large cities makes the problem particularly severe. Radical new solutions, such as balloons or drones, have been proposed to provide wireless access. The students tackled the question of where such systems could be placed to provide maximum benefits with minimal costs. This is a highly spatial engineering and economic problem, involving many variables. For example, some regions are already well-covered (e.g. urban areas in South Africa), while others are so desolate that the number of people served by covering them would be small. Political stability is a factor, e.g. a country engaged in a civil war is unlikely to maintain the system. To generate possible solutions, the students explored these factors and others using a GIS. They constructed representations of population density, political stability, and the physical requirements of the airborne system, to ascertain which countries would be the highest-pay-off investments, and where airborne systems should be positioned.

Systematic research on the effectiveness of GIS

Examples such as these highlight the potential for interventions like the Geospatial Semester that use a GIS intensively to support student spatial learning and problem solving. However, additional research is needed to investigate whether these effects hold up at a larger scale. Do students who enrol in the GSS learn to think more spatially and more effectively than students enrolled in other classes?

To address this question, we (Jant, Uttal and Kolvoord, under review[21]) conducted a quasi-experiment, comparing students' performance in the GSS to that of students in two other demanding senior-level courses, AP Physics and AP History. We interviewed students several times across the year, asking about their developing ideas for the final project, and what they had learned. In addition, we also asked the students a series of transfer questions, in which students were asked to solve new problems. The goal of the transfer questions was to assess whether students considered spatial approaches to new problems. For example, one transfer problem asked students to imagine that they were running for sheriff in their local county, and to think about how they would go about soliciting votes. This problem is not inherently spatial; it could be solved simply by saying they would run advertisements in local newspapers or through direct mail. But an effective solution will often involve thinking about different layers of spatial data, including population density, outcomes of prior elections in given areas, polling locations, etc. Thinking of the problem in a spatial manner allows one to be much more selective and efficient about where and when to allocate effort and money in the campaign.

We found that students in the GSS class approached the transfer problems in a spatial manner, thinking about the problems as involving distributions and patterns. They mentioned the kinds of data that they would need to locate and represent to solve the problem. They also recognised the iterative nature of problem solving, noting that the GIS would allow them to consider information in multiple ways. The results suggest that working with GIS can substantially alter both how students conceive of and implement possible solutions.

Conclusions

Digital versions of paper technologies offer new opportunities to support and enhance spatial learning. For example, maps have been used for thousands of years, and learning to use them is an important aspect of the development of spatial cognition (Uttal, 2000[23]; Uttal and Sheehan, 2014[24]). Maps help us to think about the world beyond direct experience and to learn about the world from others. GIS expands this basic capacity of maps by allowing the user to select and represent a large variety of different data, in different layers. As we have discussed, GIS enhances spatial thinking by allowing the user to combine information in ways that would be very difficult if not impossible to do on paper. With training and experience, GIS has the potential to expand students' conceptions of problems and their possible solutions; learning to use GIS helps students to conceive of spatial solutions to problems, and to explore a range of possible solutions to these problems.

Similarly, software that understands sketches in human-like ways make it possible to create software coaches and tutors that can provide students with immediate feedback anywhere, anytime. While CogSketch already has enough visual representations and reasoning to support new kinds of educational software, there is much research ahead before the goal of human-capable visual understanding is reached. Significant progress in at least four areas should be goals of future research:

1. Richer 3D understanding. The quantitative aspects of 3D modelling are well understood from prior work on computational geometry and graphics. But capturing the qualitative aspects of how people reason through three dimensional problems is still an open issue (Gagnier and Shipley, 2016[25]).
2. Deeper linkages to qualitative mental models. Spatial representations are typically carriers of conceptual information, and our understanding how visual properties of sketches are used to depict and reason through such conceptual information is only fragmentary at this point (Chang, Wetzel and Forbus, 2014[26]). Expanding the use of sketch understanding across multiple STEM domains would be a productive way to drive such research.
3. Integration with other modalities. People talk when they sketch with each other, so the fluency of sketching would be increased by supporting natural language, speech, and gesture in conjunction with the drawing component of sketching. Integrating sketch understanding with low-level visual analysis of images would enable systems to gain background knowledge from diagrams on the web, and work with student drawings produced outside of sketching software.
4. Multimodal memory systems. Creating intelligent software tutors and coaches that recognise common patterns of misconceptions, track students' progress by comparing their work on novel assignments, and providing useful examples and precedents for projects that a student is working on, all require systems with libraries of experiences that consist of integrated visual, spatial, and conceptual knowledge.

Policy implications

Our research has several international policy implications. These could be enacted almost immediately, and many would be very inexpensive.

1. Spatial learning is critically important for STEM education. We now know that spatial learning is a very important part of STEM education and practice.
2. Spatial thinking is malleable; it responds to training and life experiences. We must design education to teach spatial thinking explicitly to see benefits in terms of STEM participation and achievement.
3. Spatial thinking and learning can be fostered greatly by new technologies, such as CogSketch and GIS. The technologies that we have reviewed here allow teachers and learners to think spatially in powerful, new ways.
4. These technologies are either free or inexpensive; cost should not be a reason to avoid using them. CogSketch (and associated worksheets) is freely available; all that is required to use it today is a Windows computer, and within the coming year a cloud-based version that can be accessed from tablets and smartphones will become available.
5. Sophisticated, cloud-based GIS programmes are also now available free of charge for schools. Thus, the time is ripe to begin using these spatial technologies more intensively in schools.

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Chapter 9. Digital media as a catalyst for joint attention and learning

By

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In this chapter Brigid Barron and Amber Levinson argue that as digital activities become a growing part of young children's experiences globally it is vital to consider not only what content children use, but also the social context and ways families can use technology collaboratively to support development and learning in and out of school. This chapter also emphasises equity concerns – both access to technology itself and information about how to use technology with children are unequally distributed. Insights from the learning sciences support the importance of social interaction and joint engagement between parents and children in order to get the most out of digitally mediated learning activities. The chapter closes with implications for parents, policy makers, designers and educators who want to leverage media as a resource for cognitive and social development.

Across the globe, digital technologies are transforming the ways people work, communicate, learn and play. This rapid innovation has led to great enthusiasm about the potential for networked tools to provide more children with low-cost access to learning opportunities that might help minimise existing educational inequities both between and within countries. At the same time, as devices and Internet connections become more available to a greater proportion of the world's children, there is growing evidence that the quality of access and forms of use differ among more and less developed countries raising concerns that a "second digital divide" may widen existing differences in learning, achievement and other life outcomes (UNICEF, 2017[1]). Even within developed countries like the United States, adults are differentially prepared to use the Internet (Horrigan, 2016[2]) and consequently teachers' and families' understanding of how to leverage technology to support children's learning varies widely (Livingstone et al., 2017[3]).

In this chapter we argue that as digital activities become a growing part of young children's experiences at increasingly younger ages (Rideout, 2017[4]), it is vital to consider not only what content children use, but how families can use technology collaboratively to support development and learning in and out of school (Lauricella, Blackwell and Wartella, 2017[5]). We begin by summarising recent policy-oriented reports that foreground the need to continually track issues of equity related to access to tools, forms of use and the importance of building collaborative social networks that provide learning opportunities. We next focus in on families, and share insights from the learning sciences that point to the importance of capitalising on social interaction and joint engagement between parents and children for getting the most out of digitally mediated learning activities, providing findings from research in the United States, Europe and in developing countries. We close with implications of these findings for parents, policy makers, designers and educators who want to leverage media as a resource for cognitive and social development.

Global portraits of access to digital content and networked devices

A recent UNICEF report Children in a Digital World highlights both the opportunities and dangers presented by the rapidly shifting landscape of new technologies. Although concerns about data privacy, access to inappropriate content and increased potential for exploitation are raised, the report also highlights a different challenge; growing evidence of differential use by children and youth with more financial assets, digital skills, access to devices, or the quality and stability of their Internet connections that can help them use the technology in empowered ways (Dutta, Geiger and Lanvin, 2015[6]). Over a third of youth worldwide do not have Internet access and most of these young people are in developing countries. Those who speak minority languages are also at a disadvantage as most of the content provided through the Internet is in English (UNICEF, 2017[1]).

Reports based on US Census data also provide clear links between access and income (Ryan and Lewis, 2017[7]). Among households earning less than USD 25 000.00 a year, over half have do not have access to both the Internet and a computer. Overall, only 62% of households had high connectivity defined as having a desktop or laptop, a mobile device and a broadband Internet subscription. Moreover, access is linked to adults' confidence in using technology. A recent Pew Research Center report focusing on adults' readiness for using the Internet showed that adoption of technology for adult learning in both personal and job-related activities varies according to the individual's socio-economic status, race and ethnicity, and level of access to home broadband and smartphones (Horrigan, 2016[2]).

Although lack of access is a significant concern, there are also important questions about how technology can be used to support learning and what support adults need to scaffold powerful engagement. Several studies have found that teachers in less affluent schools use technology for drill and practice rather than inquiry or creation (Warschauer and Matuchniak, 2010[8]). Teachers in less affluent communities also report fewer opportunities to learn to use technology that their peers who teach in more affluent schools (Dolan, 2016[9]; Purcell et al., 2013[10]). Parents also need more learning opportunities to ensure that technology use at home becomes a resource for learning and development. Young children's time using mobile devices more than tripled between 2013 and 2017 in the United States, moving from an average of 15 minutes to 48 minutes daily with much of this time spent playing games or watching online video. At present, parents are often learning through experimentation with practices and policies at home and by getting advice from their own social networks. Several studies suggest that parents would like more help from teachers or other professionals in finding high quality digital media. Rideout (2014[11]; 2017[4]) reports that they have downloaded apps for their children, this desire for more information is critical to respond to.

As conversations around digital media and young children evolve from quantifying "screen time" to consider content and context, research in the learning sciences offers some valuable perspective that can inform best practices. In the next section, we discuss ways that digital media when selected and used intentionally can support social and cognitive development, drawing from basic research in the science of learning. In particular we build on what we know about social processes in learning and development to argue that joint attention focused on media can be a potent resource for learning between children and their caregivers. To illustrate these concepts, we share examples of powerful uses of technology for co-learning to align home and school to advance academic skills, to support interest development and to position children to create and critique new media.

Powerful uses of technology for joint engagement and learning

What can productive co-engagement with media look like in practice, according to the research? Research in the learning sciences emphasises joint attention as an important means of building a basis for inter-subjectivity – the shared understanding of what is happening and what will happen next. It allows parents and their caregivers to build common ground and a collective understanding through questions, observations and explanations. The quality as well as the quantity of joint attention matters for learning (Rowe, 2012[12]). Books, games, television and interactive media are designed artefacts that have the potential to become foci for joint attention and learning conversations that can support cognitive and social development. Through routine interactions the child acquires not only skills but the cultural tools that have been developed over long periods of time, such as writing systems, maps, language and numerical systems (Vygotsky, 1978[13]). Increasingly, these cultural tools include and are found on digital devices, and adult-child interactions with and around media have been termed joint media engagement (Takeuchi et al., 2011[14]).

Parent knowledge, skill and attitudes towards using technology are key in shaping children's digital experiences, and thus parent access to relevant information and models is extremely important in order to support productive joint engagement with media. In a survey of over 6 000 European families researchers found that parent expertise with technology is a pivotal factor in children's digital skills (Livingstone et al., 2017[3]). Parents who adopt a "restrictive" style with regard to their children's technology use may shield children from risks of online engagement, but also undermine their ability to learn and benefit from digital activities. When parents adopt an "enabling" style, which includes monitoring and mediation for safety, as well as sharing online experiences, supporting children's efforts when they request it, children can encounter more risks but are also able to take greater advantage of online resources and activities, developing their own digital literacy. This digital parenting divide is linked to parent's own feelings of confidence using technology with more confident parents reporting an enabling approach with less confident parents reporting restrictive practices. Surveys in the United States have also found that parents' use of technology for their own learning was linked to children's use of educational media at home (Rideout, 2014[11]) and in other studies parents' use of technology in their work has been shown to influence the ways they support their children's technological activities (Barron et al., 2014[15]).

For young children, digital media resources can serve as a particularly powerful learning tool when adults and children use them as a catalyst for discussions that include question generation, problem-solving, explanations and the sharing of perspectives that build connections to real world experiences. Looking more deeply at specific adult practices to support learning, Barron and Levinson (2017[16]) identified four strategies for co-engagement with media, including 1) media curation, or connecting the child with specific resources based on interest or learning goals; 2) conversational anchoring, or using media to illustrate or explain concepts; 3) interest-driven searches, in which adults and children use technology as a tool for collaborative inquiry; and 4) co-play and content creation, in which adults and children are partners in play or making creative projects. Below we summarise findings from across the research literature, organised by three major roles that co-engagement with technology can play in enhancing learning for young children, relevant in both home (parent-child) and school (educator-child) settings: to support interest development, to align home and school to advance academic skills, and to position children to create and critique new media. These roles and the associated examples are not exhaustive but provide important implications for practice.

Extending and deepening children's interests.

Parents and educators can play an active role in brokering future learning by connecting children with the specific media resources that can deepen their engagement, expertise and interests (Barron et al., 2009[17]). Studies that chart the evolution of interests prospectively or retrospectively point to the important roles of families and well as schools in sustaining engagement in science, technology, engineering and mathematics (STEM) and other academic topics (Bloom and Sosniak, 1985[18]; Crowley et al., 2015[19]). This research shows that it is typically not one experience that leads to a sustained interest but a confluence of opportunities and supports that facilitate connections to a domain. In most cases, a wide array of activities, experiences, material resources and social interactions sustain engagement in a topic (Azevedo, 2013[20]). It is the accumulation of diverse sets of variably engaging experiences over time that account for expertise development, though occasionally one powerful experience is transformative. An important implication of the distributed nature of learning is that a single experience may not have an immediately recognisable or detectable effect on knowledge or interest, despite the fact that it may contribute importantly to outcomes that show up later.

Digital media can provide access to resources related to myriad topics and can be used as a means of providing children with additional experiences that may spark, extend and/or deepen interest. For example, Levinson (2014[21]) documented a young girl's use of YouTube to develop an interest in building do-it-yourself projects with her mother. Barron and Levinson (2017[16]) describe how a single mother recorded episodes of the factual television show "*How It's Made*" that built on her son's interest in building and engineering and were the basis for family conversations on these topics. Further, books and stories can be accessed in digital form via computers and mobile devices, and can increase access to relevant reading content in local languages for communities throughout the world who may not have access to the same array of books in print form (Heavner and Lowe, 2017[22]).

Aligning home and school settings

Another powerful use of technology for learning is to create stronger connections and alignment between home and school learning. Educators and researchers have pointed to the need for better understanding between family and school contexts to support learning particularly for children from underserved communities whose families' own schooling histories and experiences may differ from those of middle or upper-SES families. Technology can play a role not only in supporting direct communication between home and school, such as messaging between parents and teachers or providing parents access to assignments and grades, it can also play a role in connecting actual learning activities that children engage in across home and school settings.

Research has indicated ways in which parent-child media activities at home can strengthen academic skills in school. In one study, parents and caregivers were given a maths app to use with children at home as a bedtime routine and found that those children's maths scores at school increased significantly more than did those of a control group who received a reading activity (Berkowitz et al., 2015[23]). Digital libraries of books, which can be accessed at school or on devices at home, can provide opportunities for students to engage with the same texts at home and in school (Levinson, 2014[21]), and also can provide data to educators on the reading students do outside of class. In school settings, technology can also provide the means to connect academic activities with out-of-school interests; for example Walkington (2013[24]) found that computer-based word problems that were personalised to students' out of school interests led to better performance for those students, and the effect was particularly pronounced for students who had been struggling with maths. In the literacy domain, Ready4K, a text messaging programme targeted at parents of pre-schoolers providing tips for supporting early literacy at home, has been linked to improved literacy scores in some areas as well as higher rates of home literacy activities and school engagement as reported by parents (York, Loeb and Doss, 2014[25]).

Co-creating with technology

Digital devices not only provide a means for searching for and consuming content and information – they are a tool for expression. Educators and researchers have argued that creating with media is an important skill set and area of literacy for children to develop (Barron et al., 2014[15]). Devices such as smartphones and tablets offer cameras, microphones and a wide range of creative applications that enable children and families to capture experiences and create original work in a variety of media. These capabilities can empower children to be creators and authors from a young age, and adults can play an important role in supporting this process.

Research emphasises storytelling and narrative as important building blocks for literacy development (Cassell, 2004[26]). Use of decontextualised language is an important foundation of literacy that children build through early storytelling practices, before they begin to produce or decode text. Common technologies such as smartphones and tablets offer multiple means for families to create and record stories orally, either using the camera function or specific applications that scaffold storytelling by providing images, prompts, or other structures. Likewise, as children develop and begin to read and write, digital platforms can become tools for composing original works including illustrated stories, comic books, graphic novels, poetry and more. Creating these works digitally not only allows children to create in rich and novel ways, it offers the potential to easily share works with audiences including family and friends. In the area of computational creation, research has also begun to explore building and creating with technology as a joint family learning activity that develops adults and children's engineering capacities, while also building on intergenerational relationships (Roque, 2016[27]).

McPake, Plowman and Stephens (2013[28]) argue for the potential of digital media to support children's communicative and creative competencies and provide examples of some ways in which this process occurs among pre-schoolers in the United Kingdom. Their case studies of 54 children document practices of young children who with the support of adult family members create and share photographs they take, search for images of favourite characters online to create puppets for imaginative play, and create original music. Barron and Levinson (2017[16]) document examples of the creative uses of technology among Latino immigrant families in the United States, including five- and eight-year-old siblings who create their own video "talk show" for their relatives in Mexico, showcasing various aspects of their lives and sharing messages. As highlighted above, adult beliefs, knowledge and attitudes regarding technology are important in shaping young children's creative activities with technology, and some parents who are not as experienced or aware of creative affordances of digital media may not be as likely to foster these practices in their children as parents who are. Studies of children internationally have further suggested that although children may regularly use digital devices for play or entertainment, more supports are needed to ensure that children also engage in the creative and participatory opportunities that technology offers (Third, 2016[29]).

Policy implications

Although the use of digital devices continues to proliferate, information about best practices is still difficult to access. Policies and programmes are needed to support equitable learning opportunities for parents and educators in order for all children and families to be able to benefit from best practices for learning with technology. There is also an opportunity to provide resources for media content developers to support them in creating media that facilitates co-engagement and learning.

Supports for parents

Many parents across the socio-economic spectrum are uncertain about how to think about screen media and studies indicate a desire for more information about how to find and choose content for their children, particularly parents with fewer years of formal schooling (Rideout, 2014[11]). Parents need opportunities not only to discover specific titles but learn how to share media experiences with their children to support social and cognitive development. Such support could include helping families find and curate high quality content, but it also needs to go beyond this to help parents imagine ways to collaborate, co-create and use media to further their child's and their own interests. Schools, workplaces and cultural institutions might all have roles to play in designing ongoing learning opportunities for parents that can help them keep up with the rapidly evolving landscape of devices, content and increasingly varied forms of interactivity.

Empowering educators as brokers

Increasingly, school settings are adopting tablets and other new devices. Schools are sites that are often intended to provide opportunities for more equitable access to learning resources, however data shows that there are still significant divides with respect to access to technologies although rates of use are changing rapidly and access to high quality content is not evenly distributed within the United States (Warschauer and Matuchniak, 2010[8]) or internationally (UNICEF, 2017[1]). In- and out-of-school educators have an important role to play in introducing children to technologies that might support learning, not only through curricular activities but also by advising families on resources for home use.

Survey results from parents in the United States suggest that they have a strong desire for more information about how to choose media to support their children (Rideout, 2014[11]) and educators are well situated to help “bridge” home and school settings by using their understanding of in-school activities to suggest supporting resources for use at home. However, teacher education programmes and professional development experiences rarely focus on this aspect of advising students and families or where to find relevant resources to recommend.

As with media practices among parents, the use of technology in classrooms varies substantially depending on schools and context (Warschauer and Matuchniak, 2010[8]). Inequities have been shown to exist regarding technology use in schools, where privileged students are more often engaged in “progressive” uses of technology that involve collaborative and inquiry-based activities, while less privileged students receive more traditional practice or drilling on devices. Educators can be better supported to lead collaborative activities that use technology as a springboard for discussions and joint inquiry. Educators need opportunities to learn what the research tells us but also to imagine and create rich curriculum that leverages technologies for school and for home. In order for teachers to serve as sources of information for students and families about productive media practices, this topic needs to be included in teacher preparation programmes and professional development. School administrators and school board members also need to be included in these conversations so that the appropriate resources and supports are provided.

Informing technology developers

The need to build on the learning sciences to guide the design of children’s apps has been nicely articulated by Hirsh-Pasek and colleagues (2015[30]). They point to four “pillars” of findings that app designers might draw on as they imagine, prototype and create interactive experiences – active, meaningful, engaged and socially interactive. In this chapter, we have emphasised that joint attention is not solely achieved through the media itself or the environment but depends a great deal on intentions, practices and strategies of those involved in the interaction. However, as Hirsch-Pasek and colleagues note – designers can build in opportunities for turn-taking, contingency and para-social relationships. Expanding content to include other languages is also critical. A large proportion of apps require English and if we hope to provide high quality content to young children and their families globally, design efforts will be needed to meet the needs of specific communities.

In closing, we have suggested that digital technologies can be an important resource for children’s learning and that they may help bridge educational divides both within and across countries globally. Achieving this goal will be a significant challenge and will require policies that attend to the distribution of devices and the quality of Internet access but they will have to go beyond these basics. To capitalise on the potential of digital technologies for human development parents and educators need opportunities to learn to curate educationally relevant content and to use it collaboratively with children for creative, critical and inquiry-based activities. The pace of innovation is not likely to slow and collective approaches to learning will need to evolve rapidly to take full advantage of the potential benefits and to avoid the exacerbating inequities that limit human creativity and well-being.

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Chapter 10. Designing joint engagements with media to support young children's science learning

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Young children are positively disposed to and a capable of developing sophisticated science, technology, engineering and mathematics (STEM) skills and knowledge. This chapter reviews the literature related to children's development of early science literacy and how designed joint engagements with media (DJEM) can, by providing rich opportunities for joint attention and academically productive talk, play a powerful role in helping children build strong early science skills and content knowledge. The chapter proposes a theory of designed joint engagement with media based on a classroom enactment of the DJEM approach and unpacks the implications of DJEM on technology development and future research.

Context

One of the world's most pressing challenges is how to provide all children, regardless of birth, with formal and informal science learning experience necessary for them to develop the scientific literacies required to participate fully in public life and have the option of pursuing careers in science, technology, engineering or mathematics (STEM) fields. This chapter explores how theories of joint attention and academically productive talk, two cornerstones in learning sciences theory and research, with empirical research on the motivational and attentional affordances of increasingly ubiquitous technology and media resources, can be leveraged to support early science learning and teaching. Readers interested in further reading on media and learning and/or early science are especially encouraged to consider chapters by Barron and Levinson and by Toub, Verdine, Hirsh-Pasek and Golinkoff in the current volume (Chapters 9 and 16).

Early science and educational media

There is a growing awareness that science learning needs to begin early in childhood. Research suggests young children are not only capable of, but also benefit greatly from, making sense of the world around them by using foundational science practices to develop deep understandings of life, earth and physical science content (National Research Council, 2012[1]). Focusing on early science can benefit all children, but can be especially powerful for young children from disadvantaged groups who are historically underrepresented in science careers (Landivar, 2013[2]). This chapter describes an approach around the use of technology and media to address this need and bridge this gap: Designed Joint Engagements with Media (DJEM).

While the use of technology and media early in childhood has been historically controversial largely due to concerns about the effects of screen time on young children's health and well-being, researchers and practitioners now agree that technology and media that is designed and used in developmentally appropriate ways can be a powerful resource and catalyst for learning (NAEYC and Fred Rogers Center, 2012[3]). This is especially true for science, where technology and media can allow access to varied content (and content that may often be hard to access) and provide powerful representations and models (Kallery, 2011[4]). Appropriate design and use of technology and media early in childhood hinges on ensuring it promotes social and collaborative learning processes, rather than isolated learning as many fear. The DJEM approach described in this chapter builds on developmental and learning sciences theories and empirical research to delineate processes that can ensure technology and media support learning in socially rich ways.

The chapter describes research effort aimed at testing the DJEM approach on the ground, including the development and field-testing of a curricular supplement that uses a curated set of engaging and developmentally appropriate video clips from Sid the Science Kid to organise and support educationally productive talk to promote engagement in science practices and understanding of science content.

Possibilities and challenges of supporting early science learning

Young children have an abiding curiosity about the natural world, are ready to engage in science practices, and can think deeply and, to a degree, abstractly about scientific concepts (Gelman and Brenneman, 2004[5]). For example, pre-schoolers at home and at school are often interested in observing and documenting their own growth or the growth of plants and are eager to explore structures and investigate how things move through building (and knocking down) blocks.

Early science learning has been associated with long-term positive outcomes, in particular, how knowledge of the social and physical world strongly predicts later academic achievement in reading and science (Grissmer et al., 2010[6]). Research has documented that high quality early science instruction is significantly associated with improved vocabulary and grammatical complexity (French, 2004[7]; Peterson and French, 2008[8]), mathematics learning (Epstein, 2007[9]), executive function (Nayfeld, Fuccillo and Greenfield, 2013[10]), school readiness (Greenfield et al., 2009[11]) and later academic achievement. Of course, children need support and scaffolding from adults to make these possibilities a reality.

Unfortunately, preschool science learning opportunities are few and far between, and preschool teachers are not often prepared to lead when it comes to science teaching. Currently preschool programmes, especially those serving children from low-income communities, offer children few planned (Nayfeld, Fuccillo and Greenfield, 2013[10]) or free-choice (Nayfeld, Brenneman and Gelman, 2011[12]) opportunities to engage in science learning. And while teachers play a critical role in scaffolding children's science learning, many early childhood educators lack the preparation and confidence needed to promote science in their classrooms, and the necessary instructional resources to integrate science into their curricula (Dominguez et al., 2015[13]). Given these circumstances, new resources and innovative methods are needed.

Leveraging educational media and technology for early learning

Decades of research on young children's learning with educational technology and media highlight their potential to support academic learning (Fisch and Truglio, 2000[14]). Educational technology and media can be valuable learning tools in preschool classrooms by promoting (National Research Council, 2012[1]) representation and organisation of ideas in a different medium, (Landivar, 2013[2]) communication of ideas and collaboration among members of a learning community (NAEYC and Fred Rogers Center, 2012[3]), visualisation and reflection on thinking of children and teachers (Kallery, 2011[4]) and extension and communication of consolidated learning (Hong and Trepanier-Street, 2004[15]). Developmentally appropriate integration of digital resources using resources that foster engaging interactions with content, peers and teachers can facilitate literacy and STEM learning in preschool settings and beyond, particularly for children from socially and economically disadvantaged populations.

Short videos, for example, can provide young children with the opportunity to observe and discuss phenomena and concepts that would not normally be accessible in classrooms given time and resource constraints (Kallery, 2011[4]). Videos can also feature characters that model engagement in science practices, which can prove beneficial for both children and adults scaffolding their learning (Dominguez, Sharifinia and Danae, 2015[16]). Mobile devices, such as tablets with touch screen technology, can also provide unique opportunities to promote science learning by allowing children to document their investigations and collect data they can revisit to reflect on their findings and by providing access to apps with unique opportunities to practice what is learned in the real world. Based on these findings, our theory of designed joint engagements with media proceeds from the insight that when technology and media use was associated with outcomes in empirical studies, it was often designed with certain features (like discussion prompts) and used in specific contexts (that supported or enabled co-engagement) that maximised the social dimensions of learning. The following section defines and unpacks the theory in detail.

A theory of Designed Joint Engagements with Media (DJEM)

We define DJEM as purposefully created, shared experiences where individuals interact with one another while simultaneously attending to a media artefact. DJEM can take many forms, including viewing a video, playing a game on a mobile device or reading a digital book together. DJEM grows out of the idea that joint attention or the co-ordinated focus of all interacting individuals on the same phenomena, is a necessary condition for joint engagement and is fundamental to human learning from an early age (Meltzoff et al., 2009[17]). Because the management of attention is fundamental to interactions (Barron, 2003[18]), DJEM also depends on theories of collaboration that highlight how attention is recruited, sustained and leveraged during interactions. Both the speaker and the listener play an important role in establishing, monitoring and sustaining joint attention during interactions, drawing both on non-verbal communication (e.g. pointing, moving to share visual perspective, etc.) and on meta-communicative verbal comments. The use of such strategies helps create a 'between-person state of engagement' that draws on both the cognitive and the social dimensions of communication (Barron, 2003[18]), and helps partners develop a shared conceptual structure in which they collaborate and learn as they engage with media together.

DJEM is informed by research on other forms of joint engagement, including studies that illustrate how collaborative parent-child conversations support young children in their zone of proximal development to reason and solve problems with increasing sophistication. These shared conversations – joint social engagements – serve as sites for knowledge construction and meaning making. A considerable body of research suggests that everyday adult-child conversations helps children learn about the physical, natural and psychological world (Jipson and Gelman, 2007[19]). Founded on shared experiences, knowledge and interests, conversations between children and adults help make children's implicit knowledge explicit (Taumoepeau and Ruffman, 2006[20]) and support children's ongoing construction and understanding of concepts, taxonomies and complex arguments. The collaborative nature of conversations with adults helps make children's knowledge explicit (Taumoepeau and Ruffman, 2006[20]); supports their engagement at a higher level of reasoning and problem solving; provides an opportunity for adults to model various strategies, such as thinking out loud, asking questions, requesting elaboration; and offers children a rich source of information regarding the norms and practices (Callanan, 2006[21]) for participating in a discourse community (Callanan, 2006[21]).

Inspired by Barron (Barron, 2003[18]), we conceptualise media experiences as a particular kind of shared space where children and their social partners can jointly address learning issues. DJEM also builds on research on co-viewing and joint media engagement (Fisch et al., 2008[22]; Takeuchi et al., 2011[23]), that shows that co-engagement with educational television programming with adults or older siblings can be favourable for young children's learning (St. Peters, Huston and Wright, 1989[24]). Previous television research suggests that caregivers who watch together with children could initiate conversations about programming that fostered learning, such as naming and identifying objects, repeating new words, asking questions, relating content to the children's own experiences, and inviting and scaffolding the children to make connections between the programme and their everyday life (Bronfenbrenner and Morris, 1998[25]; Mihalca and Miclea, 2007[26]). In the changing landscape of media use with young children, there is a growing awareness that media can support learning by promoting – rather than inhibiting – social interactions among children and between adults and children. Shared media experiences have the potential to act as a tool for scaffolding children's learning (Bronfenbrenner and Morris, 1998[25]; Mihalca and Miclea, 2007[26]; Vygotskiĭ and Cole, 1978[27]) through interactions, active mediation strategies, which encompass critical conversations between adults and children that refer directly to the media experience (Nathanson, 2001[28]) and experiential mediation, which involves the use of media as a platform for making sense of other experiences and interactions (Jennings and Walker, 2009[29]).

In DJEM, media acts as a powerful referential resource that provides a space for the highly co-ordinated, consequential social interactions that lead to learning. In various formats, media can support learning by providing a means of exposure to new ideas that can be explored more deeply in conversations. For example, a video's use of a rotting pumpkin to signify decay becomes a point of reference for facilitating discussion about how fruits and vegetables change over time and children's own experiences of decay. Developmentally appropriate media assets (e.g. educational television and videos, games, applications) can also catalyse social interactions (between adults and children and among children) that in turn activate important processes productive for learning. These include, but are not restricted to: participating in discussions; having opportunities to explain one's thinking about phenomena; listening to, eliciting and elaborating explanations; observing the modelling of language and meaning-making strategies; asking questions; evaluating and critiquing responses, and arguing to resolve differences. In this spirit, collaborative conversations that occur between adults and children in the context of a shared media experience help make children's knowledge explicit, support children's engagement at a higher level of reasoning and problem solving, and provide an opportunity for adults to model various strategies, such as thinking out loud, asking questions and requesting elaboration (Callanan, 2006[21]; Fisch et al., 2008[22]; Mihalca and Miclea, 2007[26]). Taken together, these lines of research form the foundation for the DJEM approach that explicitly integrates media experiences to support early science teaching and learning through social, media-rich, talk-centred experiences.

Classroom enactment of the DJEM approach

To test the feasibility and promise of the DJEM theory, we developed and refined a curriculum supplement, worked with a public preschool teacher partner to enact the supplement in her classroom, and conducted a preliminary exploratory study during the enactment. The teacher-partner's class of 20 children was ethnically, economically and linguistically diverse, and included many English learners. To increase the depth and quality of implementation, the teacher received coaching and on-site support from research team members before and during the implementation period.

The curriculum supplement comprised an eight-week experience on change and transformation, foundational concepts across science content areas. Modules were two weeks long and included two or three days of instruction each week that integrated video episodes, classroom discussions, teacher guided book readings and hands-on investigations. The curriculum supplement's four modules targeted type of change that children likely observed in their daily lives: decay, growth, reversible change and irreversible change. The videos that anchored each module were from Sid the Science Kid, an animated science programme for preschool children by the Jim Henson Company that explores everyday phenomena and provides models of science practices and science talk. Each Sid the Science Kid episode centres on a question that preschool-aged Sid, the inquisitive main character, has about the world and why things work the way they do. Through the process of uncovering the answers to Sid's questions, the show exposes children to the big ideas of science, helping them deepen their understanding of everyday experiences by showing how science practices support the development of scientific understandings.

The video segments preceded and provided the anchor for teacher-led, hands-on activities, during which children explored phenomena first hand. An introductory whole class activity, structured around a video excerpt, introduced science topics and provided models for how children and teachers can engage in scientific practices to explore the topic in depth. This introduction was followed by four instructional days that offered a combination of whole class and small group activities that deepened and reinforced target concepts. Whole class activities included guided book reading, focused video viewing and reflective discussions. Small group activities, such as hands-on investigations (sorting/sequencing activities and data collection/recording tasks) were designed to allow children greater opportunities to engage in and discuss science. Each module concluded with a whole class discussion, facilitated by the teacher, during which children reflected on what they had learned about the science topic.

The curriculum modules were designed to provide children multiple points of entry and the opportunity to move back and forth between media-rich and hands-on activities, each time using previous experiences to create stronger and more nuanced understandings as they reengaged with concepts multiple times. For example, after watching the episode, "My Mushy Banana", students conducted observations of a banana, using their senses of sight, touch, smell and taste; they then recorded their observations in their science journals by drawing and labelling pictures (with the help of their teachers).

Technology and research implications

Anchored in foundational theories of learning and empirical research, DJEM has the potential to guide design and implementation of developmentally appropriate media and media-rich preschool interventions. For media makers, DJEM theory suggests they can and should create educational media resources that are, at a minimum, amenable to joint engagement – videos, games and apps that are aimed at kids working together with peers, teachers or family members. Moreover, there is an opportunity for the development of a new genre of apps designed specifically for parents that can support and foster rich conversations and social experiences shown to support learning. One example of this is the Daniel Tiger app developed by the Fred Rogers Company and their partners. Another is a new genre of app for parents called a Conversation Catalyst currently in development by media producers at The Jim Henson Company and Curious Media, in collaboration with authors from Digital Promise's Learning Sciences Research team. This design-based research effort will create new early science learning resources for parents focused on ocean science, and a series of empirical studies about their implementation and effectiveness.

DJEM theory provides a foundation for other empirical research. DJEM ideas have guided the recent design and development of technology and digital resources in the Next Generation Preschool Science (NGPS) project and interventions developed in CPB-PBS Ready To Learn research. Empirical research from these studies will, in time, provide additional evidence of the promise of enacting DJEM principles at scale.

Theoretically, DJEM extends the research on joint engagement and co-viewing by demonstrating how media can be a powerful resource for situated meaning making. by generating a typology of interactions and real-world examples. This work adds to the growing body of research that illustrates how media can enhance the conditions for early learning by fostering productive interactions between adults and children. More practically, our findings offer strategies for using media to catalyse discourse and interactions, especially in domains like science that tend to be under-emphasised in early childhood education. Moreover, data support preliminary inferences about the types of interactions that might be especially challenging for teachers to orchestrate in the classroom, highlighting how curriculum materials and professional development may explicitly support teachers in scaffolding rich, productive interactions among children. Though this chapter focuses on early childhood science learning, the findings around joint engagement with media may be generalised to other learning contexts and content areas.

Policy implications

Innovative public policies are needed to make rich, shared media experiences as common at school and at home as shared storybook readings are today. As in the case of shared book reading, public policies are needed to encourage the creation of supports and resources that can transform the countless media experiences that children engage in (at school, at home, and in third places) into rich, social early-learning experiences. In addition to public policies that support and encourage development, policies and direct investments in research that supports the understanding and further development of models and genres of DJEM are urgently needed.

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Chapter 11. Social components of technology and implications of social interactions on learning

By

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Technology has revealed new insights into the role of social relationships in learning. This chapter explores the social components of technology using biologically inspired robots and computer representations (e.g. avatars and agents), and examines the implications on student learning and behaviour. The importance of theoretically sound and robust concepts such as Learning-by-Teaching and Recursive Feedback is highlighted in designing a learning relationship that can work to maximise the partnership between learner and technology. As a promising strategy for connecting research and practice, the chapter introduces practical applications for the classroom by applying learning-by-teaching concepts using computer agents, virtual avatars and programmable robotic systems.

Introduction

Educational researchers have a good history of developing coherent, empirically supported theories about learning and teaching, but their work is limited when it comes to tailoring findings to practice (Weiss, 1999[1]). Educational technology has the potential to play a significant role in strengthening this link for K-12 education, but current processes for use by practitioners are largely inadequate (Burkhardt and Schoenfeld, 2003[2]). Several reasons come to mind. Design engineers often maximise on the novelty and sophistication of technology, and do not focus on the social components of technology that are important in student learning. In order to make technology more educationally powerful, changes in the design have to be made. It is not just the design of a "thing" rather, it is the design of a social relationship between a learner and a "thing" that involves learning (Sheridan, 2002[3]).

It is important that students do not become overly dependent on technology as decision aids to the extent that they give up thinking for themselves. A critical ingredient to lifelong learning is the ability to assess individuals' own learning and find out where improvements can be made in their understanding. There is a need to identify the kinds of practices that research suggests are successful, and that can work to maximise benefits from the social components of technology. Practice needs to be well-grounded in theory to be able to explore how or why things work (Gomez and Henstchke, 2009[4]), in order to ensure that the learning trajectories are clear and robust enough for the classroom. The importance of this research in relation to K-12 education is that it identifies the kinds of practices that work well with technology, enabling us to equip students with well-designed tools and self-learning skills to self-assess, make informed decisions, identify problems on their own and learn throughout their lives.

This chapter examines how 1) maximising the social components of technology; 2) focusing on the design of the relationship between a learner and technology; and 3) well-grounded theories in learning can help tailor research findings to practice. The latter section of the chapter examines robotics education as a promising strategy for connecting research and practice, followed by policy implications.

Social components of technology in learning and behaviour

Social interaction has many benefits for learning that are not attributable strictly to socialness, such as observing a mature performance (Rummel, Spada and Hauser, 2009[5]), receiving questions, generating explanations (Roscoe and Chi, 2007[6]), and engaging in social motivation and conditions that sustain learning interactions. In many instances, the effects of socialness on learning also are attributed to the timing and quality of the delivery of information, which computers can mimic and control (Okita, 2014[7]). The definition of "social" has expanded dramatically with technology, allowing students to communicate remotely through virtual avatars without being physically present. Sociable computer agent programmes can engage in contingent social dialogue for long periods, and biologically inspired robots can model physical human behaviours. Technology has revealed new insights into the role of social relationships in learning, but little is known about the impacts of such social components on learning.

Neurological evidence indicates that attributions of humanness engage different brain circuitry (Blakemore et al., 2003[8]), and people's interaction patterns differ depending on whether they believe they are interacting with an agent or an avatar. A study examined whether believing that a virtual representation was an agent (computer) or an avatar (human) affected learning (Okita, Bailenson and Schwartz, 2008[9]). Thirty-five college students participated in a study that compared these two conditions. In both conditions, the participants asked identical questions, and the virtual human provided identical, pre-recorded verbal and non-verbal responses. In this way, the study isolated "social belief" from other important aspects of social interaction. The findings indicated that the "belief" in the avatar condition resulted in significant learning gains and higher arousal measures (i.e. skin conductance level (SCL)) compared to the agent condition. Greater arousal correlated with better learning, with the peak SCL being reached when the participant was reading the last portion of a question. This suggested that the locus of the learning effect might occur when people take the socially relevant action of reading, and the arousal during this action prepared them to learn from the response.

The above-noted possibility led to a replication of the study with an additional avatar-silent condition. Participants read the questions silently rather than aloud to the avatar. This way, they could not take any socially relevant action. People might not learn as well through passive listening of an avatar. The results replicated the avatar and agent condition from the previous study. However, the avatar condition showed a moderate advantage over the avatar-silent condition when the problem progressed to more difficult inferential questions. The SCL scores for the avatar and agent condition were similar to those in the first study, but the SCL scores for the avatar-silent condition were smaller than those for the agent condition. This replication study separated the effect of the social element (belief of being social) and the socially relevant action on learning. The result implied that making students believe that they are "being social with a human" (rather than a computer programme) increases factual knowledge, but not deep understanding, unless "socially relevant actions" are involved.

The physiological and learning measures may also help index some internal processes that can inform possible ways to design relationships in which technological artefacts may anticipate people's needs and thus help devise the next step of their learning experiences. For example, in special needs education, robots can assist autistic children in developing social skills (e.g. taking turns and sharing) by repeating specific behaviours when opportunities arise (Robins et al., 2004[10]).

Designing a relationship between a human and a "thing"

Biologically inspired robots have interesting implications for learning, as they have boundary-like properties that elicit strong responses from people (e.g. humanoid robots with human form and motion, but still have machine-like properties). For researchers, robots provide a range of design choices (e.g. tone of voice, gesture, feedback) that can be used to influence social interactions (Okita, Ng-Thow-Hing and Sarvadevabhatla, 2011[11]). This section explores how the transition from the design of a "thing" to the design of a relationship between a human and a "thing" can be beneficial for learning and behaviour. (Nickerson, 1999[12]) suggests that children exposed to thought-provoking objects or situations are more likely to develop deep genuine interests in those objects. In an experiment, children were presented with several biologically inspired robot dogs each performing varying levels of intelligent behaviours (i.e. dancing to music, finding and kicking a ball, and a turned off robot). Robots were used as vehicles to probe children's understanding of artificial intelligence, biological properties and agency (Okita and Ng-Thow-Hing, 2014[13]). The study involved 93 children ages three to five-years-old, and it was found that the complex nature of these robots challenged children's beliefs and prompted them to do some serious thinking. For agency, children made inferences that robots had to have a remote control to move, but they also believed that these robots could jump on the couch when no one was around. For biology, children believed that robots get hungry, have a heart, but cannot grow because of their hard exteriors. Findings revealed that children may bring a syncretic set of beliefs when slowly developing their understanding of an unfamiliar object (i.e. robots) in a piecemeal fashion. Children seemed to shift their discrete beliefs based on a mixture of facts that they had acquired through observations and interactions (Inagaki and Hatano, 2002[14]). These findings on naïve biology can influence instruction when teaching biological phenomena (e.g. child life interventions in hospitals). In a classroom study, a computer application assessed student's prior knowledge in physics, so teachers could use the information to better design instruction (Thissen-Roe, Hunt and Minstrell, 2004[15]).

Other studies have explored differences in children's learning and behaviour based on their relationship with robots. One study engaged children in a learning task using different turn-taking scenarios with the life-sized Honda humanoid robot (e.g. table setting, learning about utensils). The robot exhibited different learning relationships with children, e.g. as a teacher, a peer-learner robot or a robot engaged in self-directed play. Little difference was found between the older children (7-10 year-olds). However, the younger children (4-6 year-olds) in the peer-learner robot relationship learned and performed as well as the older children on the post-test, which indicated that different relationships between children and the robot can influence learning outcomes (Okita, Ng-Thow-Hing and Sarvadevabhatla, 2011[11]). In another study, 30 children between the ages five to seven-years-old participated in an individual, 20-minute study with Honda's humanoid robot (Okita and Ng-Thow-Hing, 2014[13]). The study explored three different social scenarios to see how close children will allow robots to approach them. The robot slowly steps forward while engaging in different social scenario dialogues assigned by condition. The robot says "Captain, may I take another step?" when using Familiar Game Playing condition, "I am going to take another step" in the Announcing Intent condition, and randomly takes steps forward unannounced for the No Notification condition. The robot continues to take steps until stopped by the child. Results showed that designing a dialogue around a game that the child was familiar with, such as "Captain may I?" could significantly reduce the distance between the robot and the child, compared to other conditions. Implications include assisting sensory technology when physical distance is crucial in detecting and avoiding collisions and identifying users (e.g. facial recognition). The studies found that a child's ability to pretend or engage in social interaction with robots was often constrained by what the robot could do in response. Until robots have the intelligence to flexibly respond to a wide range of interactive bids, designing a human-robot relationship around a familiar schema or script can be useful in guiding a social interaction.

Recursive feedback during Learning-by-Teaching

A critical ingredient to lifelong learning is being able to assess one's own learning trajectories, and finding where further improvements can be made in understanding. Learning-by-Teaching (LBT) is a form of peer learning that can provide informative assessment of one's own content knowledge (Bargh and Schul, 1980[16]). The LBT cycle has three phases, i.e. preparing to teach, teaching a peer, and recursive feedback. This section focuses on Recursive Feedback, which refers to information that flows back to teachers when they have the opportunity to observe their pupils independently perform in a relevant context (e.g. coach watching the soccer team play). Recursive feedback in LBT reveals discrepancies they notice from observation, and leads to the realisation that potential deficiencies in pupil understanding may not be due exclusively to how the material was taught; rather, it could reflect a lack of precision in the teacher's own content knowledge. A series of studies tested whether recursive feedback maximised the benefits of LBT on peer learning (Okita and Schwartz, 2013[17]), and identified situational variations for effective implementation in other settings.

A human-human (laboratory) study involved 40 graduate students who met face-to-face with another student (the confederate). The potential value of recursive feedback was isolated through the study design, which systematically removed various elements from the full LBT cycle. For instance, one control condition had tutors prepare and teach, but they did not observe their pupils perform. Students who prepared, taught and observed their pupils perform exhibited superior learning of human biology relative to several control conditions, which included elements of LBT but not recursive feedback. For recursive feedback to be effective, tutors had to maintain representations of their own understanding, of what they taught, and of the understanding of their pupils. Doing so helped the tutors sort out which aspects of the pupils' performances related to which levels of representation. Results indicated that recursive feedback enhances the effectiveness of LBT instructional models.

Avatar-Avatar (Online Virtual Reality Environment): Two additional studies examined whether the benefits of recursive feedback extend to an online virtual reality environment. Thirty-nine graduate student participants communicated through virtual avatars, but they never communicated in person. The first study replicated the human-human study with the same study design and procedures, but took place in an online virtual reality world. The previous findings were replicated, as tutors who taught and observed their pupil avatar interact with an examiner exhibited superior learning relative to the control conditions that included LBT elements but not recursive feedback (Okita et al., 2013[18]).

Virtual environments offer additional design choices that may influence recursive feedback. A follow-up study with 20 graduate students added two recursive feedback conditions that incorporated different design choices, i.e. 1) a customised pupil avatar; and 2) a doppelgänger look-alike, where the pupil avatar looked like the participant. Previous literature has demonstrated that look-alike appearances can affect decision-making and influence behaviour (Bailenson, 2012[19]). The results showed that the generic pupil avatar (control) condition had the highest performance, followed by the customisation and the look-alike conditions. Too much or too little customisation seemed to hinder performance. Too much customisation (31+ times) may have increased the tutor's sense of ownership and thus her/his association with only the avatar's surface features. Too little customisation (<15 times) possibly did not develop any sense of ownership or relationship. Since participants in the control condition focused only on developing the tutor-tutee relationship (i.e. content knowledge), perhaps they were able to focus more on the pupil avatar's performance during recursive feedback. The lower performance in look-alike avatars may come from the learners' tendencies to perceive their own appearance and performance better than objectively warranted (Lerner and Agar, 1972[20]). Possibly designing look-alike avatars that perform better than the actual learner may invite active involvement. Recursive feedback in LBT naturally brings many positive forces for learning, and is a powerful learning method that can be applied in classrooms (e.g. reciprocal teaching), teacher education, online learning and other technology enhanced learning environments.

Robotics programming in education

Educational robotics involves learning to program computers by explicitly formalising the rules in a learning environment (e.g. programming interface) and then observe an external source (e.g. robot) interpret and carry out the command in its entirety. Students observe the output given by the robot and then backtrack to ferret out the algorithms (e.g. debug) that dictate the robot's behaviours. Schools typically give students problems to solve, but rarely ask students to search out problems on their own (Houtz, 1994[21]). Programming is unique in that students actively work to find answers to problems they create. Learning robotics also has strong constructivist implications for teaching (DiSessa, 1988[22]; Jaipal-Jamani and Angeli, 2017[23]) because a student's experience can create a "time for telling" that leads to more learning and transfer by taking the knowledge from this experience and applying it to new situations (Schwartz and Bransford, 1998[24]). Educational robotics can have a prominent role in helping students connect with science, maths and other skills they have acquired in school.

Forty-one elementary school students in fifth and sixth grades learned to program simple robot movements. Students assigned to the high-transparency environment learned visual programming to control robots (e.g. visual icons/LEGO Mindstorms NXT-G). Students assigned to the low-transparency environment learned syntactic programming to control robots (e.g. RobotC programming). A midway performance test showed that students in both conditions learned how to debug familiar programming problems equally well. Then, the students were asked to debug unfamiliar programming problems. The low-transparency (syntactic programming) group was more successful in adapting its knowledge to debug unfamiliar high-transparency (visual programming) problems after observing the robot's behavioural output. Students in the high-transparency (visual programming) group were less successful. Even after the students became familiar with both environments, the low-transparency group continued to perform better than the high-transparency group. This has practical implications on the order and manner in which knowledge is constructed, because findings suggest that whether students can make better use of what they know may depend on how they developed that earlier form of knowledge (Okita, 2014[7]). Similar limitations were found in learning fractions when comparing tile and pie wedge manipulatives (Gick and Holyoak, 1983[25]; Martin and Schwartz, 2005[26]).

Policy implications

Educational technology can have a significant role in strengthening ties between research and practice in K-12 education, but the processes for use and the preparation for pre-service teachers are largely lacking (Burkhardt and Schoenfeld, 2003[2]). Current teacher education programmes still struggle to place emphasis on K-8 science, technology, engineering and mathematics (STEM) disciplines that involve technology and engineering (Bybee, 2010[27]). Many teachers feel they lack knowledge and expertise in applying the methods that research suggests are successful (Nadelson et al., 2013[28]), and research findings are usually not usable "as is" in the classroom, and technologies are often built without clear learning trajectories.

Robotics is an integrative discipline that brings together basic math, science, applied engineering and creative thinking. Preparing pre-service teachers to teach STEM using robotics has been suggested as a promising way to improve students' experience of, and attainment in, science and mathematics. Similar approaches are also seen internationally (Papanikolaou, Frangou and Alimisis, 2008[29]).

Very few examples combine research, practice and commerce early in the process of developing ideas and tools. It is important for policy leaders to help support educational foundations to undertake initiatives in educational venture philanthropy to support joint development between research, practice and commerce. This is particularly important for educational robotics since commercialisation can lead to low cost tools that can be more affordable for schools (Gomez and Henstchke, 2009[4]). Robotics systems often are open sourced, which allows the independent development of educational content. This can be a direct link to commerce, allowing faster feedback between research, practice and commerce.

Often times, designing a positive learning condition depends on situations that bring together a well-chosen confluence of effective learning methodologies, theories and choices of partnerships with technology. To bridge the gap between research and practice, this chapter identified the kinds of concepts research suggests are theoretically sound and robust, can work to maximise the social components of technology, and have practical applications for learning and behaviour. Policy often has a key role in shaping the demands for specific instructional services in schools, but teachers and policymakers need to know what learning is lost and gained when selecting one choice over another (Gomez and Henstchke, 2009[4]). The findings can inform teachers about the pedagogical risks and how specific instructional approaches may encourage certain kinds of learning when used with technology. As strengths and weaknesses becomes visible, incentives shift, and teachers may be more open to new ideas and methods.

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Chapter 12. Teaching basic experimental design with an intelligent tutor

By

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Students in middle and elementary school have a poor understanding of basic experimental design – commonly known as the "Control of Variables Strategy" (CVS). The TED Tutor is an intelligent, computer-based, tutor that adapts instruction on experimental design to individual students based on its assessments of their knowledge and ability, and provides continuous feedback on students' actions. We are embedding the TED Tutor in an adaptive computer-based instructional context in which a child selects a topic for a science fair project, and then designs and implements an experiment to explore that topic. The theoretical contribution of the Inquiry Science Project Tutor will be to determine the extent to which presenting CVS instruction in the context of other inquiry activities elicits sceptical scientific mindsets that evoke science goals of identifying causal factors, rather than engineering goals of trying to achieve specific outcomes. The practical aspects will be to increase robust learning when TED instruction guides students in their design of unconfounded experiments.

Introduction

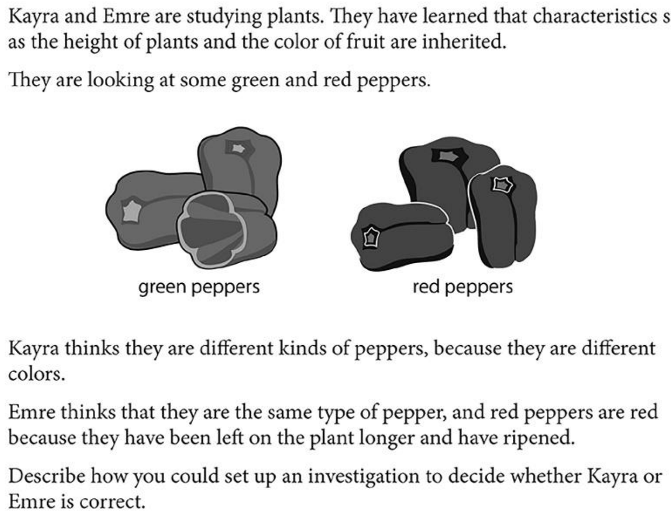
There is a broad international consensus that children's understanding of the principles and processes of basic experimental design – commonly known as the "Control of Variables Strategy" (CVS) – is an essential component of science, technology, engineering and mathematics (STEM) education. For example, in the United States, the recently published "Next Generation Science Standards" recommends that, starting at "the earliest grades", students should learn how to "plan and conduct an investigation collaboratively to produce data to serve as the basis for evidence, using fair tests in which variables are controlled", The "National Curriculum" for England includes a "statutory requirement" that, during grades 5 and 6, 9-10 year-olds, pupils should be taught to plan different types of scientific enquiries to answer questions, including recognising and controlling variables where necessary". The curriculum further states that "working scientifically" will be developed further at key stages 3 and 4, 12-14 year-olds, once pupils have built up sufficient understanding of science to engage meaningfully in more sophisticated discussion of "experimental design and control". Mastery of the experimental method is included in South Korea's science standards (Wichmanowski, 2015[1]) as well as Japan's national science standards (Ministry of Education, 2008[2]). And even though its fundamentals are not explicitly addressed by the German national science standards, CVS's underlying logic and procedures are characterised as crucial sub-skills of "experimental competence" (Wellnitz et al., 2012[3]). Furthermore, both national and international assessments (e.g. TIMSS, PISA) invariably include several items assessing CVS-related skills and understanding.

A solid understanding of the causal reasoning that underlies unconfounded experiments is necessary for both the design and interpretation of their outcomes. This knowledge can also be applied well beyond the science classroom, for example, when citizens attempt to understand and interpret correlational findings, such as those publicised in the media, often presented to support a particular public policy. Having this knowledge may help to protect citizens from uncritically accepting findings from correlational studies, or those containing confounds.

However, instructional research in the United States has repeatedly demonstrated that students – from third to seventh grade – have a surprisingly poor understanding of CVS (Chen and Klahr, 1999[4]; Siler et al., 2010[5]). Moreover, international assessments have consistently found poor performance on items that assess children's mastery of experimental process skills – including CVS. Consider, for example, two of the items that were on the open-ended grade 8 test (TIMSS, 2011[6]). For the item in Figure 12.1, only 14% of students (worldwide) provided the correct answer, with scores for individual countries ranging from 2% in Indonesia to 44% in Singapore. For the item in Figure 12.2, the average was 21%, with individual country scores ranging from 3% in Saudi Arabia to 65% in Japan.

Figure 12.1. Example of a TIMMS test item to assess the ability of grade 8 students to design an experiment to answer a specific question

Released-construction response item (S042297) assessing grade 8 students' experimental skills



Kayra and Emre are studying plants. They have learned that characteristics such as the height of plants and the color of fruit are inherited.

They are looking at some green and red peppers.

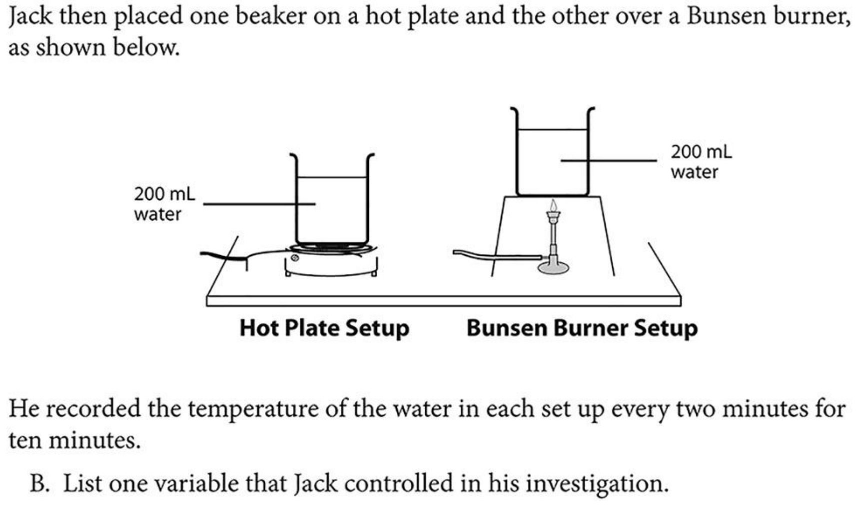
Kayra thinks they are different kinds of peppers, because they are different colors.

Emre thinks that they are the same type of pepper, and red peppers are red because they have been left on the plant longer and have ripened.

Describe how you could set up an investigation to decide whether Kayra or Emre is correct.

Note: A correct response refers to either 1) planting (seeds from) green and red peppers AND observing the colour of the fruit; or 2) planting (seeds from) green peppers AND observing if the fruit turns red. Example: "I would take one seed from each of the peppers and plant them under the same condition and at the same time. Observe them at the same time after the peppers start to grow. If the red peppers become red and the green peppers did not, this would show that the red and green peppers are a different kind."
Source: (TIMSS, 2011[6])

Figure 12.2. Example of a TIMMS test item to assess grade 8 students' understanding of the concept of "all other things being equal" in an unconfounded experiment



Jack then placed one beaker on a hot plate and the other over a Bunsen burner, as shown below.

He recorded the temperature of the water in each set up every two minutes for ten minutes.

B. List one variable that Jack controlled in his investigation.

Note: This item requires the student to notice – and correctly name – at least one of the following features that are the same in each "Setup": the temporal interval (2 minutes) and duration (10 minutes), the beakers (same shape, size and materials), the water (same volume and type). Several other factors, unmentioned in the diagram or accompanying text are – presumably – also the same in each setup: the thermometer type, position for taking readings); the location and surrounding temperature of each setup.
Source: (TIMSS, 2011[6])

Our own studies suggest that within-country variance on CVS skills (as well as much broader knowledge of scientific processes (Normile, 2017[7])) may be even greater than between-country variance. In one study conducted with students from a mid-sized metropolitan area in the mid-Atlantic region of the United States, we found extremely substantial SES-associated discrepancies in children's initial understanding of CVS, as well as in their post-instructional mastery rates in transferring any knowledge of CVS to other domains (13% and 62%, respectively) (Siler et al., 2010[5]). SES-related differences in understanding of science-related skills such as CVS are very common in the United States. For example, Lorch et al. (2010[8]) and Siler and Klahr (2012[9]) conducted a large-scale evaluation of various strategies for teaching CVS with nearly 800 students from 36 different fourth-grade classrooms in the state of Kentucky. Students were taught CVS through interactive classroom discussions. On a post-test requiring them to evaluate experiments, students in schools serving predominately lower-SES populations performed very poorly – only slightly above chance – and significantly worse than students in schools serving predominately higher-SES populations.

In our own research (Siler and Klahr, 2012[9]), analyses of the explanations students gave during remedial tutoring sessions about CVS revealed that lower-SES students were more likely to make characteristic mistakes and harbour robust schema-related misconceptions that interfered with their CVS learning. In particular, when challenged to design an unconfounded experiment that could isolate a causal factor, students would frequently, and incorrectly, interpret the question as asking them to achieve what Schauble, Klopfer and Raghavan (1991[10]) termed an "engineering goal" (producing a desired effect), rather than as a "science" goal (identifying causal factors). Students also expressed their beliefs about the effects of the domain-specific variables (e.g. "I think the steep ramp will make the ball go faster"); that is, students focused on the surface features of instruction rather than on the procedural and conceptual aspects of experimental design (Siler and Klahr, 2016[11]). Moreover, we found that students interpreted "fair comparisons" or "fair tests" as those having equivalent conditions (i.e. where the two condition are set up exactly the same). We have no reason to believe that these types of deep misconceptions and misinterpretations – which can be quite robust – are unique to students in the United States. To the contrary, we suspect that they may be quite general challenges to effective CVS instruction, particularly among students who have little experience with science inquiry.

In contrast, what is predictive of students' ability to transfer their understanding of CVS to new domains is whether they are able to articulate the rationale for controlling variables (i.e. so that only the one variable under investigation can impact the results) (Siler et al., 2010[12]; San Pedro, Gobert and Sebuwufu, 2011[13]). In another study, (Siler et al., 2011[14]), we had an experimental condition in which students' understanding of the rationale for controlling was supported by prompting them to indicate which non-focal variables could have caused a hypothetical difference in outcomes between conditions (i.e. we explicitly asked them to identify any potential confounds, or other variables that could have caused the outcome). These students showed better transfer performance than those students who did not receive these additional prompts. Thus, supporting students' explicit understanding of the rationale for controlling variables appears to be at least one way to produce a robust understanding of CVS.

Science inquiry support

Although CVS is fundamental to the scientific enterprise, it tends to be presented in science textbooks in a shallow manner. The short shrift given to CVS, per se, is exemplified in one widely used fourth-grade science text that allocates only 8 of its nearly 600 pages to lessons about "the experimental method". Typically, only the procedures for designing experiments are explicitly taught in textbooks, while the conceptual basis for why those procedures are necessary and sufficient for causal inference is seldom addressed. For example, in Foresman's "Science" (Foresman, 2000[15]; Foresman, 2003[16]), middle school textbooks, experimental design is explained as: "Change one factor that may affect the outcome of an event while holding other factors constant." Nothing else is mentioned. Similarly, in the FAST curriculum textbook, "The Local Environment" (Pottenger and Young, 1992[17]), experimental design is explained in the context of an experiment as: "This second group will be used for the control. What happens to the control is the basis for comparing effects." Again, nothing further is mentioned. Such brief statements about experimental design procedures, without subsequent instruction on the rationale for such designs, appear to be the norm, at least in the US textbooks that we have examined.

Similarly, websites aimed at providing support to teachers who engage their students in experiment-based science inquiry (e.g. Science Buddies: www.sciencebuddies.org, Discovery Education: http://www.discoveryeducation) tend to briefly address procedures for conducting controlled experiments without further discussing the underlying rationale. For example, the popular Science Buddies asserts: "It is important for your experiment to be a fair test. You conduct a fair test by making sure that you change only one factor at a time while keeping all other conditions the same" (Note the implicit use of "conditions" and "factors" as synonymous!). Similarly, the only explicit CVS instruction presented in a 21-minute video on the Scientific Method on the website Discovery Education is simply: "Identify a single test variable and control other variables, so only one condition is being tested."

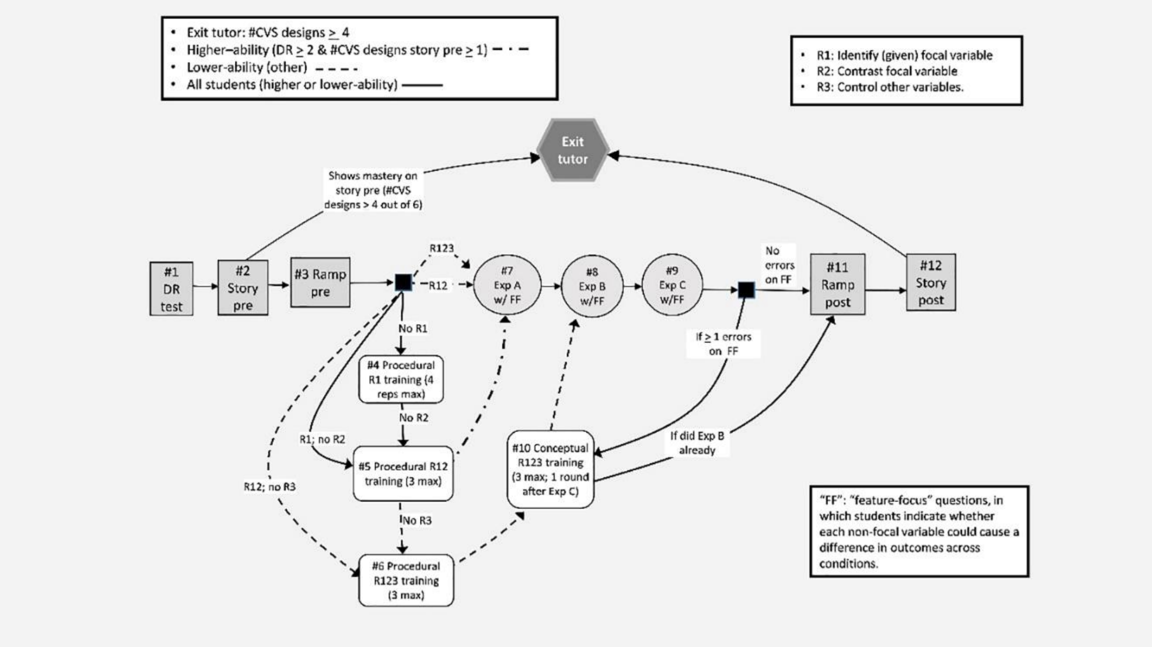
Further, web-based materials for experiment-based science inquiry (e.g. Science Buddies; Discovery Education) generally fail to provide direct support for active student learning. That is, they do not include scaffolding for students as they set up their own experiments or provide feedback, even though such instructional actions have been shown to promote student learning (Bloom, 1984[18]; Vanlehn, 2011[19]). Rather, most online websites that address experiment-based science inquiry offer pre-existing science projects that students can choose, accompanied by step-by-step instructions for doing a particular experiment (e.g. Science Buddies: www.sciencebuddies.org; Education.com: www.education.com; The Lawrence Hall of Science: www.lawrencehallofscience.org). Thus, students are not given the opportunity to design their own experiments and receive feedback on the quality of their experiments.

Some websites do include features that allow students to design experiments (e.g. biologycorner.com); however, they often do not provide feedback on the quality of the experimental design. PhET (phet.colorado.edu) is a popular website that provides various simulations of physical processes (e.g. alpha decay, pressure, electrical circuits) that students can manipulate to see how variables are interrelated; however, direct feedback on experimental design is not given. Going further, Inq-ITS (www.inqits.com) allows students to form hypotheses, design experiments, virtually run experiments in given domains and draw conclusions. Although it does provide immediate feedback on some student actions, it does not provide automatic feedback on the experiments they design. Among the few publicly available online websites that provide scaffolding and feedback to students as they engage in inquiry processes, WISE (Linn, Clark and Slotta, 2003[20]; Slotta and Linn, 2009[21]) does provide support for students' exploration of various science topics. However, the instructional emphasis is on conceptual learning and knowledge integration rather than domain-general experiment-based inquiry skills. In sum, we found no freely available online programmes or websites that supported middle school-aged students' active engagement when designing experiments that were also interactive – providing student-specific support, including feedback and scaffolding.

TED Tutor: Overview

Given 1) the centrality of CVS mastery to a large part of any curriculum that includes the experimental aspects of science; 2) the poor understanding of these concepts often found among middle school students, including the array of alternative conceptions, misconceptions and misunderstandings of CVS instruction; and 3) the dearth of publicly available online programmes or websites that support active engagement with experimental design, we developed the TED Tutor (publicly available at: www.tedtutor.org). The TED Tutor adapts instruction to individual students based on its assessments of their knowledge (including misconceptions) and ability, and provides students with continuous feedback on their actions. These pathways are shown in Figure 12.3

Figure 12.3. Overall flow of TED Tutor, showing branching instructional event paths based on student responses to various assessment events.



Because the rationale for controlling variables is a relatively complex concept for middle school students, we hypothesised that students who are better able to integrate information (i.e. are able to make deductive inferences) would be better able to understand and articulate this rationale. In an analysis of log-file data that was generated by students using TED, we found that students' deductive reasoning achievement scores were highly predictive of whether students explicitly expressed an understanding of the rationale for controlling variables, which (as previously discussed) was in turn significantly related to students' CVS transfer performance (Siler et al., 2010[12]) Thus, in the TED Tutor, students' deductive reasoning is initially assessed (#1 of Figure 12.3) and can be used to determine the type of instruction they receive from TED.

After they complete the deductive reasoning test, students' initial understanding of CVS is assessed (#2-#3 of Figure 12.3) In the "Ramp pre-test", in which students design an experiment for each of the four ramp variables, they are asked to indicate why they set up their experiment as they did by selecting responses from a series of drop-down menus, starting with their goal in setting up the experiment. This is intended to prompt explicit metacognitive reflection on what otherwise might be implicit goals.

Pathway 1 (higher-ability). Students who show a basic understanding of CVS (i.e. who at least contrasted the variable under investigation on the Ramp pre-test) and/or better reasoning skills can be taken to the "baseline" instruction of TED (#7-#9 in Figure 12.3). In this baseline instruction, which is based on instruction given in Chen and Klahr (Chen and Klahr, 1999[4]), students evaluate three given experiments, and are given feedback on their responses. To promote their understanding of the rationale for controlling variables, they are asked if they could "tell for sure" that the focal variable caused a hypothetical difference in outcomes across conditions. To further reinforce their understanding of the rationale for controlling variables, they are asked whether each of the other (non-focal) variables could have caused the hypothetical outcome, and then they receive feedback on their responses.

Pathway 2 (lower-ability). Students who perform poorly on the CVS pre-tests and/or deductive reasoning test (#1) – and who therefore may be less able to follow the explanations given in the baseline instruction – are given a simplified, "step-by-step" version of the initial instruction. In this instruction, which is given before the baseline instruction, students are scaffolded in applying [the] three basic rules of CVS:

- R1: Identify the variable under investigation
- R2: Contrast that variable
- R3: Control/make same all other variables

Students' responses inform a Bayesian Knowledge Tracing engine, which determines how many rounds of questioning to give an individual student (#4-#6 and #10 of Figure 12.3). We have found that this simplified instruction supports students' understanding of the goal of the task as learning how to set up experiments that allow them to find out whether or not a variable affects an outcome. Students then progress to the baseline instruction for further instruction on the rationale for controlling variables and afterward set up experiments in the instructional domain ("Ramp post-test") and other domains ("Story post-test").

Effect of adaptive instruction for lower-reasoning students. We compared the effect of adding Pathway 2 to TED for lower-reasoning US sixth- and seventh-grade students (i.e. students who scored low on the deductive reasoning pre-test). As expected, the low-reasoning students performed significantly better on the transfer post-test when they were assigned to the more incremental Pathway 2 than higher-level Pathway 1. However, higher-reasoning students performed similarly in Pathway 1 and Pathway 2. In summary, adapting instruction to individual students' deductive reasoning skills led to better outcomes. In particular, the addition of the lower-ability pathway improved transfer outcomes among lower-reasoning students.

Policy Implications

As noted at the beginning of this chapter, understanding how to design and interpret experiments is an essential component of STEM literacy, and every K-12 science curriculum includes many opportunities for children to engage in the experimental process.

Nevertheless, there is consistent evidence from national and international assessments that a solid grasp of the process and rationale underlying the creation, execution and interpretation of informative experiments is exhibited by a scant proportion of the world's population. Thus, it is important to develop instructional procedures that will increase the likelihood that children will master both the procedural and conceptual aspects of CVS.

However, an oft-repeated critique of the number of substantive topic areas crammed into the K-12 science curriculum in the United States is that it is "a mile wide and an inch deep" (Schmidt, 1997[22]). But teachers attempting to convey the substantive knowledge base in their disciplines rarely have the luxury of devoting a full class (or two) to teaching the domain-general aspects of CVS procedures and concepts. Instead, at the beginning of a class devoted to some lab work associated with a particular topic, teachers typically introduce a brief overview (if any at all) about experimental procedures and concepts, but almost always in the domain-specific context of the particular topic being taught.

However, even though, as we noted earlier, instruction on CVS is rarely given adequate time, students' understanding of it is invariably assessed on high-stakes tests. We created TED to address this problem. Our vision is that – prior to a lesson involving, for example, an experiment in electricity, or simple machines – teachers could direct students to TED's online, user-friendly, adaptive and individualised instruction that would bring them "up to speed" with respect to the rudimentary conceptual and procedural aspects of a "good experiment". Having completed this kind of domain-general, albeit limited, instruction, students would be in a much better position to really understand the steps and the reasoning that will enable them to obtain information and further develop domain-specific knowledge from their subsequent experiments about various topics.

As the next step in our research, we are embedding the TED Tutor in a context in which children will be engaged in selecting a topic for, and then designing and implementing, an experiment to create a science fair project. This Inquiry Science Project Tutor (ISP Tutor) has both theoretical and applied aspects. The theoretical contribution will be to determine the extent to which presenting CVS instruction in the context of other inquiry activities elicits the type of sceptical scientific mindset that evokes a science goal, i.e. a goal of identifying causal factors, rather than an engineering goal: trying to achieve a specific outcome. From our earlier work, we expect the elicitation of science goals to lead to increased learning and transfer. The practical aspects will be to increase learning and transfer outcomes when TED instruction guides students in their design of unconfounded, albeit highly motivated, experiments. The ISP Tutor will provide support to students as they conduct inquiry activities about topics largely of their own choosing. We believe that this project is timely, given the accumulated findings of the importance of engaging students in such activities (Minner, Levy and Century, 2010[23]), as reflected in recent guidelines such as the US K-12 Framework (2012) and NGSS (2013); England's National Curriculum (2014); Japan's Courses of Study (2008) (Ministry of Education, 2008[2]); and Singapore's Science Curriculum Framework (Ministry of Education, 2008[24])

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Chapter 13. Practical learning research at scale

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Many decades of attempts to use science to improve education has produced limited success. Greater success will be achieved through research done within the practice of education. The suggestion is not to simply apply learning science to practice but rather to produce new learning science in real educational settings. The increasing use of technology in schools, from intelligent tutoring systems to mixed-reality games, makes it feasible like never before to engage in systematic experimental investigations of principles of learning and techniques for best supporting it. Systematic investigation is necessary because it is now clear that among the trillions of different ways to support learning, existing science tells us too little about what works best. We present the Knowledge Learning Instruction (KLI) framework to provide guidance on how to do learning research in practice in a way that is driven by data, advances new learning theory and provides a roadmap to better education.

Education is fundamentally important to the world's progress. Science and technology are increasingly creating new learning opportunities that are yielding better outcomes, better instruction and better data-driven decisions. Progress in applying learning science comes with some bad news, good news and even better news. The bad news is that there is a large implementation gap between what we know in the learning sciences and what is being used in educational practice (Chapter 18, by Means, Cheng and Harris). The good news is that a considerable amount of progress has been made in developing a science of learning that is relevant to improving educational practice. For example, recent evidence demonstrates that applying learning science in technology-enabled courses can double learning outcomes. Other chapters in this book provide further examples (Chapter 8, by Forbus and Uttal; Chapter 12, by Klahr and Siler; Chapter 14, by Rose, Clarke and Resnick). The even better news is that there remains a lot unknown about how human learning works and how it can be optimised. Thus, as new insights accumulate about how learning works and how it may be optimised, it may be possible to not only double the current rate at which people learn, but perhaps make it five or ten times more effective or efficient.

One of the reasons for the implementation gap noted above is that often education stakeholders, from parents and teachers to school administrators and policy makers, do not believe what the science is telling us. Some scepticism is warranted, but a fundamental reason for undue scepticism is that stakeholders are driven by their own intuitions about learning and these intuitions are based on limited information. How learning works in our human brains is not directly visible after all. We often experience illusions of learning both in observing ourselves and others. What learning scientists do is use data about what students know and how it changes over time to make inferences about when and how learning is working. To unlock the many remaining mysteries of human learning and turn insights into radically better education, we need both scientists and educational practitioners to work together to engage in scientific analysis of bigger and better learning data.

We need a practical learning science endeavour that operates at scale in real educational settings and we need it to address two substantial challenges. The first challenge is in developing deep insight into the educational subject matter we teach, whether it is reading, maths, collaboration skills or learning skills. Turns out, you cannot just ask experts what they know. Experts are only consciously aware of about 30% of what they know, that is, they do not know what they know (Clark et al., 2007[1]). The second challenge is in figuring what are the best ways to teach. When one considers the combinations of the many recommendations that learning science literature provides, it becomes evident that the design space of alternative ways to teach and support learning is immense (Koedinger, Booth and Klahr, 2013[2]). Further extending this challenge, there is accumulating evidence that instructional designs that work well in one context (e.g. with a particular student population or course content) do not work in other contexts (Koedinger, Corbett and Perfetti, 2012[3]).

We raise these challenges not to criticise the current state of learning science and its practical application, but rather to suggest that there is great opportunity for the application of better learning science and technology to make revolutionary improvements upon the current state of educational practice. Educational technology is not only increasing spreading access to high-quality and sometimes personalised instruction, but it also has the great potential to provide the data we need to address these grand challenges and advance a practical learning science that can revolutionise education (Singer and Bonvillian, 2013[4]). Student learning could be many times more effective than it is today!

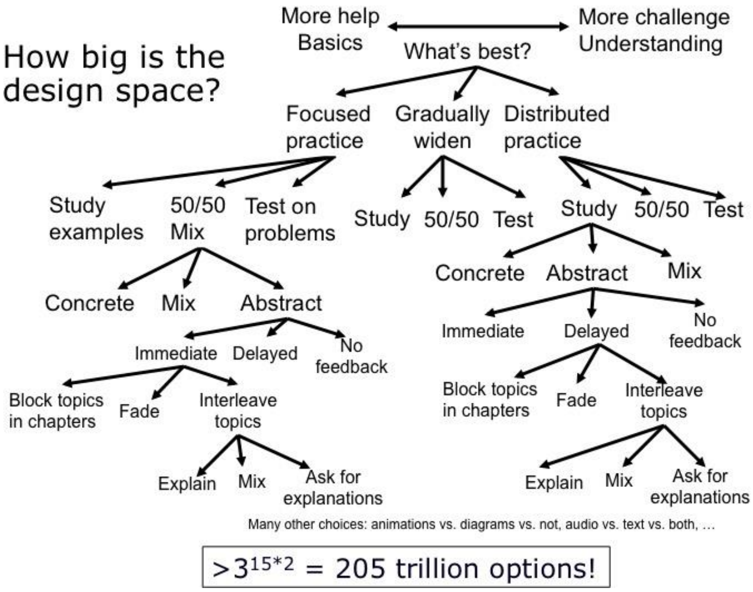
Practical learning science challenges

Learning is a bit like magic – filled with lots of illusions as it occurs, in our brains, behind a curtain of limited self-conscious reflection. Both students and instructors generally think they know they or their students are learning. However, evaluations of students' judgement of learning have found quite low correlations between students estimates of learning and actual test scores (Eva et al., 2004[5]). One reason learners fail to accurately predict their own learning is that they have insufficient mental resources to learn and monitor their own learning (Moos and Azevedo, 2008[6]). As non-experts, they do not know what to monitor: How can they compare their emerging ideas and skills with correct ideas and behaviours when they do not yet have the expertise to know what is correct? Learners experience further illusions of learning when they base their judgements on what they like – what students actually learn from a course has been shown to be poorly correlated with how much a student likes a course (Sitzmann et al., 2008[7]). For similar reasons, instructors can be fooled by observing students' facial expressions. Many seek happy faces and avoid looks of confusion. But student struggle and confusion can often aid long-term learning outcomes as international research (Bjork, 1994[8]; Kapur and Rummel, 2012[9]).

Public dialogue argues between learning basics vs. understanding, as though there are two dimensions to learning. Learning science research, on the other hand, elaborates more dimensions (Clark and Mayer, 2012[10]; Pashler et al., 2007[11]) and many contradictions. For example, many studies indicate that spaced practice is better than massed practice for long-term retention (Pashler et al., 2007[11]) yet, under certain circumstances massed practice is better (Pavlik and Anderson, 2008[12]). Direct instruction is sometimes better than discovery learning (Klahr and Nigam, 2004[13]) but in other contexts active learning is emphasised (Wieman, 2014[14]). Often which type of instruction is more beneficial has to do with either reducing students' cognitive load by offering more instructional assistance or creating desirable difficulties by reducing instructional assistance for students to construct their own knowledge (Koedinger and Aleven, 2007[15]).

The instructional design space for learning is roughly organised along the two dimensions argued in the education wars (i.e. basics vs. understanding or more assistance vs. more challenge). Koedinger, Booth and Klahr (2013[2]), articulated 30 dimensions with numerous combinations (e.g. study worked examples or do practice problems or a mixture of both, more concrete or more abstract problems, more immediate or more delayed feedback, etc.) illustrating the vastness of the design space and the wide spectrum of possibilities beyond the two condition comparison (see Figure 13.1). There are over 200 trillion different ways to design instruction!

Figure 13.1. Illustration of the enormity of instructional design space



Source: Koedinger, K., J. Booth and D. Klahr ((2013[2])), "Instructional complexity and the science to constrain it", *Science*, Vol. 342, pp. 935-937.

Scaled applications of learning by doing with feedback

Approximately a half million students per year are using Mathematics Cognitive Tutors in K-12 classrooms for about 80 minutes a week (roughly two class periods). A recent big study (~149 schools) by RAND Corporation showed a doubling of student achievement in a Cognitive Tutor Algebra course over the school year as compared to a traditional algebra course (Pane et al., 2014[16]). Note that these results are a consequence of using the text and teacher professional development materials that are part of the course, not just the technology.

In addition, college-level online courses such as the Open Learning Initiative (OLI) at CMU have incorporated the learn-by-doing approach and have reached some fairly good scale. About 30 college introductory courses are in use in approximately 1 000 colleges. These kinds of educational technologies that are widely used, not just cognitive tutors and OLI courses but also language learning online courses and some educational games provide an opportunity to do basic research in the context of functioning courses. One striking demonstration of improving learning through data-driven design of a course was a study that compared a traditional introductory statistics course taught over a full semester with a blended version of the course that used OLI materials, had a classroom instructor and was taught in half a semester (Lovett, Meyer and Thille, 2008[17]). The blended course taught in half a semester had an 18% pre to post gain on a standardised test vs. a 3% gain for the traditional course.

In other words, large amounts of data generated by widespread use of educational technologies creates a cyberinfrastructure for doing science in practice. Researchers like educational psychologists and cognitive psychologists can get out of the laboratory and run studies in real classrooms. Collaborations can be fostered with diverse groups of professionals across a global front inspiring creative investigations and experimentation.

The Knowledge Learning Instruction (KLI) framework

Lessons learned from the hundreds of cross-domain in vivo experiments were critical in the development of theory for making sense of the contradictory research results in the instructional design space.

The Knowledge Learning Instruction (KLI) framework (Koedinger, Corbett and Perfetti, 2012[3]) provides means to understand the inconsistencies and competing recommendations across the different disciplines of the learning sciences. Inconsistent results and competing recommendations are not a simple consequence of limited data or poor research designs but can often be explained by noting differences in the nature of the knowledge that is to be acquired across different research studies.

The KLI framework maintains that the success of different instructional principles across domains is dependent upon knowledge goals (see Figure 13.2). Furthermore, understanding the learning for these different kinds of knowledge goals will help determine what instructional principles are most effective (see Figure 13.2). For example, if your goal is learning Chinese vocabulary which is essentially about learning facts, then memory processes are critical and instructional supports that encourage memory (e.g. optimal scheduling – see bottom left corner of table in Figure 13.2) would be best. But to the extent that the goals involve inducing some general rule or skill then optimal scheduling is unlikely to be a good principle to apply, instead a learning process that does some kind of induction and perhaps refinement would be more appropriate (e.g. worked examples). Whereas if the knowledge goal involves a deeper understanding and rationales, then supporting students in collaborative dialogue can be beneficial. Misapplying instructional principles will most likely be unproductive (as seen by the zeroes in Figure 13.2).

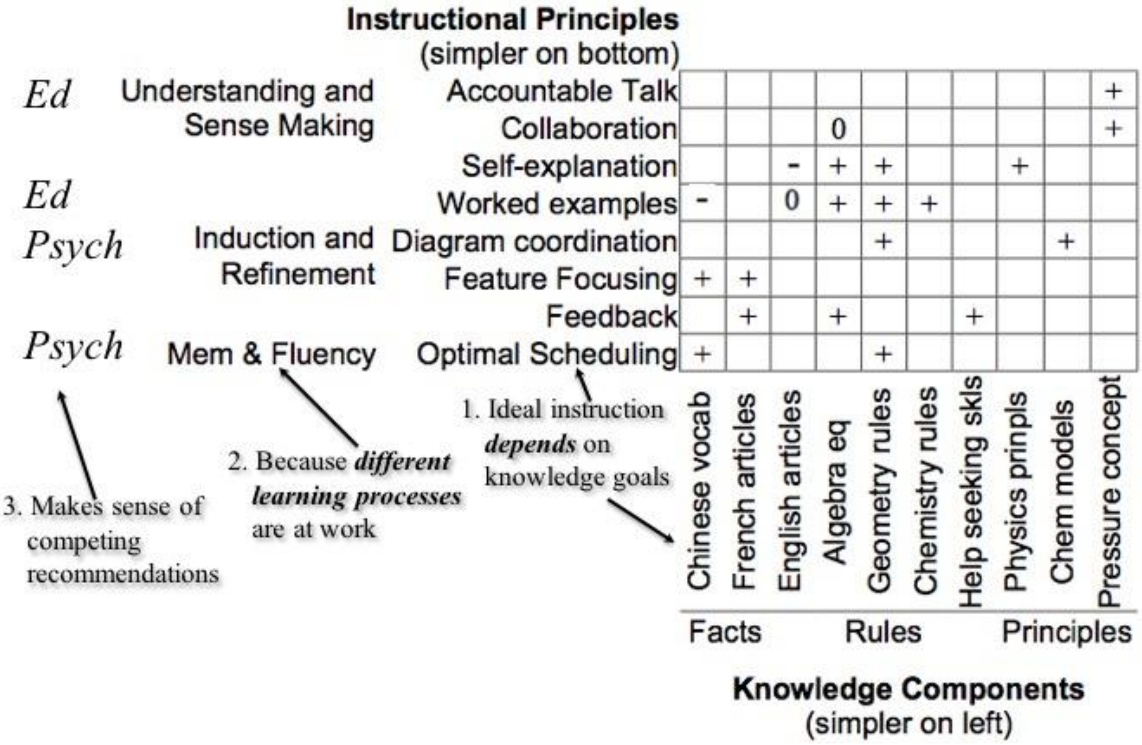
For example, the testing effect has been well studied by cognitive psychologists and postulates that testing enhances later retention more than additional study of the material (Roediger and Karpicke, 2006[18]). In contrast, educational psychology research originating in Australia (Sweller and Cooper, 1985[19]) and especially pursued in Europe (Paas and Van Merriënboer, 1994[20]; Renkl and Atkinson, 2010[21]) suggests students do too much practice and not enough study of worked examples. Theoretically, both have plausibility. The testing effect reflects a more general phenomenon and is more of a challenge for students, thus, produces "desirable difficulties". Conversely, the worked example effect offers more guidance to reduce "cognitive load" and that premature practice encourages floundering and misconceptions.

Are these two positions really contradictory? First, both literatures show that an intermediate value (some combination of example study and problem-based test) is better than an extreme (i.e. all worked examples or all practice problems). Second, is the worked example effect even found in an online tutoring system where step-by-step support is available (as opposed to whole solution feedback), thus reducing cognitive load to the point that worked examples might be irrelevant.

In lab studies using a geometry tutor, students in the practice or testing condition generated a solution and explained their result with help from a glossary. They received feedback on both. In contrast, the worked example condition had half of the steps given as examples and they had to explain the worked-out steps with help from a glossary.

Lab results showed that worked examples improve both efficiency of learning (20% less instruction time to study worked examples then to do problems) and conceptual transfer (in one of the two lab studies) (Schwonke et al., 2009[22]).

Figure 13.2. Positive (+), neutral (0) and negative (-) outcomes of difference instructional principles employed to achieve the learning of different kinds of knowledge.



	Chinese vocab	French articles	English articles	Algebra eq	Geometry rules	Chemistry rules	Help seeking skls	Physics prinpls	Chem models	Pressure concept
Accountable Talk										+
Collaboration				0						+
Self-explanation			-	+	+			+		
Worked examples	-		0	+	+	+				
Diagram coordination					+				+	
Feature Focusing	+	+								
Feedback		+		+			+			
Optimal Scheduling	+				+					

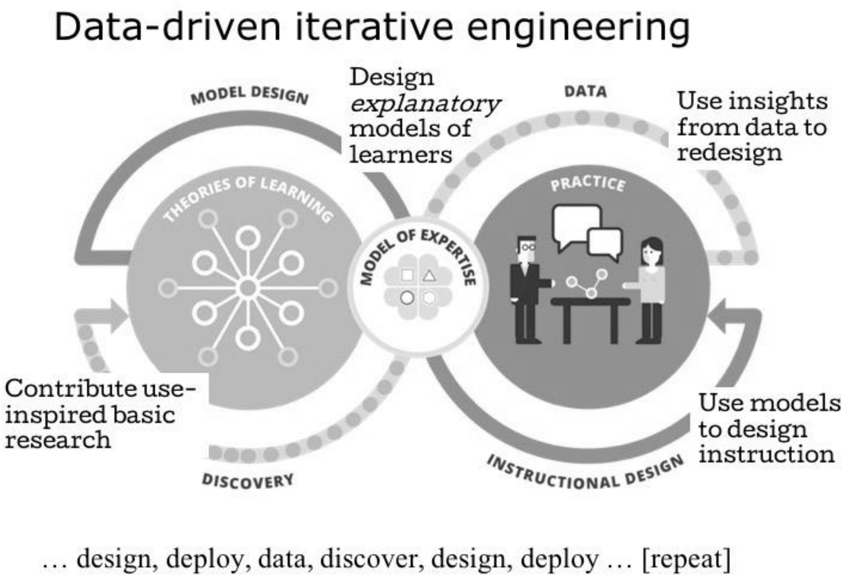
Source: Koedinger, K., A. Corbett and C. Perfetti (2012[3]), "The knowledge learning-instruction (KLI) framework: Bridging the science-practice chasm to enhance robust student learning", *Cognitive Science*, Vol. 36, pp. 757-798.

In classroom studies, adaptively fading examples to problems yielded better long-term retention and transfer (Salden et al., 2009[23]). Similar results were found with in vivo studies with chemistry tutors (McLaren et al., 2006[24]; McLaren et al., 2016[25]) and algebra tutors (Anthony, Yang and Koedinger, 2008[26]), always a reduction in time and sometimes improvement on a long-term retention test. Thus, the worked example effect generalises across domains and populations. Understanding the different goals will help with understanding the differences in learning processes. KLI does not simply identify content treatment interactions but provides theoretical guidance for what instructional treatments are most likely to work given a particular knowledge acquisition goal.

Scaling practical learning research

In the last 10-15 years, the US Department of Education has spent millions of dollars on big randomised field trials with about 10% having positive results. One reason for the dismal outcomes is a disregard for external validity issues of transfer. Moreover, and as illustrated in the testing vs. worked example effects, learning scientists, especially ones from different disciplines, do not always agree on what is best. Consequently, scaling science to practice is not simply taking learning theories and applying learning science to instructional design. The answer is not to apply learning science but to do data-driven iterative engineering. As depicted in the graphic in Figure 13.3, the iterative cycle involves: Start with existing theories, design explanatory models of learners and models of the desired expertise, use the models to design instruction, then collect data, interpret the data to gain insights, and redesign your models and your instruction. Repeat these loops of design, deploy, collect data, discover, (re)design, deploy and so forth.

Figure 13.3. Data-driven iterative engineering



Note: A practical learning science demands that researchers and school professionals work together in iterative cycles of science-based design and data-driven redesign. This kind of collaboration is more akin to an engineering design process than a straightforward application of scientific principles
Source: Simon Initiative: www.cmu.edu/simon

A better social cyberinfrastructure is consistent with the idea of doing science in practice. This data-driven iterative process is needed in all institutions such that every school and university becomes a LearnLab (learnlab.org) where a culture of iterative improvement is fostered and assessments, data and analytics are shared. But it is not just about doing the loop of continuous improvement rather we need university administrators to foster a culture and to change incentive structures (e.g. credit for making improvements in courses not just for research done).

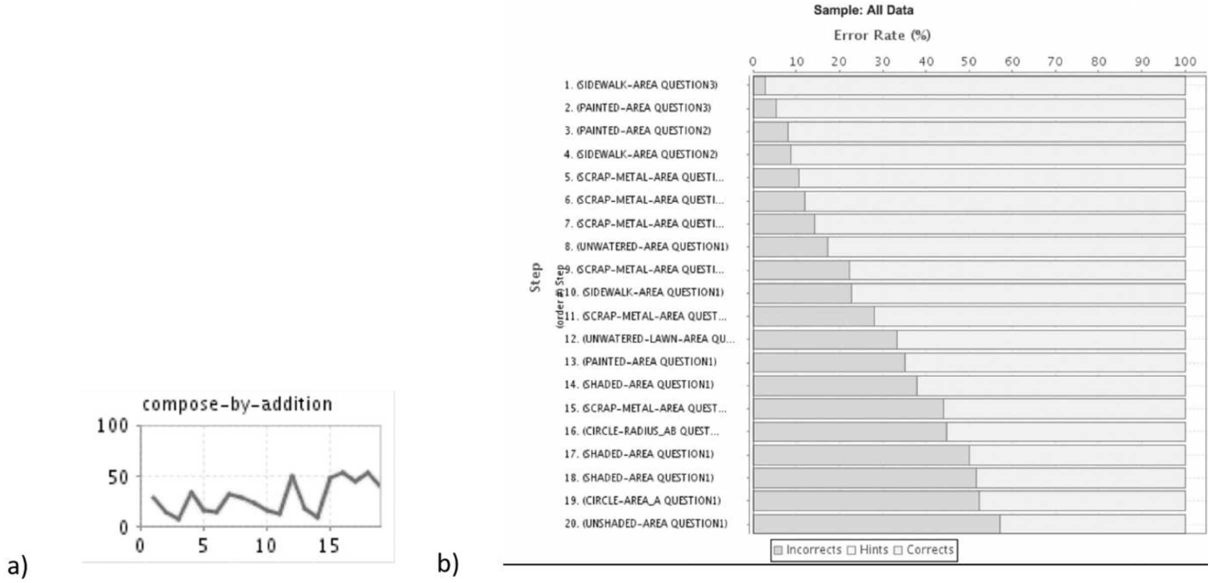
Scaling deep content analytics

Course data and learning theory are the forces behind making improvements to instruction and instructional design. A proven method for improving course design is doing a Cognitive Task Analysis (CTA) whose goal is to identify the underlying cognitive processes students need to learn a given task and to provide data for creating an accurate cognitive model. Research shows that courses modified by CTA produce better learning. For example, in a qualitative CTA, Clark et al. (2007[1]) found a 1.5 SD effect size when comparing a CTA modified course on catheter insertion for medical students to the traditional course (Velmahos et al., 2004[27]). One explanation for such results came after Clark ran a series of CTA studies. He observed and made the claim that 70% of what experts know is outside conscious awareness, that is to say, that most learning is implicit and garnered through imitation and practice (Clark et al., 2007[1]).

A more quantitative approach to CTA can be applied by using visual representations of student data (e.g. learning curves). When data is organised such that a good characterisation of the unobservable skills and concepts or a good cognitive model of the domain is available, then a smooth learning curve is produced. Bumpy curves suggest an opportunity for improvement as do flat curves. An upward blip in error rate in a curve (Figure 13.4A) often indicates that the current cognitive model is wrong – it is not accounting for critical elements of learning difficulty that students experience. A course analyst can thus identify and articulate a new critical component of knowledge that students need to acquire. Scientifically, such knowledge component (KC) discovery improves the fit of the model to the data, better accounting for error rates and producing smoother learning curves. Practically, such discovery leads to better learning support, including new instruction and new ways to practice the discovered KC.

LearnLab's DataShop (Koedinger et al., 2010[28]) provides tools to help technology developers and learning engineers doing this kind of quantitative CTA. For example, the Performance Profiler (Figure 13.4) is a visualisation tool that can highlight discrepancies in error rates that may signal the need for new KC discovery. In Figure 13.4 we see a wide range of error rates (shown in dark grey) on tasks hypothesised to demand the same geometry planning skill – clearly some of these tasks (at the bottom) have greater knowledge demands than others (at the top).

Figure 13.4. Student performance data helps discover hidden skills and improve their learning



Note: An example of two LearnLab DataShop visualisation tools. Part (a) shows a bumpy learning curve with blips suggesting further investigation into the cognitive model and part (b) shows a varying error rate for a given knowledge component suggesting other KCs are potentially hidden.

Source: DataShop, https://pslcdatashop.web.cmu.edu/.

In this example, we found students struggled with finding the area of complex figures not because finding the area of individual shapes was difficult but because they were lacking the critical knowledge for planning solutions via selecting multiple relevant formula (Koedinger, Booth and Klahr, 2013[2]). New tasks were designed for the online tutoring that support students in learning this critical planning skill. These tasks isolated practice on such planning without wasting students' time performing the execution steps they have already mastered. A classroom-based in vivo experiment comparing the adapted tutor to the original showed both much greater efficiency to mastery (25% less time) and greater effectiveness on a post assessment.

Scaling iterative course improvement

In summary, learning is invisible and both students and instructors need to be aware of illusions of learning. Data can break those illusions. Students need feedback on their progress, need formative assessment, and need long-term assessments and instructors need assessment data. We need learning engineers who 1) can use CTA techniques and data to deeply understand learning goals and how the human mind achieves them; and 2) can routinely employ learning science theories and methods to design and test new teaching techniques, in practice, through experiments that compare outcomes of these new techniques against outcomes of existing teaching. Once such experiments become part of standard practice in schools and universities, we will begin on a rapid path towards understanding which of the 200 trillion instructional options work best for which particular learning problem.

Policy implications

Learning science and technology are revolutionising education. Technology is already widening access to educational resources and making those resources increasingly more adaptive to student needs through advanced AI-fuelled algorithms. More importantly, practical learning science research is going to continue to unlock the mystery and power of human learning in ways that will have dramatic impact on education and, consequently, on the state of our world.

What do we need to do to make this learning revolution happen? We need to build social and technical infrastructure that better connects universities, educational technology companies, and especially schools such that learning science and practice is not a one-way technology transfer but a high-speed, internet-enabled many-way communication. We need to make schools and colleges, our institutions of learning, into learning institutions. Rather than being consumers of generic learning science, our schools must become producers of contextually specific and practical learning science. These institutions need government direction and financial support to transform themselves so as to regularly engage in continuous data-driven improvement. With the help of learning scientists, these institutions, not the learning scientists, will be the ones who discover what teaching techniques and technologies work best for the vastly different learning goals and student populations they serve. We need policies that foster adoption of continuous improvement processes that make it much easier for all educational stakeholders, from students and parents through teachers and administrators to educators and learning scientists, to collect and make use of high-quality data to inform which human and technology-based learning supports work best.

This institutional transformation will need to be fuelled by better higher education programmes that can produce the research-oriented teachers and learning engineers of the future. Collectively these new "learning workers" must have interdisciplinary expertise and collaboration skills to bring together scientific understanding of human psychology, technical skills of AI and machine learning, deep understanding of subject-matter domain content and how human brains acquire it, and methodological skills for designing experiments and using data towards continuous improvement. Just as science and technology have helped us to travel many times further and faster, from the early carriage to today's jets, science and technology will also help us to learn many times better and faster.

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Chapter 14. Scaling up ambitious learning practices

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This chapter reports on findings from an effort to train teachers to adopt classroom facilitation practices referred to as Accountable Talk (AT) while jointly training students to engage in articulation of reasoning and transactive exchange in the midst of teacher-led classroom discussions as well as in computer-supported collaborative learning (CSCL) activities with one another in small groups. A key enabler in this work was AI-enabled scaffolding for collaborative discussions in the form of intelligent conversational computer agents that acted as discussion facilitators using the same AT practices that were the target of the teacher professional development. A key finding was that support for student engagement in transactive exchange prior to teacher-led discussion facilitated teacher uptake of AT practices.

Introduction

A danger of the growing emphasis on scale in education is that ambitious learning practices, such as many forms of discussion-based and group learning, may be eliminated in favour of efficiency-based individual learning practices. An extreme emphasis on efficiency that might crowd out opportunities to develop communication and collaboration skills threatens the ability of K-12 school systems to meet the demands of the 21st century working world. This chapter argues from evidence both that ambitious learning practices involving collaborative and discussion-based learning are feasible and beneficial to students in K-12 education even in challenging urban environments, and that the elimination of ambitious learning practices is not necessary for achieving effective learning at scale.

In particular, in this chapter we espouse a concept of discussion-based learning that integrates a set of classroom facilitation practices referred to as Accountable Talk (AT) (Michaels, O'Connor and Resnick, 2008[1]; Resnick, Michaels and O'Connor, 2010[2]; Resnick, Asterhan and Clarke, 2015[3]) paired with a key property of collaborative discourse practices referred to as Transactivity (Azmitia and Montgomery, 1993[4]; Berkowitz and Gibbs, 1983[5]; De Lisi and Golbeck, 1999[6]; Gweon et al., 2013[7]; Teasley, 1997[8]). At the core of both of these practices is the aim to keep student reasoning at centre stage. Though these frameworks grew up in separate research communities, specifically AT in the classroom discourse community and Transactivity in the collaborative learning community, they dovetail perfectly in that the key facilitation moves of AT appear to be designed to elicit transactive contributions from students (Adamson et al., 2014[9]). Specifically, a transactive contribution is one that makes reasoning explicit and connects it with an articulation of reasoning from earlier in the discussion, which may be the student's own expressed reasoning, but more often is the reasoning of another student.

Demonstrations of the positive impact of AT and similar practices have been in evidence worldwide (Resnick, Asterhan and Clarke, 2015[3]). In particular, we know that in large-scale evaluations of AT, what has been reported are steep changes in student achievement (Bill et al., 1992[10]; Chapin and O'Connor, 2004[11]) retention for up to 3 years (Adey and Shayer, 1993[12]; Topping and Trickey, 2007[13]) transfer across domains for up to 3 years (Bill et al., 1992[10]; Adey and Shayer, 1993[12]; Chapin and O'Connor, 2004[11]). There are reports of students performing better on non-verbal reasoning tests e.g. Ravens (Wegerif, Mercer and Dawes, 1999[14]) while reasoning itself also improves (Kuhn et al., 2013[15]). Similarly, we know that Transactivity is a property of discourse where students are working on reasoning together, where students make their reasoning explicit and integrate or connect it with the expressed reasoning of other students. The finding is that the concentration of Transactivity correlates with learning gains in many studies of collaborative learning (Azmitia and Montgomery, 1993[4]).

Nevertheless, teachers may feel daunted by the demands of facilitating collaborative learning groups in the classroom or assessing student writing or the products of collaborative groups, automated support both for facilitation and assessment have recently been achieved (Rosé and Ferschke, 2016[16]). The purpose of this chapter is to illustrate how these technological advances can achieve positive impact in the classroom in a challenging, urban school environment through a large-scale professional development effort. Success in this environment serves as a proof-of-concept that ambitious learning practices can feasibly be implemented with typical teachers in challenging urban settings with positive impact in K-12.

In the remainder of the chapter, we first offer a historical overview of the work. We then detail the theoretical underpinnings of the work and describe first an investigation we conducted in the context of a school-district-wide professional development effort. Next, we describe how similar principles were used to motivate the design of a novel protocol for team formation in team-based Massive Open Online Courses (MOOCs), which demonstrates the generality of applicability of the theoretical framing as well as its potential in facilitating scale without sacrificing the employment of ambitious learning practices like team-based project learning (MOOCs). We conclude with implications for policy and practice.

Historical perspective

Our work builds on an international compendium of insight related to AT and similar teaching practices (Resnick, Asterhan and Clarke, 2015[3]). Despite growing evidence that AT produces measurable advances in student learning, most teachers – especially those teaching students from low socio-economic backgrounds and students of colour – do not employ these strategies. Several studies have documented that it is rare to find this kind of instruction in “high need” learning environments, and that teachers struggle in shifting the ways in which they use talk in classroom learning. Much of the evidence of success of these approaches come from research that has been conducted in elite schools, with master teachers.

In contrast, our project, in collaboration with the Learning Research and Development Center (LRDC)’s Institute for Learning (IFL), aimed to extend the success of AT to an urban school district with more typical teachers. The approach integrated the expert coaches of the IFL with technology for dynamic support of collaborative learning developed at Carnegie Mellon University (CMU) (Adamson et al., 2014[9]; Kumar et al., 2007[17]; Kumar and Rosé, 2011[18]).

The goal of our work was to develop protocols for achieving scale without sacrificing ambitious learning practices. We did this by building on the foundation of a key insight that we consider the DNA of well-functioning discussion-based and collaborative learning. That DNA is the phenomenon of students positioned as active reasoners who take responsibility for their reasoning, understanding and learning together (Howley, Mayfield and Rosé, 2013[19]; Sionti et al., 2011[20]). We began an investigation into this approach in the midst of a professional development effort that positioned both the teacher and the students as having agency to bring about change, each with a role to play in order to bring success (Clarke et al., 2016[21]). Note that students play a key, active role in this configuration, and technology support for collaboration acts as a catalyst, aiding in their effective role-taking within the configuration. In particular, the professional development effort involved first, a district-wide effort where human coaches worked directly with teachers and second, a computer-supported collaborative learning (CSCL) intervention in classrooms where technology support enables reaching out to an arbitrary number of small groups simultaneously such that students are better prepared to take their important role within the changing classroom culture (Adamson et al., 2014[9]; Clarke et al., 2003[22]; Dyke et al., 2013[23]). The implication is that with appropriate technology support, the push towards scale need not push out desirable, ambitious learning practices. In particular, the teacher professional development interventions focused on developing teachers’ capacity to promote active engagement between students using AT. In addition, we deployed artificially intelligent interventions, termed AT agents, in online collaborative learning experiences to support students’ capacity of engaging in this kind of learning dialogue.

During a five-year period of time, this district-wide collaborative effort aimed to impart AT discussion facilitation practices focused on ninth grade biology classrooms. The study was structured at two levels. First, there was a macro-study involving the professional development programme in which teachers across the school district were engaged in intensive workshops on AT facilitation practices. A subset of the teachers within the school district, who opted to participate in the research study, were then audio-recorded leading whole-class discussions in which they demonstrated the extent to which they had appropriated AT practices in their teaching in each unit of ninth grade biology. Observations occurred at the beginning and end of each unit. In the midst of this longitudinal professional development programme, we also introduced in vivo micro-studies, in other words, controlled experiments run within classrooms, where we evaluated interventions for supporting small group discussion activities meant to prepare the students for the whole group discussions. The interventions in the small group were aimed to intensify transactive exchange between students using conversational computer agents employing automated AT facilitation practices (Adamson et al., 2014[9]). By preparing the students for active engagement in the discussions, the hope was to better enable the teachers to put their training into practice in the classroom, and the evidence confirmed this effect (Clarke et al., 2003[22]).

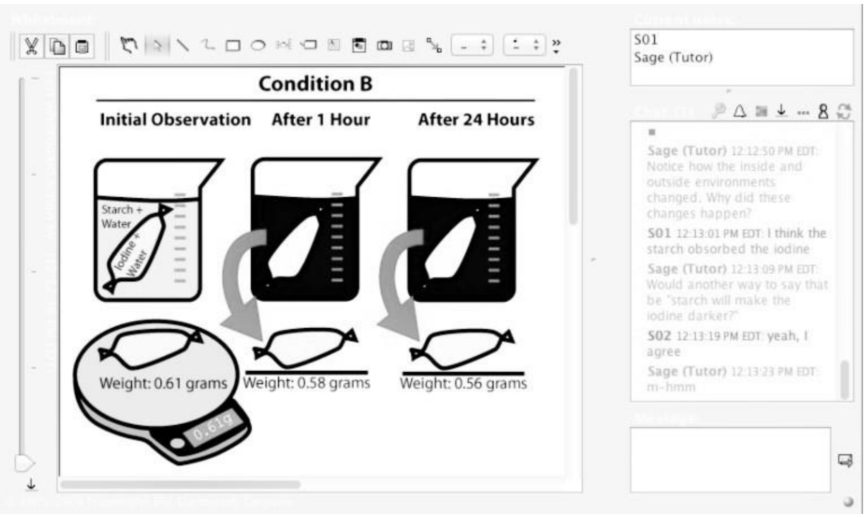
We evaluated the success of the professional development programme using a design-based research approach employing a synergy of qualitative and quantitative approaches. At the same time, we evaluated the effects of the in vivo interventions as short-term studies quantitatively while also observing the effect of the interventions within longitudinal analyses on the nature of whole group teacher-led discussions in the classrooms that housed the in vivo studies using hierarchical time series models.

Overall, we observed positive growth over time in teacher uptake of AT practices, with significant intensifications immediately following interventions involving small group automated coaching of AT practices. The significant intensifications surrounded three specific studies of automated AT facilitations. Using LightSIDE (Mayfield and Rosé, 2013[24]) we are able to code transcripts of whole-class discussions and small group discussions in order to observe where students and teachers were engaging in important facilitation behaviours. Multilevel growth models offer a path towards accomplishing this measurement. Using growth-modelling techniques, we were able to measure growth over time both at the teacher level and at the student level in terms of frequency of appropriation during class discussions. The teacher and student trajectories, that are constructed using latent variable techniques within this framework, allow us to control for dependencies between successive opportunities, as well as the complexities of the contextual influence of groups and classrooms. With this as a tool, we were able to systematically study the factors that affect teacher learning of discussion facilitation behaviours. An analysis of discussion transcripts from the first two years of the professional development programme demonstrates that there is a significant local effect on teacher uptake of facilitation behaviours from the training resulting from students participating in online collaboration activities prior to the teacher-led discussion, with an effect size of 1.7 standard deviations (Clarke et al., 2003[22]).

Technology support for collaboration

Our research in CSCL demonstrates that students benefit from interactions in learning groups when automated support is provided, especially interactive, context-sensitive support administered by intelligent conversational agents (Adamson et al., 2014[9]; Kumar et al., 2007[17]). This dynamic form of collaboration support “listens” to student conversations in search of important events that present opportunities for discouraging dysfunctional behaviour or encouraging positive behaviour using automated analysis of collaborative learning processes.

Figure 14.1. Screen shot of collaborative interface



S01
Sage (Tutor)

Sage (Tutor) 12:12:50 PM EDT: Notice how the inside and outside environments changed. Why did these changes happen?

S01 12:13:01 PM EDT: I think the starch obsorbed the iodine

Sage (Tutor) 12:13:09 PM EDT: Would another way to say that be "starch will make the iodine darker?"

S02 12:13:19 PM EDT: yeah, I agree

Sage (Tutor) 12:13:23 PM EDT: m-hmm

Note: Screen shot of collaborative interface. On the right-hand side is the chat panel where students interact with one another, supported by the computer facilitator whose turns are labelled Sage (Tutor).

Enabled by technologies including Bazaar (Adamson et al., 2014[9]), TuTalk (Jordan et al., 2007[25]; Rosé et al., 2001[26]; Mayfield and Rosé, 2013[24]), and LightSIDE (Mayfield and Rosé, 2013[24]), we have built interventions in which conversational computer agents employ AT practices, like re-voicing moves and agree-disagree moves, in order to test causal connections between AT moves, self-efficacy and learning in lab studies using automated analysis and conversational agent technology both in ninth grade biology and in college level Chemistry (Adamson et al., 2014[9]).

Lab experiments, such as the cell model lab illustrated in Figure 14.1, are a valued component of most secondary school science instruction. But in practice, classroom experiments and demonstrations are difficult to manage and may produce less academic content learning than educators hope for. It is hard to insure reliability of experiment outcomes, given variability in materials, measuring instruments and the like. Furthermore, when teachers ask students to discuss the outcomes of their class experiments (a frequent suggestion in the biology curriculum in the urban district in which we did our work, textbook and many other widely used textbooks), few students have the tools necessary to conduct these discussions. They are unfamiliar with techniques for summarising and interpreting data, and they do not know what their group discussions should attend to or how to build upon or challenge each other’s interpretations. As a result, while classroom experiments are engaging for students, it is often the case that little substantive learning takes place. Under pressure to produce measurable learning results within limited time spans, teachers often tell students what they “should” be seeing in their experiments, rather than building students’ capacities to design and interpret experiments themselves. Our goal has been to give students more time to reflect on what is happening in lab exercises, supported by conversational agents triggered in a context-sensitive way using automatic analysis of the collaborative discussion behaviour and to prepare them to take these insights back to the classroom for further whole-class interaction there, and in that way, the engagement in small groups enhances the efforts of the teachers to foster dynamic group discussions with student reasoning at centre stage.

The interventions we designed acted as scaffolding for small group discussion of classroom labs. We tested the effectiveness of these techniques in increasing students' ability to interpret experimental results and improving learning of the core biology concepts that are involved. In collaboration with the teachers participating in our study, we selected classroom experiments from the curriculum. We designed structured activities in which students specified hypotheses, recorded data and interpreted their data. Students worked through the activities in collaborative groups. Pre- and Post-tests on the biology content of the experiments and students' skill in interpretation of data were administered and all worksheets collected, permitting comparison of learning in the collaborative and the individual condition.

Our classroom evaluations of AT conversational agents as support for collaborative learning demonstrate their significant positive effect on student learning. First, in a January 2011 in vivo study, students in the experimental condition where they did a small group activity with the support of a conversational agent, were significantly more active in the immediately following whole group discussion than the students in the control condition, who did not have the support of a conversational agent during their small group activity. In the January 2012 in vivo study, students in the re-voicing agent condition learned significantly more on the immediate post-test than students in the control condition that did not have the support of the AT agents during collaboration. In the March 2012 in vivo study, students in the condition with re-voicing agents learned marginally more from the whole group discussion that immediately followed the intervention than students in the control condition who did not have the support of re-voicing agents. The series of studies were discussed in a review of early studies of AT agent support for collaborative learning (Adamson et al., 2014[9]).

Into the future: Fostering collaboration on Massive Open Online Courses (MOOCs)

Above, we have argued that Transactivity is a property of effective collaborative discourse that can be thought of as the DNA of a well-functioning group. On the one hand, Transactivity is frequently thought of in connection with its cognitive underpinnings, in that it signifies that students are openly sharing their reasoning and integrating their reasoning. This behaviour creates opportunities for students to experience cognitive conflict, which explains the correlation we see between the prevalence of transactive exchanges and learning. But, Transactivity also has social underpinnings (Gweon et al., 2013[7]). It signifies the experience of power balance, intimacy and a desire to build common ground. In recent work, we have leveraged the social underpinnings of Transactivity, using a measure of the exchange of transactive contributions in one setting as an indicator that a pair of students would collaborate well in a different setting. We developed a paradigm for team formation based on this idea, validated it in a controlled experiment in a lab setting and then deployed it in a successful team-based MOOC. Here we report briefly on this work, which is more fully described in separate publications (Wen et al., 2017[27]; Wen et al., 2018[28]).

In typical team-based MOOCs, team formation occurs immediately upon starting a course, and usually it is done through self-selection. Using this protocol for team formation, many of the teams fail. In our enhanced protocol, students first complete some individual work upon starting a course. During this time, many students who are not committed to the course quit. Those who are committed enough to complete the work are then required to post the work to the public discussion forum, and students are then asked to give feedback to a few students publicly within the forum. An automated analysis of these exchanges is then performed using a Transactivity detection model. Then, for each pair of students, we count the number of transactive contributions that were exchanged. After that, an approximate constraint satisfaction algorithm is used to assign students to groups of four in such a way that students are more likely to end up in the same team with others they have had transactive exchanges with during the public feedback discussion. The automatically assigned teams then do their teamwork together.

In order to validate the team formation protocol, we tested it in the Amazon Mechanical Turk environment. We ran the protocol several times, each time either using the full team formation protocol or using the same paradigm but with random assignment of teams rather than basing the assignment on the measure of Transactivity as in the full protocol. We then compared the extent of knowledge integration in the group proposal constructed during the collaborative phase. In this experiment, we found a significant advantage for the Transactivity based matching over random assignment, with an effect size of three standard deviations.

Finally, partnering with the Smithsonian Institute, we developed a three-week team-based MOOC in which we adapted the team formation protocol. Though there was no experimental manipulation, we measured the correlation between observed Transactivity during the feedback stage of the groups that were formed and their ultimate task success and found positive correlations that were consistent with our expectations based on the experimental study.

Conclusions and current directions

In this chapter, we have briefly described first, a theoretical construct referred to as Transactivity, which operationalises a key quality of well-functioning collaborative discourse, and which has both cognitive and social underpinnings. We have identified AT practices, as well as other similar discussion facilitation techniques (Resnick, Asterhan and Clarke, 2015[3]), which can be viewed as tools that stimulate higher concentrations of transactive exchange in student discussions. We first recounted a district-wide professional development effort that offered evidence that enhancing transactive exchange through automated AT facilitation in small groups leads to enhanced learning, and that experience of these collaborative learning encounters also facilitates greater uptake of AT facilitation practices among teachers. In a second investigation, we leveraged the same concept of Transactivity, but this time we used it as an indicator used in automated team formation. The new paradigm was validated in a crowdsourcing environment and then tested in a real MOOC deployment, which was successful.

Policy Implications

The implications of this work for policy synergise with those associated with Intelligent Tutoring technology discussed separately in this volume (Chapter 13, by Koedinger). Specifically, scaffolding for learning enabled by technology and designed to support the cognitive processes underlying learning and problem solving holds great promise for enhancing K-12 education at scale. In this chapter, specifically, we focus on learning through argumentation, developing learners' identities as reasoners and problem solvers (Chapter 3, by Meltzoff and Cvencek). We specifically address learning through social interaction, which engages learners not just as cognitive systems, but also as social beings who must develop the ability to function in a 21st Century world, which demands the ability to communicate and work in teams (Chapter 19, by Law and Ming Cheng). What we uniquely offer is a demonstration of specific technology that can act as a catalyst in facilitating widespread use of ambitious learning practices such as team-based project learning and collaborative learning more broadly to achieve these ends. While a push for efficiency and scale has sometimes resulted in minimising inclusion of classroom discussion, collaborative learning and engagement in writing with peer review both in teaching and in assessment, we offer evidence that with the support of technology, teachers can learn to enact collaborative and other discussion-based learning and social learning practices in their classrooms, and students benefit when they do, even in challenging urban environments. Resources have been made publicly available to facilitate widespread uptake of these practices.[1]

Note

[1] http://dance.cs.cmu.edu.

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Chapter 15. Music, cognition and education

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While the prioritisation of science, technology, engineering and mathematics (STEM) is a logical step in the effort to develop curricula that meet the increasing technical demands of society, methods of training broad cognitive and pro-social skills such as communication, cooperation, attention and creativity are elusive, yet critical, to the development of a dynamic workforce and healthy society. A growing body of evidence suggests that the practice and study of music may be one such method. The present chapter examines ways in which the practice of music may support education by driving aspects of cognitive development while also calling attention to the fact that music learning, cognitive development and education themselves are inextricably connected to their socio-cultural context. This fact holds important implications both for scientific research on music and for appropriate implementation of music in K-12 curricula.

A new focus towards improving educational outcomes through a well-rounded education includes a directive for parity between arts education and science, technology, engineering and maths (STEM) education in our nations' schools. Thirty years of vacillating US policy over the importance of the inclusion of the arts in K-12 curricula was fortified by the Every Student Succeeds Act (ESSA), which was signed by President Obama in December 2015. The act echoed the sentiment of the 2006 UNESCO conference that the arts – beyond merely meeting the goal of contributing to the creation of a multifaceted individual – are an essential component of education.

The present chapter examines ways in which the practice of music may support education, by driving aspects of cognitive development while also calling attention to the fact that music learning, cognitive development and education themselves are inextricably connected to their socio-cultural context. This fact holds important implications both for scientific research on music and for appropriate implementation of music in K-12 curricula.

Education primarily takes place in the context of a classroom setting, providing the challenge of unifying individuals to form a successful group. Interacting effectively in a learning environment is not trivial: individuals must fluidly regulate attention, integrating action within their personal control with the overall dynamics of the group. Fundamental to this process is the individual ability to generate predictions based on perceptions of temporal patterns in such things as the speech and gesture of those in the group. These temporal predictions allow enhancement of processing at key points in time, thereby increasing both accuracy and efficiency of taking in and conveying information in a classroom setting (Jones and Boltz, 1989[1]). The ability to integrate into a group is thereby an important skill-set that is refined through interactions that occur countless times throughout the day within a socio-cultural context and is thus strongly affected by this environment. One uniquely expressive element of any socio-cultural environment – one that is intrinsically temporal and centrally involves group integration – is the practice of music.

Music in education

Throughout recorded history, music has been a significant and participatory component of human culture. Beyond being a means for expressing emotion, defining ethnic identity, and accompanying a variety of activities and ceremonies, music is a form of communication. As such – from nursery rhymes to concert band – music has always been a part of traditional education systems. For example, both Plato in ancient Greece and Confucius in ancient China emphasised music as central to education, reviewed in (Park, 2015[2]; Stamou, 2002[3]) and today music is practiced in classrooms from Indonesia to Norway.

The question of transfer

Recent shifts in educational policy, as manifest in the United States by the ESSA, call for "providing all students access to an enriched curriculum and educational experience" (ESSA, 2015[4]). Whereas this law, and policies like it in other nations, provides some impetus for inclusion of music in education, the role of music in contemporary education remains unclear and often contentious. Instead, skills that apply directly to the needs of an increasingly technical global workforce, such as computing and mathematics, are readily prioritised. Below, however, we will see that instruction in STEM areas can be augmented by specialised programmes that connect STEM skills and concepts to music (Minces et al., 2016[5]). Nevertheless, a main source of contention is whether musical skills transfer: do cognitive, behavioural, and cultural skills and fluencies gained through music practice transfer to domains outside of music? Simply put, does music learning improve academic learning, personal and life outcomes? And, if so, how can this guide implementation into school curricula?

One of the most prevalent theories of music transfer has to do with structural similarities between music and language. Music and language share many features that may enable benefits from music training to affect language processing. Briefly, both are systems of communication in which simple sounds are combined according to hierarchical rules to create words/phrases/paragraphs. Both use variations in pitch and timing to communicate meaning. In the time domain, music and speech both comprise temporal events, or "rhythms", that take place at multiple, nested timescales ranging from 10s of milliseconds to 10s of minutes or even hours. While rhythms at each of these timescales require precise integration of processing, a high degree of integration across timescales is necessary for successful communication. Below, we present scientific evidence for connections between rhythms at various timescales and particular aspects of learning.

A recent summary of work in the field systematises the rationale for expecting music training to benefit language, because of the structural similarities between music and speech, but emphasising the intensive, repetitive, and emotionally and socially engaging nature of music practice, all factors thought to lead to greater brain plasticity (Patel, 2014[6]). That is, the intense, repetitive, rewarding attention to nuances of sound involved in music training may place greater demands on brain circuits, thus improving an ability to process sound in general, including improved perception of language.

Recent studies on music and language find that more practice and an early beginning to music training (around five years of age) are associated with better speech sound analysis in the brain (Musacchia, Strait and Kraus, 2008[7]). With better analysis comes faster and sharper brain response time to speech sounds as well (Musacchia and Schroeder, 2009[8]). This means that musicians who start playing early (and continue to practice) have a remarkably robust internal model of the speech sounds they hear. The effects reported in these studies have been replicated and expanded across dozens of investigations at several ages and in many countries (Gordon, Fehd and McCandliss, 2015[9]; Patel, 2014[6]).

A large body of research investigates connections between music, language and literacy. School-age children who participate in music classes, either as part of the standard curriculum or after school hours, show better standardised reading scores (Tierney and Kraus, 2013[10]). Reading benefit is present even among students who had no previous music experience, although the effect is larger in those who participate in music longer. While the link between oral language and literacy has been implemented through phonics since the turn of the century, these new data suggest that music training provides an additional, or alternative, route to strengthen the development of sound-to-letter correspondence. This may be especially valuable for the large and growing number of extraordinary children in our school system that face language-learning problems.

In music, at slower timescales, isochronous beats can be organised into units (i.e. groupings of strong and weak beats). These units establish music's metrical structure. For example, marching music usually follows the duple metre structure (2 beats per unit: strong-weak) whereas waltz follows the triple metre structure (3 beats per unit: strong-weak-weak). Recent neuro-imaging studies have demonstrated that, in addition to the auditory system, the motor system is involved in tracking isochronous beats, including the motor cortex, basal ganglia and the cerebellum (Grahn, 2012[11]). The processing of metrical structure has also been described by event-related responses and oscillatory responses in the brain (Iversen, Repp and Patel, 2009[12]; Zhao et al., 2017[13]).

The timescale over which metre is perceived is similar to that of prosody in which syllables are structured into larger groupings with strong and weak accents. Speech sounds remain intelligible when speech is intentionally degraded at faster timescales yet prosodic rhythm is preserved; supporting the idea that prosody plays an important role in speech perception (Shannon et al., 1995[14]).

Learning prosodic and metrical structure begins very early in life. The acoustic information relevant for processing information on the prosodic/metric timescale is available to infants even before birth. It has been demonstrated that newborns can detect violations in musical metre (Winkler et al., 2009[15]) and also discriminate languages that have different rhythmic characteristics (Nazzi, Bertoncini and Mehler, 1998[16]).

In a study that directly connects prosodic structure in speech with musical metre, (Zhao and Kuhl, 2016[17]), first demonstrated that a one-month music intervention at 9 months of age not only enhanced infants' neural processing of music metre, but also syllable structure in speech. The effect was interpreted as an enhancement of the infants' ability to extract temporal structure information and to predict future events in time, a skill affecting both music and speech processing. Notably, this skill might also be a fundamental building block of the ability to temporally integrate into a group setting.

Despite their parallel structures and many similarities, an important distinction between music and language exists in the tendency to synchronise musical behaviour to a periodic rhythm, a "beat". From tapping a foot to playing in an ensemble, this tendency to synchronise to music is ubiquitous in human culture, and indicative of special brain circuits not widely shared in the animal kingdom (Iversen, 2016[18]). The phenomenon of beat perception and synchronisation is noteworthy because it involves the interplay of the outside world and an internal rhythmic, predictive process, which creates expectations about future events that may guide attention.

Although there are various forms of attention, one view of attention describes a dynamic process that fluctuates over short periods of time. Dynamic Attending Theory (DAT) (Jones and Boltz, 1989[1]) proposes that greater attention is allocated to points in time at which future events are expected, thus maximising processing abilities at points of greater importance, while potentially reducing attention to times in which informative cues are unlikely to occur. In support of DAT, multiple studies have found facilitated processing of events that occur at expected times (Arnal and Giraud, 2012[19]). This temporal facilitation even extends to the processing of non-auditory events. For example, visual image processing was facilitated when images occurred on (vs. off) the beat of an accompanying auditory pattern (Escoffier, Sheng and Schirmer, 2010[20]).

A connection between the ability to synchronise to a beat – a capacity that is based on the generation of temporal expectations – and ability to focus or maintain attention has been borne out in several recent studies. Tierney and Kraus (2013[10]) found a correlation between ability to tap in synchrony with a metronome beat and ability to focus attention. While tapping with a metronome beat clearly relates to rhythmic ability, synchronising rhythmically with other individuals – a fundamental aspect of many music cultures worldwide – is a somewhat different task, involving interaction on many levels. Khalil et al. (2013[21]) found a correlation between the ability to synchronise in a group music setting and the ability to maintain attention in a classroom environment. The ability to generate and act on appropriate temporal expectations of a group dynamic may, thus, be relevant to the ability to function effectively in a classroom setting. Group rhythmic synchrony has been found to increase pro-social behaviour in infants (Cirelli, Einarson and Trainor, 2014[22]), young children (Kirschner and Tomasello, 2010[23]) and adults (Hove 2009). Significantly, group rhythmic synchrony has also been found to enhance the ability to co-operate (Valdesolo, Ouyang and DeSteno, 2010[24]). These studies point towards an important aspect of the learning environment: the group dynamic. Classroom learning does not simply depend upon each individual's cognitive skills and aptitudes, rather, it also can be enhanced, or degraded by the ability of the entire classroom to co-ordinate and co-operate. Integrating music into the classroom, then, may benefit not only each individual but also the group as a whole.

Further, while creativity has often been associated with "defocused" or "diffuse" attentional states, recent research has shown that creativity is more closely related to the capacity to modulate attention, moving dynamically through various states during the creative process (Vartanian, Martindale and Matthews, 2009[25]). In this way, creative problem solving – and creativity in general – may be related to a form of dynamic attending.

The universal language?

Whereas music is commonly referred to as a "universal language", and some generally universal features do exist in all music, such as the use of periodic rhythmic structures, consensus in the field of Ethnomusicology is that it is not universal (Campbell, 1997[26]). The affect and meaning of any given music is largely culture specific. Even the processing of musical structures such as metre becomes culture specific very early in life, as experience shapes the abilities of the underlying universal neural mechanisms. For example, in a series of studies, Hannon and Trehub (Hannon and Trehub, 2005[27]), demonstrated that infants growing up in North America at 6 months of age could detect metrical structure violations in both metrical structure (2-beat groupings) common in Western European music as well as a complex metre that is more common to Eastern European music (7 beats/group). However, by the age of 12 months, infants in North America can no longer detect metrical structure violation in the Eastern European (less familiar) complex metre. This demonstrates that even very early in life, human beings adapt their capabilities at prediction to match the temporal dynamics of the world around them, facilitating communication between like-cultured individuals. However, only 2 weeks of passive listening to Balkan music at home at this age (20 minutes/day) reversed this narrowing. This supports the intriguing possibility that the practice of music, when implemented in a multi-cultural setting, may be leveraged as a way to facilitate communication between individuals of different cultures.

The fact that music is not a universal language and so requires awareness of socio-cultural context in its implementation while other subjects such as mathematics do not require this to the same extent, remains a significant challenge in music education worldwide. Many nations continue – either through maintaining education systems developed under colonialism, or through having adopted Western education systems – to feature Western music in the classroom despite the fact that students experience completely different and equally rich music outside the classroom (Bradley, 2012[28]). In Ghana, for example, Western music continues to dominate music curricula, particularly in higher education. This is particularly interesting, given that Ghana is a nation whose traditional music is significant worldwide, having influenced the formation of pop-music and in its most traditional form is taught at many universities around the world (Otchere, 2015[29]).

Implementation of music and the socio-cultural environment

When music implementation is attuned to socio-cultural environments many direct and indirect benefits may arise. For example, in the Nyanza region of Kenya traditional songs have been woven into the school curriculum to enhance learning by connecting school learning with material learned outside of school (Akuno, 2015[30]). Cultural relevance is proposed to be of key importance to music in urban classrooms due to the increasing heterogeneity of the cultural background of students in such schools (Doyle, 2014[31]). Beyond direct music learning, it is important to note that music is not a stand-alone activity. Rather, it is ubiquitous in human behaviour and activity and so may be integrated into curricula in a variety of ways outside of formal music learning classes, yielding surprising benefits.

Music and STEM education

Throughout most of human history, music has been an integral part of scientific academic development. The connections between music and science are ubiquitous, and several scientific concepts have been advanced in terms of their relationship with music (Pesic, 2014[32]). Given these relationships, teenagers' intrinsic interest in music (North et al., 2000) offers a relevant avenue for students to explore and engage in STEM fields. One example of this educational approach is "Listening to Waves", a programme developed by Victor Minces with Alexander Khalil that engages students in the physics of sound waves through music (www.listeningtowaves.com). Through this programme, interest in and intuitive knowledge of music motivates students to approach challenging physics concepts. Not only does this approach engage students with physics but it also affords opportunities for STEM engagement for students of diverse backgrounds (Minces et al., 2016[5]). Ultimately, students also use their newfound knowledge of the physics of sound to create instruments and sound installations, allowing for cultural expression through scientific and technological practices.

Policy implications

The practice of music has been an intrinsic component of education, both formal and informal, throughout human history and across cultures. While direct benefits of the study of music may at first appear to be limited to the development of musical skills, recent research identifies ways in which music may be used in the classroom to enhance learning of humanities and STEM education, improve classroom culture, and even enhance cognitive skills that support learning in interpersonal settings. Through music practice, students may strengthen their ability to learn both individually, and in a group. Therefore, we submit that music can play an important role in curricula across all ages and levels.

Whereas it is difficult to generalise from a limited number of studies to general policy in either music research or research on learning, some general guidelines might be useful.

For example, appropriate implementation of music learning in schools would be inclusive, and not exclusively centred on elective ensembles that are focused on performance. This view is conceived in much the same way that physical education (PE) is meant to involve all students regardless of the presence of specialised afterschool sports activities. A great deal of research on music has been conducted with small sample sizes, in a limited number of schools, and/or in laboratory settings. We recommend developing research methodologies that integrate the collection of data into the fabric of music learning programmes themselves, allowing research to record music classes and track students' musical and scholastic progress. In this way, the long-term impact of music education may become a research priority to support the development of evidence-based practices.

A key element both for implementation of music programmes and conducting research is awareness and integration of socio-cultural context. Perception of temporal patterns in the world, and all of the cognitive processes that are involved, is refined through interpersonal interaction within a given socio-cultural context. The engagement and rewards of these interactions are social in nature. Appropriate implantation of music learning in school curricula should not only take socio-cultural context(s) into account but also leverage it, thereby improving school culture and even the value of education. In an increasingly interconnected world, scientists who study cultural phenomena such as music must focus their attention not only on cognitive mechanisms that may underlie these phenomena but also on how these mechanisms – and human perception itself – are mediated by culture.

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Chapter 16. Shapes, blocks, puzzles and origami: From spatial play to STEM learning

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We often take for granted our reliance on spatial skills in everyday life, as well as in a variety of professional pursuits. Spatial skills help adults interpret charts, read maps and visualise things they cannot see. They are malleable and foundational skills that start developing early in life and contribute to children's learning and success in science, technology, engineering and mathematics (STEM). Play with spatial toys in early education and home settings offers a promising and underutilised avenue for supporting 21st century skills. In this chapter, we summarise evidence of relations between spatial skills and STEM success. We then present ways in which spatial play activities might support spatial and STEM skills with relatively minor additional investments of parents' or educators' time or money. Suggestions include practical tips for caretakers to use during play. Before concluding, we highlight areas for future research and consideration.

Shapes, blocks, puzzle and origami: From spatial play to STEM learning

There is a growing worldwide acknowledgement that spatial skills exercised during puzzle play, building with construction toys, solving mazes and creating origami are foundational in supporting learning in science, technology, engineering and mathematics (STEM). Spatial skills involve mental manipulation of information about objects in the environment (Uttal et al., 2013[1]) and these skills are malleable. However, educators have likely not exploited them to their full potential in propelling the skills necessary for the 21st Century. Play with spatial toys offers an avenue for addressing this need. Policies that promote spatial toys for parents or integrate them into preschool curricula would likely improve not only spatial skills, but school-age children's learning in a number of subject areas that are of critical worldwide importance.

Adults call on spatial skills every day. Putting together IKEA furniture, remembering where you parked your car, and even something as mundane as navigating in the dark for a midnight bathroom break all require multiple spatial skills. Though we often take these skills for granted, there are negative consequences to common spatial mistakes, like scraping your car as you pull out of a small parking space. Many minor mistakes are only an inconvenience, but spatial errors can be fatal. Improper strap placement when installing a child's car seat can render the seat ineffective. Careers, such as air traffic control, city planning, and architecture, require precise thinking about objects in space, and errors in these careers can be expensive and disastrous.

Activities in which children use their spatial skills may look very different from the spatial activities adults engage in, but the applications are equally varied. As children insert shapes into a sorter, they practice perceiving angles and sizes and manipulating each shape to align it with its slot. When parents name and describe shapes, children start associating those shapes and their features with their labels. Building with blocks, children can visualise the supports their tower needs to stand without toppling and practice remembering where they last saw a needed block. These seemingly playful activities, and many other experiences navigating and exploring their world, provide children the practice they need to perceive, manipulate, label, visualise and remember objects in space.

Despite their importance, spatial skills get exceedingly little attention in formal education. Playful spatial activities like building with blocks are often limited in early education classrooms (Miller, Almon and Cramer, 2009[2]). Instead, the focus is on explicitly teaching the "three R's" (reading, writing and arithmetic). Our tendency to ignore spatial skills might be, in part, due to a belief that people are simply either good or bad at them naturally (Newcombe and Stieff, 2012[3]). Many adults readily admit, without shame, that they have an awful sense-of-direction. Would those people admit if they could not read or do basic addition? We assume that most people can and should learn to read and do basic mathematics but rarely think that they should be competent in spatial skills.

Research demonstrates that both children and adults can improve through spatial training (Hawes et al., 2015[4]; Uttal et al., 2013[1]). In this chapter, we argue that spatial skills are a key part of early learning and build the foundation for development in STEM domains. We first summarise evidence of relations between spatial skills and STEM success. We then present ways in which spatial play activities might support spatial and STEM skills with relatively minor additional investments of time or money. Before concluding, we highlight areas for future research and consideration.

Spatial skills and science, technology, engineering and mathematics (STEM)

Recent decades have seen a global focus on STEM education to better prepare children for the 21st Century workplace. Despite increased attention, though, international rankings show that student performance in mathematics and science remain distressingly low, even for 15-year-olds in many resource-rich countries like the United States (OECD, 2013[5]). Attention to findings from the science of learning can address this problem. Ample evidence reveals empirical links between spatial skills and many STEM domains (Newcombe, 2017[6]). For example, correlational work indicates that individuals with stronger spatial skills perform better in STEM fields (Mix and Cheng, 2012[7]) and high school spatial skills predict later markers of success in STEM careers, like income, patents and achieving tenure at a university (Wai, Lubinski and Benbow, 2005[8]).

Neuroscience offers converging evidence for spatial and STEM skill links. For example, a brain area called the intraparietal sulcus is active when we think about either spatial problems or mathematical magnitudes (Ansari, 2008[9]). Also, certain developmental disabilities involve deficits in both 1) spatial or visual working memory; and 2) learning about mathematics fundamentals like numbers (Szűcs, 2013[10]).

Though more research is required to fully understand the underlying mechanisms, longitudinal work with preschoolers suggests causal links between spatial and STEM skills (Verdine et al., 2017[11]). In addition, benefits of strong spatial skills for STEM outcomes appear to exist regardless of socio-cultural factors like parent education or ability levels in other domains, like executive functioning (i.e. the abilities to control impulses and think flexibly) (Verdine et al., 2014[12]). Support for early spatial development could therefore have broad impacts and, by all current indications, help children from a broad range of nations and cultural situations to learn STEM subjects.

Improving spatial learning

The data from basic science point towards practical applications to support spatial skill development in early childhood. Children's spatial and mathematics skills and the relations between these skills emerge by preschool (Verdine et al., 2017[11]). Although there are a limited number of spatial intervention studies for young children, early indications are promising for important and long-term influences of early training. Mental rotation training, for instance, can positively impact later spatial skills (Hawes et al., 2015[4]), and activities like creating patterns with shapes and building with blocks (Brock et al., 2018[13]) can influence STEM-related skills.

Informed by such research, Head Start and the Common Core Standards have increased their emphasis on spatial concepts. Further, the National Research Council (2006[14]) suggested spatial instruction be blended into the existing curricula. These steps for formal education are promising, but since young children spend most of their time outside of school, experiences in more informal settings are also key to supporting spatial and STEM skills.

Playful learning as a promising pedagogy

Research from the science of learning shows that children learn best when cognitively engaged in activities that present content meaningfully and through social interaction (Hirsh-Pasek et al., 2015[15]). This would suggest that "playful learning" might offer one evidence-based way to facilitate spatial learning and the foundations for STEM development (Hirsh-Pasek and Golinkoff, 2011[16]).

Playful learning encompasses both free play and guided play (Hirsh-Pasek and Golinkoff, 2011[16]). Free play has been characterised by children's unconstrained exploration of objects and situations; guided play is tantamount to constrained tinkering. In guided play, children continue to be in charge, but they do so in a supportive environment that will lead them towards a learning goal. Adults might support children's play by populating the environment with specific toys meant to promote spatial play and by using spatial language. Adults might also scaffold children's learning by asking provocative questions or providing commentary. Based on existing empirical literature, we focus here on a few, readily available, concrete and small-scale playful activities that exemplify promising opportunities for early spatial and STEM learning.

Playful activities

Shapes

Many toys and activities for toddlers and preschoolers feature circles, squares and other geometric shapes. Shape sorters, which require children to insert shapes into matching openings, provide opportunities to manipulate objects in space and to use objects' spatial properties to decide how they fit together. With other toys, too, as children stack shapes, press them to play songs and so forth, there are opportunities for them to learn new words to describe objects, compare and contrast shapes, and count and measure sides or angles. They can also see how shapes relate to each other (e.g. a square can be split into two right triangles). Especially with adult support, children can also use shape toys to identify and complete patterns (e.g. solving for "x" in ▲■■:▲■x). Data suggest that pattern work likely helps children build skills useful in early mathematics (Rittle-Johnson et al., 2015[17]), and the symbolic and analogical reasoning involved relate to broader STEM skills.

One concern about shape toys is that most do not feature a wide variety of shapes (Resnick et al., 2016[18]). Triangles, for example, are usually only represented in the "typical" equilateral form; few toys feature more "atypical" right, isosceles or scalene triangles. This focus on one iconic version might lead children to misunderstand shape categories. For instance, children might believe that all triangles have a point on the top and equal length sides rather than three sides and three angles. Concept learning research suggests that exposure to little shape variety likely contributes to delays in knowing shapes' defining features (Satlow and Newcombe, 1998[19]). While teachers tend to ask children to identify shapes, they less often ask questions or add information to help students learn the features that actually define them (Sarama and Clements, 2004[20]), though such help can be effective. Researchers showed 4- to 5-year-old children typical and atypical real shapes as well as "fake" shapes (e.g. three sides with a gap between two of them) (Fisher et al., 2013[21]). The experimenter used one of three approaches to teaching the differences: a guided play approach to explore distinctions together, a didactic approach where the child was told the differences, or an approach where children played freely with the shapes without adult involvement. Children in guided play showed the strongest ability to identify both typical and atypical real shapes, showing that young children can learn unfamiliar defining features of shapes and that guided play can support these gains. In a forthcoming study, authors of this chapter found that simply including more shape variety got children and adults to use more spatial language during a play session.

If toy developers incorporate more atypical shapes into toys and adults purposely draw children's attention to a variety of exemplars, we can better support early shape knowledge. At the intersection of spatial, language and mathematical skills, shape knowledge is as an important aspect of preschoolers' school readiness, with even kindergarten Common Core curriculum drawing on students' shape knowledge.

Blocks

Construction toys like blocks are relatively affordable, widely available and invite children to experiment with different shapes and sizes. After placing a heavy block atop an unsteady tower, children might also better understand physics concepts, like gravity, as they watch the tower fall. They might then visualise other constructions, increasing their skills in mentally manipulating spatial representations. Such block play involves spatial problem solving and basic engineering.

Using interlocking blocks for new constructions or to recreate models also offers early mathematics practice. Children can count blocks or compare pieces that are four studs long to those that are only two. This play likely promotes concepts of units and part-whole relations, which support understanding of magnitudes, numbers and fractions.

Block play is enjoyable at many ages, which has three advantages: 1) purchases are a long-term investment compared to toys that are quickly "outgrown"; 2) children of mixed ages can learn through each other in joint play; and 3) adults enjoy participating, making it a natural venue for guided play. Though some of the mechanisms for how block building might support specific spatial or mathematical skills are still somewhat speculative, we have seen that children who perform better on spatial construction tasks or who play with more blocks have better spatial skills later (Verdine et al., 2014[12]). Mounting evidence from training studies also shows that experience with construction activities is causally related to growth in spatial skills (Brock et al., 2018[13]).

Puzzles

Another activity for providing spatial education that can be fun for all ages is puzzle assembly. With many puzzles on the market, we can also find puzzles with themes and difficulty levels that are appealing to any child. Vygotsky's zone of proximal development theory suggests that children learn new skills best when challenged but not faced with overly difficult tasks. Many children start with wooden peg-board puzzles that simply require matching the images and shape of each piece to a space in a board. Next is often wooden puzzles with pieces that still overlay directly on an image, but the pieces all fit together inside one large indentation. Finally, children graduate to interlocking jigsaw puzzles where the picture to be replicated (often on the box top) is a different scale, and the builder has to figure out the overall size and shape. Jigsaw puzzle difficulty depends on the size, number and shape of the pieces and on the complexity of the target image.

With so much variety, puzzles can provide opportunities for children of all ability levels to learn and building any of these puzzles involves spatial skills. When children use individual pieces to create the goal image, they tap into part-whole knowledge. They will become faster and more skilful if they develop ways both to predict the appearance of missing pieces and to find them. Adults often help by suggesting children start with a jigsaw puzzle's outer borders, since straight edges will then identify the best candidates. A shape-focused strategy might become increasingly effective as puzzle difficulty increases, based on the number of pieces and repeating patterns (Verdine et al., 2008[22]). Children also might create mental representations of what missing pieces must look like by studying the shapes of the holes they will fill. If unused pieces are in the wrong orientation on the table, the search might invoke mental and physical rotation skills, too.

Though there is still much to learn, current evidence suggests that puzzle building is a good spatial activity. A study of elementary-aged children's puzzle building found high, positive correlations between puzzle performance and mental rotation, spatial perception, and spatial visualisation (Verdine et al., 2008[22]). Another study showed that 2- to 4-year-old children who played with puzzles at home had better spatial skills at 4.5 years old, even after controlling for parents' education, income and language (Levine et al., 2012[23]). Children using harder puzzles experienced more parent engagement and spatial language exposure, too. These results are consistent with puzzle building promoting spatial skills, especially with appropriately difficult puzzles and the supportive context of guided play.

Origami

In origami and other paper building activities, like making paper airplanes, the goal is to fold a piece of paper to create a particular shape, often recreating a model provided through step-by-step diagrams or live demonstration. Children trying to produce a specific crane design must recognise the relation between the model and their own piece of paper, imagine the necessary transformations, and determine if their folds are correct. Origami can also expose children to new spatial terms and concepts, such as mirror images, which are foundational for mental rotation skill development. We know that young adults asked to think aloud while doing origami projects include spatial terms in their speech and produce behaviours indicating spatial concepts (Taylor and Tenbrink, 2013[24]). Researchers have also found increases in spatial skills following origami activities (Taylor and Hutton, 2013[25]), suggesting the origami experience might cause gains.

Techniques for supporting spatial development during play

Regardless of the activity, research identifies specific techniques that are effective for spatial support, and these techniques emerge organically during guided play.

Spatial language

For example, children might put the red block atop the green one as the adult comments, "Wow – you put the triangle on top of the square. Can you find another triangle?" When using guided play with blocks, adults model not only simple shape names, but also descriptions of spatial features, as in, "Are there any smaller triangles in the pile? Do you think it will balance on its point?" Exposure to spatial terms in everyday activities is linked to better spatial skills. In one study, 14- to 46-month-olds whose parents used more spatial terms with them produced more spatial language (concurrently and at 54 months) and scored higher on spatial tasks at 54 months (Pruden, Levine and Huttenlocher, 2011[26]). Other researchers showed preschoolers where they were hiding an object near a box and described the location using either spatial descriptors (e.g. "on the box") or generic language (e.g. "here") (Loewenstein and Gentner, 2005[27]). When researchers asked the children to find another object hidden in an analogous location in another box, those who heard spatial descriptors were more successful than those who heard generic descriptors. Such results suggest that adults can infuse guided play with spatial terms to support spatial learning.

Gestures

Similarly, adults can model and respond to the use of gestures in guided play. If their hands are free, adults might intuitively use gestures that illustrate what they are saying aloud, including their spatial language. For example, during origami, adults can gesture with their right and left hands accordingly, saying, "Now, fold the right side and the left side in so the edges meet in the middle of the piece of paper." Children whose parents accompany more of their spatial language with gestures produce more spatial language themselves (Cartmill et al., 2010[28]), likely supporting their spatial skills. Importantly, children's and adults' gestures sometimes communicate spatial information that is not clear from speech alone (Sauter et al., 2012[29]). Gestures are important aspects of communication that facilitate spatial learning during play.

Future directions

While the current research points to the value of spatial play, further work on the causal relations between different types of spatial activities and gains in specific STEM skills will help further solidify recommendations for interventions. Besides blocks, puzzles and other concrete manipulatives, there is a growing number of digital apps available. More research is needed to better understand how they might facilitate early spatial and STEM skills (Hirsh-Pasek et al., 2015[15]), but a number of chapters in this book indicate that well-designed technology products and other digital media can be useful in education (Chapter 8, by Forbus and Uttal; Chapter 9, by Barron and Levinson; Chapter 10, by Llorente, Moorthy and Dominguez; Chapter 11, by Okita). Regardless of the medium, we also need more data on group and individual differences in the benefits gleaned from spatial play, how much of this play is "enough", and how long effects will last.

Conclusion: Maximising benefits of spatial play

An initial step towards providing early spatial education is ensuring access to toys like shape sorters, blocks, puzzles and origami that lend themselves to spatial play. Even if children then play freely, they will likely encounter spatial experiences. Using guided play, teachers, parents, other adults or older siblings can inject spatial language and gestures and draw attention to spatial components, while still respecting children's direction and interests. Play partners can also adapt to address design features of toys and activities that limit spatial experiences, like having only one type of triangle.

Spatial skills are central to STEM learning, and their malleability suggests that it is worth our effort to promote their development. While further research is needed to identify specific benefits of various activities and test the theoretical links, we already have good evidence that spatial play can increase children's spatial skills. With a general pedagogical approach of playful learning, we can and should embrace these activities and infuse children's play with opportunities to build foundational spatial knowledge.

Policy implications

As a policy, and at a bare minimum, schools should have the suggested spatial materials available to students to use in time they are given for free play. Once materials are in place, teachers can be educated about the importance of spatial skills and encouraged to use the materials. Because many of these spatial materials can be used in fun and playful ways, children tend to enjoy them, which makes it easier for teachers to focus on adding value to their instruction as opposed to managing classroom behaviour. Finally, the general indications are that time spent on spatial training has as much benefit for performance on STEM subjects as time spent on STEM curricula (Lowrie, Logan and Ramful, 2017[30]). Therefore, though it makes sense to try to integrate spatial training into existing instruction, it appears that students across the world would benefit from these recommendations even if some of the time they spend on spatial training replaces time spent on the traditional STEM-focused curricula.

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Chapter 17. Research-practice partnerships in STEM informal learning environments

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Chapter 17 explores the science, technology, engineering and mathematics (STEM) educational opportunities that emerge when research-practice partnerships (RPPs) involve informal learning environments (ILEs). Specifically, three variants of the Living Laboratory model are described to demonstrate different collaborations that leverage the unique experience that ILEs provide. This chapter suggests that by having local university researchers engage with community educators and the public, a mutually beneficial relationship develops. University partners gain experience with public communication and have an opportunity for data collection. Furthermore, the exposure to local scientists, and the chance to participate in a research experiment offers encouragement for community members of all backgrounds and ages to pursue STEM fields, helping to reduce educational disparities and promote lifelong learning.

The education system in the United States has not been successful in preparing students for the careers of tomorrow in spite of multiple policy adjustments, including most recently former President Obama's Every Student Succeeds Act. Many students see coursework in science, technology, engineering and mathematics (STEM) as a necessary evil to be tolerated in exchange for high standardised test scores. Others reject STEM subjects as they do not see themselves in future STEM careers. These students miss the important link between STEM and the innovations used daily in their own lives, such as video games, smartphones and social media. They miss the underlying power of a STEM education that teaches how to create solutions to tough problems by making observations, quantifying data, interpreting evidence, drawing inferences and testing possible solutions. To transform learning opportunities for all learners, we need to utilise all available resources, especially those found at nearby colleges and universities. Thinking creatively about engaging students in STEM can break down barriers between traditional disciplines and provide greater opportunity for all learners, regardless of background.

This chapter examines how research-practice partnerships (RPPs) in STEM informal learning environments (ILEs) can create unique educational opportunities that are enriched by the sociocultural networks in which they are embedded. These partnerships are inherently interdisciplinary and cross multiple levels of analysis, inviting learners to consider an array of STEM approaches to both scientific and societal challenges. This approach has implications for creating large-scale educational impact by leveraging community partnerships effectively, and provides opportunities to reach learners traditionally underserved by specialised STEM programming.

The importance of informal learning environments

Educational policies largely focus on schools as the main learning delivery vehicle, however, the majority of a child's time is actually spent outside of school (Jackson, 1968[1]). This fact makes educational opportunities outside of school important, especially if the school environment is not fully resourced or the student is not engaged (National Research Council, 2009[2]). Although many places, including a home and a library, can be considered an ILE, there are locations that specifically cater to STEM learning. These locations include science centres, museums, zoos and aquariums, where members of the community can learn about a subject by interacting with exhibits, watching films and speaking to curators. What is often overlooked is the ability of these STEM ILEs to connect local communities of research with communities of practice.

ILEs engage children in socially embedded and interest-driven experiences that acknowledge and build on their own unique past learning experiences (Tudge, Scrimsher and Vygotsky, 2003[3]). STEM ILEs provide an opportunity for inquiry in a way that is both playful (Weisberg et al., 2014[4]) and emphasises the importance of family for STEM learning, especially for young learners (Fries-Britt, Younger and Hall, 2010[5]).These personal experiences can be used as a scaffold to engage children in the process of science (Eberbach and Crowley, 2009[6]).

By connecting community members to the research at regional colleges and universities, STEM ILEs are naturally positioned to leverage RPPs for the benefit of a large population of learners in a playful environment that is inclusive of family and friends. A well-designed informal learning opportunity can bring unique, engaging and importantly ongoing STEM experiences to an audience of learners of diverse backgrounds, ages and interests.

Models for research-practice partnerships in informal learning environments

RPPs for formal education environments are defined as well-established collaborations between practitioners and researchers that share the goal of investigating problems and solutions for formal education (Coburn, Penuel and Geil, 2013[7]). RPPs focused on improving formal education settings are seen as promising, however research on the efficacy of these relationships is just beginning (Coburn and Penuel, 2016[8]). Nikias and Tierney (2012[9]) called for the removal of what they termed the "firewall" between universities and public schools in the United States. They noted the relationship between socio-economic status of students and performance in college, observing that underprivileged students were behind their affluent counterparts in test scores, high school graduation rates and future salaries. However, Nikias and Tierney (2012[9]) assert that research universities, especially, can reduce this gap by engaging with their surrounding environment, creating both discipline-specific as well as interdisciplinary RPPs to benefit the broader community. Their analysis emphasises the need for participation and support from many community researchers and professionals.

Within this trend is an opportunity to nurture a variant of these partnerships that involves both educational researchers as well as STEM content experts as partners working in informal science learning environments. Such collaborations can leverage the community positioning of informal science learning environments and create mutual benefit for university partners on an individual, group and institutional level. Here we will describe a model and some variants of RPPs in ILEs.

With the support of the National Science Foundation, the Living Laboratory at the Museum of Science in Boston (http://livinglab.org/) developed an educational model blending the concepts of research and outreach (Corriveau et al., 2015[10]). Research teams offered experiments for museum patron participation with several goals in mind. The researchers sought to actively connect with the public around a scientific question. Museum patrons (typically parent-child pairs) engaged in an experiment with the researcher on the museum floor, out in the open for other museum patrons to see. The LivingLab model was created in response to the realisation that adult visitors within family groups were not partaking in learning experiences during their visit. The research teams sought to educate the public around their research in child development regardless of participation in the experiment. Typically, this occurred through short discussions between museum patrons (typically parents or caregivers) and another researcher who was not actively engaged in the experiment, and often involved an explanatory pamphlet. Finally, but importantly, the LivingLab sought to use the connections between the researcher team and museum staff to enhance mutual professional development. They did this in multiple ways including lunch and learn meetings where researchers presented their findings to the museum team and also by having museum staff participate in the experiments themselves and provide feedback on clarity of the information offered. Communication with the public is often a challenge for myriad reasons (Fischhoff, 2013[11]) and this feedback can help improve future dialogue with the public. Longstanding relationships between several universities in Boston and the Museum of Science in Boston are at the core of the LivingLab, but the group has expanded through a model where the LivingLab provides a small project stipend and training to museum research partners. One additional piece that has emerged from the LivingLab is the availability of research toys (Hadani and Walker, 2015[12]). Even a large research team cannot be on the floor of the museum interacting during all open hours. To address this gap, research toys that capture the essence of the experiment have been created so they can be left behind at the museum for patrons to engage. These research toys come with short explanations of the experimental goal, how to use the props provided and the typical results observed.

An alternative, albeit dramatic, way around research team availability is to site a research lab in a science centre or museum. A former researcher participating in the LivingLab at the Museum of Science in Boston approached the local science centre as he began his faculty position at the University of British Columbia in Canada. Science World in Victoria was undergoing a large-scale capital campaign and renovation. The success of the LivingLab model incentivised the group to try something that would bring even more research to the science centre – they literally built a research lab at Science World (https://www.scienceworld.ca/lab). This model certainly demands more resources, but has advantages. For example, some research, including many studies of cognition, demands quiet concentration and does not work well on the museum floor. The waiting area of the lab has two large monitors that show what is occurring in each of the two (quiet) research rooms, and in addition, the museum-facing wall of the waiting area is glass, so other Science World patrons can also observe the research from outside. Research on the malleability of implicit associations across development (Gonzalez, Dunlop and Baron, 2017[13]) is one example of the work conducted at the Lab in Science World. It is worth noting that this study involved approximately 1 200 participants – a feat that would be difficult to accomplish at a university lab.

Another variant of the LivingLab model engaged participants of all ages in an experiment measuring static balance and manual reaction time at the Fleet Science Center in San Diego (Suarez et al., 2015[14]). This LivingLab-supported project also included a blend of research and outreach, but was different in that the goal was to stimulate participant inquiry around their own balance and reaction time scores and to interpret these with respect to population data. The study used new technologies to collect balance and reaction time data and receive immediate results. Children commonly asked questions regarding the u-shape of the data and the discussion focused on a relative lack of balance control for young children and the elderly. However, children also inquired about the variability of scores at a given age and this prompted discussion on how some individuals of the same age might have different scores because of different training or exercise routines. The goal of the data collection was to develop a normative database for balance and reaction time in typical individuals that could be used for balance intervention studies of individuals with developmental disorders. That goal was shared with whomever asked, however, in the science centre, researchers sought to promote inquiry and highlight balance as a foundational motor skill. The researchers invited participants to ask questions and test their hypothesis. For example, a researcher would ask the patron, “What is your guess: is your balance better with your eyes open or with your eyes closed?”. Due to the simple and quick task using our balance-measuring device (BTrackS Balance Plate, Balance Tracking Systems, Inc., San Diego, CA), the participants made their guess and were allowed to test their hypothesis, giving them the opportunity to engage some aspects of the scientific method. Through the BTrackS interface, patrons viewed a clear representation of the amount of sway in each trial and condition. Additionally, participants were invited to practice a favourite movement activity (for example, soccer, dance or skateboarding) while on the balance board, allowing them to view how their balance changed with different types of movement. The FitLight Trainer System (FitLights, Corp., Aurora, Ontario) was used to measure reaction time and it also reported average reaction time immediately. These in real-time results allowed for our tasks to quickly escalate into a competition among family members or groups of friends in terms of minimising sway in the balance task and maximising speed in the reaction time.

These tasks allowed museum patrons of all ages to actively engage in the experiment in a way that was both fun and supported STEM inquiry.

Content-related programming around a specific exhibit can create an opportunity to bring scientists to public venues. For example, the GameMasters exhibit (ACMI, 2015[15]) at the Fleet Science Center created the opportunity to connect with local researchers who use video games in their work. Through a series of lectures and demonstrations researchers shared diverse uses of video games, including surgical training. Chukoskie and colleagues (Chukoskie, Westerfield and Townsend, 2018[16]) participated in multiple presentations for different audiences to share games designed to train attention and focus, as well as other games for reducing anxiety. As part of the Fleet's "Genius in the House" events, winners of two recent San Diego Hackathons demonstrated their innovative ideas and game-based solutions for museum patrons alongside the GameMasters exhibitions. Museum patrons were invited to try out these creations and ask questions. This exchange provides another example of the unique opportunities that can emerge from RPPs.

STEM learning outside the science centre

The Fleet Science Center has created and implemented 52 Weeks of Science, providing residents of two local neighbourhoods the opportunity to participate in free, hands-on STEM activities every week. 52 Weeks of Science is unique in that it is bringing science literally into the neighbourhoods where learners live. The success of this project requires the involvement of many different individuals, leading to the formation of Neighbourhood Leadership Groups, which connects STEM advocates, school district representatives, higher education institutions, STEM industries, libraries, parent groups and more. These Neighbourhood Leadership Groups allow for a network of STEM influencers to communicate, possibly leading to more future collaborations benefitting the community. The creation of this innovative outreach programme has stimulated interest from university partners who are interested in studying different aspects of the programme and helping to seek funding for 52 weeks ongoing support and expansion into other low-resourced neighbourhoods in San Diego County. A recent application of social network analysis (Daly, 2012[17]) of STEM learning resources in San Diego County is providing a useful perspective for next steps with the 52 Weeks of Science programme.

One group participating in 52 Weeks of Science is also highlighted in the chapter "Music, cognition and education" (Chapter 15, by Khalil et al.), as a physics programme called "Listening to Waves". This programme engages students in physics concepts through music and making instruments. Opportunities such as this are an effective way to introduce children to STEM concepts through interests they already have.

Although our primary focus is in children, RPPs in informal STEM learning environments are ideally situated to promote and study lifelong learning. Kagawa, Japan was involved in the 1973 OECD Educating Cities initiative and has prioritised lifelong learning by implementing policies and city projects at different municipal levels (Choi and Min, 2008[18]; Yang and Yorozu, 2015[19]). Japan has community centres, known as "Kominkan", that serve as hubs for citizens of all ages to partake in activities that cover an array of concepts, including personal development and social learning. Kominkan are often partnered with schools and museums (MEXT, 2008[20]) to facilitate these meetings. Additionally, Japan has established 150 Citizens' universities, which allow the public to take lectures and courses from a range of subjects (Yang and Yorozu, 2015[19])

Feedback loops in research-practice partnerships

As mentioned above, research on the efficacy of RPPs, especially in STEM ILEs, is still in its infancy. Evaluation of the outcome of any particular RPP's implementation ought to be separately considered from the value that the partnerships themselves may provide as a crucible for future innovation. Another layer of these partnerships focuses on what cognitive science research can bring to our understanding of engagement for better interactive design for both exhibits and demonstrations. Engagement is a construct that encompasses a number of cognitive parameters including focused attention, affect and motivation (Attfield et al., 2011[21]). It is typically assessed through survey and interview tools (O'Brien and Toms, 2010[22]). Moreover, to obtain a fingerprint of the experience during the experience using a survey, we must take the visitor away from the interactive, even if only momentarily, thus breaking the very engagement we hope to cultivate and assess.

A recent review highlights the need for more objective and physiologically based methods of assessing engagement, especially in technology-mediated learning environments (Henrie, Halverson and Graham, 2015[23]). Using advances in eye tracking, we can very quickly quantify the proportion of time spent "off task" (Miller, 2015[24]) and from those instances, determine where the user was looking before switching to off task behaviour. By aggregating such events across visitors, we will build a picture of what aspects of the exhibit interaction might be leading a visitor off task, and also how individuals with different levels of expertise are engaging with the content (Stofer and Che, 2014[25]). These ideas for the real-world study of engagement can incentivise researchers who may not otherwise have engaged RPPs to reconsider.

What is needed to encourage more research-practice partnerships?

Although existing literature suggests positive outcomes through RPPs (Coburn, Penuel and Geil, 2013[7]; Coburn and Penuel, 2016[8]) few collaborations between universities, local schools and community organisations have been explicitly studied for efficacy of different aspects of the RPPs. There are multiple barriers to improved participation. One struggle RPPs face is structural. Academic researchers are simply not rewarded for this type of partnership unless it results in a fast publication. These partnerships need time and investment to develop and do not typically lend themselves to fast publication. Academic review structures would do well to consider both the time investment as well as potential community investment from an RPP in evaluating an academic file. Another struggle RPPs face is the multifaceted challenge of effective scientific communication (Fischhoff, 2013[11]). When communicating their research to the public, researchers often forget their audience and use jargon that is unfamiliar to the public, and also fail to recognise that the conceptual framework of the patron will likely not be the same as the scientist, so some scaffolding must occur to build understanding. The LivingLab model prioritises mutual professional development partly for this reason. Museum educators facilitate discussions with researchers on clear communication and interaction with visitors. In turn, researchers can share their content expertise with the staff. Although RPPs can address this challenge in part, improving public-directed communications is part of a much larger effort. As an example, The Portal to the Public (Storksdieck, Stylinski and Canzoneri, 2017[26]) is an NSF-funded effort to improve communication through science centres.

For a successful RPP, all parties must find value and demonstrate willingness to work towards a common goal. Universities can be incentivised through the research conducted via the RPPs. RPPs provide faculty the option to collect useful data from a diverse range of participants, rather than be restricted to young adult subjects typically available at a university – and the volume of the participants can be quite large. However, it is not just the resulting data that are appealing. Faculty trainees will gain unique research experiences as they are invited to consider and directly address societal needs in education as part of the blended research-outreach experience (Coburn and Penuel, 2016[8]).

For community organisations, alignment with a particular research programme can create a strong desire to partner with certain groups within local colleges or universities. STEM ILEs, such as museums, frequently have strong connections to local K-12 schools through their own programming and field-trips, however, the connections with higher education institutions are weaker. Typically, one of the goals of STEM ILEs are to provide a fertile environment for cultivating the next generation of STEM leaders. ILEs should view local colleges and universities as a tool to leverage their impact on this next generation. ILEs can fill the role of mediator by exposing children to higher education options and possibly future field interests.

Policy implications

This chapter discussed the power of RPPs in ILEs to stimulate STEM learning in a way that builds sociocultural networks and promotes research to examine efficacy. The network analysis engaged by 52 Weeks suggests an intriguing step forward. Perhaps we ought not to categorise RPPs that work within versus outside of standard school environments, but instead use RPPs and the networks that emerge from them to knit together opportunities that connect children's learning both in and out of school environments. This holistic approach prioritises learning, not where it happens. Additionally, to stimulate more involvement from university partners, academic review policies will need to reconsider the societal value of RPPs and the time that is needed to nurture such partnerships. RPPs can play a role in improving science communication in our communities more broadly. By increasing the frequency of interaction between STEM experts and the community, we increase opportunities for discussion and learning. Finally, but importantly, the lifelong learning approach should not be seen as diverting resources away from young learners, but instead creating a community that surrounds all children with the excitement of STEM learning opportunities.

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Chapter 18. How the science of learning is changing science assessment

By

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Mandated tests exert a strong influence both on what gets taught in schools and on how it gets taught. In the past, conventional multiple-choice tests have inclined educators towards broad content coverage rather than deeper learning in science as well as in other academic subjects. But over the last decade, the prerequisites for a major shift in the nature of science assessments have emerged. New frameworks and standards for science learning, such as the Next Generation Science Standards, are based on conceptions of science proficiency coming out of learning sciences research. In combination with advances in interactive, adaptive digital systems and psychometric modelling, this learning sciences conception of what it means to develop science proficiency is stimulating new ways to capture students' science ideas, concepts and practices simultaneously in the context of rich, extended scientific investigations.

The assessment of student learning is fundamental both to improving instruction (Black and Wiliam, 1998[1]) and to making judgments about the effectiveness of school systems (OECD, 2013[2]). In the past, different kinds of assessments have been used for these two purposes, and neither classroom assessments nor mandated large-scale assessments have rendered a full picture of what we now understand to be needed science proficiencies. An understanding of the latter, based on learning sciences research, has provided the basis for new science education standards in the United States and has influenced international assessments, such as the Programme for International Student Assessment (OECD, 2016[3]). In this chapter, we argue that rich technology-based environments will be necessary to assess the science proficiencies described in those standards and that such technology-based assessments have the potential to resolve the challenge that many countries face in trying to align and reconcile classroom-based and national learning assessments.

Origins of testing practices.

While national tests of educational achievement are relatively new to many countries (OECD, 2013[2]), they have a long history in the United States. The US approach to large-scale testing of elementary and secondary school students evolved from 20th-century efforts to identify those who were and those who were not fit for certain tasks – originally, serving in the armed forces during World War I and later, entering various professions or going to college. The methods for developing and interpreting assessments were attuned to the goal of discriminating among levels of a hypothesised construct, such as general intelligence or maths skill. The logic underlying classical test development is that a sample of items drawn from the universe of all possible items would elicit examinee responses that would justify inferences about how the test taker would have performed if every possible test item had been administered. To administer assessments to large numbers of examinees in as little time as possible and with low cost, test developers rely on questions with one right answer and multiple-choice formats. Such tests produce reliable scores and can be scored automatically. Unfortunately, the multiple-choice format has a serious downside: it tends to lure the test item writer into focusing on discrete bits of knowledge and highly structured problems – a far cry from the model of science proficiency and expertise that has now emerged from learning sciences research.

Learning sciences perspective on the nature of science expertise

Everyday conceptions of expertise regard the individual who has retained large numbers of science facts and data points as a science expert. But cognitive studies of expertise starting in the 1980s and more recent fine-grained analyses of the inter-personal and social nature of learning and competence suggest that this layperson's view of expertise is fundamentally misleading (Bransford, Brown and Cocking, 2000[4]; Chi, Glaser and Farr, 1988[5]; Sawyer, 2005[6]). Expertise lies not so much in the number of facts an individual can state but in the way in which that knowledge is organised and the ability to apply it flexibly and appropriately in new situations. Moreover, the long-admired virtues of critical thinking and problem solving are no longer viewed as generalised capacities for abstract thinking, but rather as forms of thinking within particular domains that are necessarily manifested in combination with content knowledge (Bransford, Brown and Cocking, 2000[4]; Chi, Glaser and Farr, 1988[5]; Sawyer, 2005[6]). In addition, we now understand that scientific standards of evidence and forms of argument are socially constructed norms that are maintained through collaboration and communication (Lemke, 2001[7]).

These learning sciences insights into the nature of expertise exerted a major influence on The Framework for K-12 Science Education Practices developed by the National Research Council in 2012 (National Research Council, 2012[8]). In contrast to the earlier National Science Education Standards that treated science inquiry processes and core concepts in the various domains as separate learning goals, the Framework makes a strong statement that science practices and science content must be integrated in order for students to become proficient in science. The Framework describes proficiency in science as the integration of concepts (such as causality) that cut across many fields of science, (OECD, 2013[2]; OECD, 2016[3]) the practices that scientists and engineers use (such as evidence-based argument), and (OECD, 2016[3]) core ideas in particular science disciplines (such as natural selection). Science proficiency lies in the ability to orchestrate all three dimensions (practices, crosscutting concepts and core ideas in the domain). Science learning is a trajectory in which these inter-related dimensions of proficiency emerge over time, with expected progressions of increasingly sophisticated understandings, not just within an instructional unit, but over multiple experiences and years (National Research Council, 2012[8]).

Research on learning progressions with respect to understanding a number of core science ideas and crosscutting concepts (Alonzo and Gotwals, 2012[9]; Corcoran, Mosher and Rogat, 2009[10]; Molnár et al., 2017[11]) had a major influence on the vision articulated in the Framework. Cognitive and science education researchers participated along with scientists in the fields of physical, life, earth/space, and engineering sciences in developing the Framework. When US state representatives and other stakeholders subsequently organised to lay out the Next Generation Science Standards (NGSS) based on the Framework, their descriptions of performance expectations for different grade bands were shaped by the learning progressions research. We note that this conceptualisation of science competencies in the Next Generation Science Standards now widely influential in the United States, treats science proficiency as crossing multiple specific scientific domains (e.g. ecology and genetics) rather than as expressions of domain, independent or general problem solving skills as conceptualised by many European researchers (Csapó and Funke, 2017[12]; Molnár et al., 2017[11]; Zoanetti and Griffin, 2017[13]).

Implications for assessing science proficiency

Assessing progress towards attainment of science proficiency as set forth in the Framework and the NGSS requires assessing students' application of practices, crosscutting concepts and core disciplinary ideas all at the same time within some larger problem context (National Research Council, 2014[14]). These three dimensions of proficiency will need to be assessed through multiple tasks that vary in what they ask students to do, including tasks calling on students to develop and use models, construct explanations, and evaluate the merit of others' ideas and methods. Science assessments will also need to call on students to make connections between different science ideas and crosscutting concepts. Finally, they will need to be designed to provide information at multiple points in time about students' progress with respect to the levels in the learning progressions incorporated in the NGSS.

In addition, the statistical models developed to produce scores and interpretations of test results for assessments of a single dimension are not sufficient for multi-dimensional assessment tasks consistent with the Framework. These models assume that all the items on a test are sampled from a single achievement domain and that responses to different items are independent of each other. Assessments meeting these criteria could not possibly capture the multiple, inter-related facets and complexities of the proficiencies defined by the three dimensions in the Framework.

The importance of technology advances

To assess such combinations of the three Framework dimensions, we need more open-ended, multi-part problem contexts, and we must also allow for a student's response to one portion of the problem to constrain responses to other portions (with the consequence that items are not independent). Recent advances in the capability of interactive learning technologies to present virtual environments, models of complex systems, digital workspaces and simulations are supporting efforts to address the challenge of providing rich problem contexts to all of the students being assessed. And, simultaneously, advances in psychometric theory and modelling have been such that we can now build measurement models for such complex, multi-part assessment tasks (Mislevy, Steinberg and Almond, 2003[15]; National Research Council, 2001[16]; Shute et al., 2016[17]). It is no longer unrealistic to think about measuring the kinds of thinking that scientists and engineers do in different domains using computer-based assessment tasks that are both engaging and systematically presented and scored.

Example of a technology-based science assessment task

An example of how assessment tasks can elicit the three intertwined dimensions of the NGSS comes from the ongoing work of the Next Generation Science Assessment project, a multi-institutional research and development collaboration to design, develop and validate sets of technology-enhanced assessment tasks for teachers to use formatively in classroom settings. The assessments are designed to help teachers gain insights into their students' progress towards achieving the NGSS performance expectations for middle school science. The research team is using an evidence-centred design approach (Mislevy, Steinberg and Almond, 2003[15]; National Research Council, 2014[14]) to create computer-based, instructionally supportive assessment tasks with accompanying rubrics that integrate the three NGSS dimensions (Harris et al., 2016[18]).

The developers systematically deconstruct each NGSS performance expectation into a coherent set of learning performances, which can guide formative assessment design. Learning performances are statements that incorporate aspects of disciplinary core ideas, science practices and crosscutting concepts that students need to attain as they progress towards achieving an NGSS performance expectation. Each set of learning performances helps identify important formative assessment opportunities for teachers aligned with the proficiencies in a performance expectation. Learning performances are akin to learning goals that take on the three-dimensional structure of the performance expectations – they articulate and integrate assessable aspects of performance that build towards the more comprehensive performance expectation.

The learning performances then guide the design of assessment tasks that integrate the NGSS dimensions and collectively align with the performance expectation. Table 18.1 shows a set of learning performances derived from an NGSS performance expectation for the middle school topic of matter and its interactions.

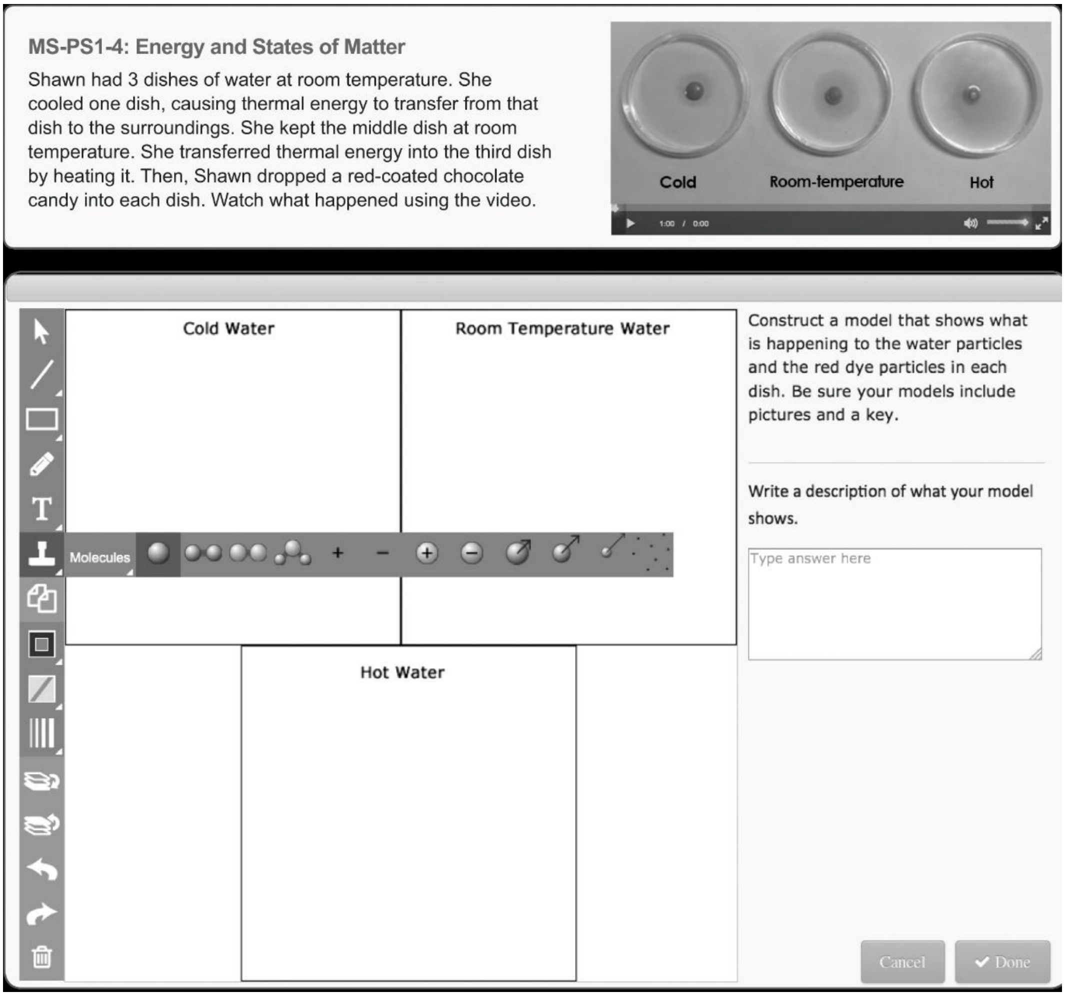
Table 18.1. A middle grades NGSS performance expectation and related set of learning performances

Performance Expectation:
MS-PS1-4. Develop a model that predicts and describes changes in particle motion, temperature and state of a pure substance when thermal energy is added or removed.
Related Learning Performances
LP 1: Evaluate a model that uses a particle view of matter to explain how states of matter are similar and/or different from each other.
LP 2: Develop a model that explains how particle motion changes when thermal energy is transferred to or from a substance without changing state.
LP 3: Develop a model that includes a particle view of matter to predict the change in the state of a substance when thermal energy is transferred from or to a sample.
LP 4: Construct a scientific explanation about how the average kinetic energy and the temperature of a substance changes when thermal energy is transferred from or to a sample, based on evidence from a model.
LP 5: Develop a model that includes a particle view of matter to predict how the average kinetic energy and the temperature of a substance change when thermal energy is transferred from or to a sample.

Source: Next Generation Science Assessment Collaborative, http://nextgenscienceassessment.org/.

Each of the learning performances developed for a performance expectation then becomes the learning outcome for a multi-part technology-based assessment task. Figure 18.1 shows an example of a task addressing all three NGSS dimensions for a learning performance aligned to the NGSS performance expectation for thermal energy and particle motion. In this task, students watch a short video of what happens when dye-coated candies are placed into water at different temperatures. Students then develop models and write a description of what is happening as the dye spreads differently at the different temperatures. The task assesses disciplinary core ideas around temperature and the kinetic energy of particles, the science practice of developing models, and the crosscutting concept of cause and effect. It requires students to integrate knowledge about particles, temperature and kinetic energy and the underlying mechanism linking cause (water temperature) and effect (spread of the dye) with the ability to develop a model of a phenomenon using drawings and written descriptions.

Figure 18.1. Assessment task example: Thermal energy and particle motion



MS-PS1-4: Energy and States of Matter

Shawn had 3 dishes of water at room temperature. She cooled one dish, causing thermal energy to transfer from that dish to the surroundings. She kept the middle dish at room temperature. She transferred thermal energy into the third dish by heating it. Then, Shawn dropped a red-coated chocolate candy into each dish. Watch what happened using the video.

Cold Water

Room Temperature Water

Hot Water

Construct a model that shows what is happening to the water particles and the red dye particles in each dish. Be sure your models include pictures and a key.

Write a description of what your model shows.

Source: Next Generation Science Assessment Collaborative: http://nextgenscienceassessment.org/

Role of technology-based learning environments for supporting learning and assessment

Even though we now have appropriate measurement models to assess multi-dimensional science proficiencies, the practical problem of finding time to administer multiple complex assessment tasks persists. Fortunately, the use of learning technologies in classrooms is increasing, and students' daily instructional activities often involve the use of digital resources and instructional software (e.g. simulations, serious games, etc.). As a result, the distinction between "learning" and "assessment" is becoming blurred. Digital learning environments can be designed to elicit student thinking and proficiencies as a natural by-product of interacting with the system.

In the River City virtual environment, for example, students seek the source of an infectious disease by exploring various parts of the virtual city and its environs, performing environmental tests (which reveal the hypotheses they are entertaining) and making online journal entries with their findings and interpretations (revealing how students reason from data and put different pieces of information together to form inferences). These online activities are opportunities both for learning and for assessment. With a learning system like River City that is continually gathering information relevant to student proficiencies, there is no need to stop learning activities to see what students know and can do. It is possible to bring an assessment perspective and modern measurement models to this endeavour so that assessment becomes something that is "always on" during learning rather than a special event with different materials, formats and rules than either classroom learning or normal functioning in the world. The log file traces from River City, for example, have been used as assessment data, providing a basis for making inferences about students' science inquiry processes (Ketelhut and Dede, 2006[19]).

Other powerful examples of tech-based formative assessments of multi-dimensional competencies are being developed that capitalise on ongoing assessment approaches. Researchers in Luxembourg have analysed log files from students using Genetics Lab to assess students' competencies in systematically exploring relationships among variables determining genotypes and phenotypes (Csapó and Funke, 2017[12]). ChemVLab simulates a chemistry stockroom and workbench for carrying out a wide array of investigations, providing students with practical, simulated exposure to wet-lab work, data collection and interpretation, problem solving and sense making (Davenport et al., 2012[20]). Again, using student log data, reports to students and teachers provide ongoing progress monitoring and allow teachers to adjust their instruction accordingly.

Implications for large-scale testing and assessment systems

To date, most of the research and development around rich technology-based assessment environments such as River City, Genetics Lab and ChemVLab has focused on low-stakes uses for formative purposes within classrooms. In part, this is because the learning sciences-based view of the multi-dimensional nature of science proficiencies described above is at odds with the nature of large-scale testing practiced in the United States and in many other countries as part of educational accountability systems. In the United States, most states conduct state-wide end-of-year assessments in science just three times during a student's K-12 schooling, once in elementary school, once in middle school, and once in high school, as required by federal education legislation.

These large-scale test administrations have been characterised as "drop in from the sky" assessments because they come from outside the classroom, interrupt the flow of classroom learning activities, and vary in the degree to which they relate to the curriculum students have been studying. The total amount of time US classrooms are being required to spend on drop-in-from-the-sky assessments has been a source of contention in recent years, but even so, it should be realised that the state assessment in any one subject area is quite limited in duration. For example, state science assessments in the United States typically are completed in 60-90 minutes on a single day. It can be argued that the combinations of practices, crosscutting concepts, and core ideas that comprise the proficiencies in the Framework and NGSS cannot possibly be exhibited within such a constrained time-period (Pellegrino, 2016[21]). Rather, these proficiencies come into play when learners work with complex problems and challenges over an extended timeframe.

A strategy for addressing the challenge of obtaining a meaningful assessment of domain-embedded science proficiencies as now understood without unduly burdening teachers and students with many hours of testing is to supplement (or replace) state testing activities with information about student proficiencies gleaned from formative assessments done within classrooms as part of instruction (Csapó and Funke, 2017[12]; Zoanetti and Griffin, 2017[13]) for a European view of this alternative). Because such classroom assessments are part of the learning process rather than an isolated, unrelated activity, they naturally occur over time and generate much more information about students' science thinking and performance than any single drop-in-from-the-sky test could. Such ongoing, curriculum-embedded assessments also provide many more opportunities for examining the emergence of conceptual understanding and proficiency over time, consistent with the trajectories and learning progressions emphasised in the Framework and NGSS.

Challenges remain

Clearly, there are many challenges to using data from classroom-based assessment activities within accountability systems. Different classrooms use different curricula and sequence the treatment of science topics differently both within and between grade levels. District and state assessment data systems cannot accommodate a hodgepodge of different kinds of assessment data gathered differently in every classroom. Maintaining data over time and formatting it in some standard way for submission to the district or state would place a significant burden on teachers and schools. More importantly, meaningful comparisons over time or across schools could not be made if the testing content and conditions varied in unknown and drastic ways.

It is unlikely that these barriers could be overcome without using technology-based assessments. In the case of science learning, technology-based activities within microworlds and simulations that are geared to grade-level science performance expectations and combine learning and assessment in a seamless whole could provide some traction. As noted above, if a principled approach is applied to learning system design, the log file of a student's actions while working with that system can be analysed automatically to yield assessment data. Now that a significant number of states have adopted the NGSS, investment of the resources needed to develop high-quality digital learning and assessment systems becomes more attractive because there are more potential users of such systems. To a large extent, the technology can provide for standard assessment conditions across classrooms and for standard data outputs that can be aggregated across classrooms, schools and districts.

While some researchers envision a time when externally mandated tests are replaced entirely by such classroom technology-based assessments (DiCerbo and Behrens, 2012[22]; Shute et al., 2016[17]) others suggest that some combination of data from externally mandated summative assessments and more detailed information from classroom technology-based assessments is the best path forward (Pellegrino, 2016[21]).

New opportunities

The influence of large-scale testing and accountability systems on classroom instruction has been well researched. Teachers, especially those in schools serving students from low-income backgrounds, have a tendency to narrow what they teach to the content that will be on mandated tests (Dee, Jacob and Schwartz, 2013[23]; Koretz, 2009[24]; Shepard, 2000[25]), (Koretz, 2009[24]). Further, teachers often tend to model their classroom assessments on the item types and formats used in large-scale testing (Shepard, 2000[25]). These very natural reactions to testing and accountability regimes have resulted in science instruction featuring shallow treatment of a large number of topics rather than investigation and formation of connections among core ideas and crosscutting themes in science.

But the zeitgeist is shifting. As described above, the Framework and NGSS were crafted based on a research-informed perspective on the goals for science education and the nature of science proficiency. State adoption of the new science standards is approaching critical mass, and states are looking for new assessment instruments that measure student performance against standards-aligned performance expectations. The standards also are inspiring the development of new science curricula incorporating interactive digital learning resources such as simulations, models and virtual environments (Harris et al., 2015[26]; Roseman et al., 2015[27]).

Policy implications

If properly designed, new digital learning systems can capture a rich set of data documenting students' science proficiencies and conceptual understanding as portrayed in the NGSS. As discussed above, modern statistical modelling techniques, principled approaches to assessment design, and technology affordances will be critical supports for the creation of assessments embedded in digital learning systems. State and national consortia should invest in research and development on the use of science assessments embedded in digital learning systems at scale. New federal education legislation (replacing No Child Left Behind with the Every Student Succeeds Act) has reduced pressure on states to show continually rising test scores, and this factor too helps to create a window for innovation in assessment practices. If states, districts, research and development labs, and commercial developers take advantage of this propitious set of circumstances to design and implement assessments reflecting learning science findings as embodied in the Framework, we can indeed improve not only our understanding of how well students are prepared for the science challenges of our century but also the quality of the instruction we offer them. The creation of such assessment systems would constitute a tremendous contribution of basic learning sciences research to educational practice.

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Part III. Global convergence in science of learning: International perspective

Chapter 19. The Science of Learning Strategic Research Theme at the University of Hong Kong

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This chapter introduces developments in the Science of Learning research at the University of Hong Kong (HKU) from 2008 to 2018 within the context of institutional priorities and international trends. The Strategic Research Theme on Sciences of Learning (SoL-SRT) was initially established at HKU and led by the Faculty of Education in 2008 to provide a platform that brings together researchers in diverse fields to foster interdisciplinary research focusing around pedagogical issues and practices related to learning. Based on experiences of the first five years, the university supported a second phase of funding for the SoL-SRT that is underpinned by a complex system model of human learning as multilevel phenomena (from neural to individual behaviour to institutional and social), and more connected with the global Science of Learning movement and networks.

Introduction

Learning Sciences was established as a Strategic Research Theme (SRT) at the University of Hong Kong (HKU) in 2008 as an institutional initiative, led by the Faculty of Education, to build cross-campus, interdisciplinary research teams and projects that would advance research, policy and practice in education. The first phase, which can be considered as an exploratory phase, ended in 2012. The university subsequently gave further funding support for a second phase of the SRT in 2013 upon approving a major change in the strategic approach and clearer focus of the SRT. The title of the SRT was later renamed to the Science of Learning Strategic Research Theme (SoL-SRT) in early 2015 to better reflect the vision and aspiration of the SRT. This chapter describes the rationale for the establishment of the SRT and the subsequent developments, with a focus on Phase 2 goals, strategies and outcomes. The final section reflects on the potential contributions and challenges that such a university-led Science of Learning initiative faces.

Need for educational policy and practice to be underpinned by interdisciplinary research beyond the educational sciences

Learning lies at the core of all aspects of human performance. Learning transcends educational institutions and underpins a large part of human activities, as individuals, in teams, organisations and communities. Therefore, a better understanding of how people learn would contribute to the improvement of all aspects of human lives. Education, by its nature, is systematic programmes of learning designed by human beings. By definition, learning should be the core business of education. However, even in the field of education, it is only in recent years that people have recognised the significance of learning as an area of research. Various efforts around research on learning have been integrated to form what has been referred to as the "learning sciences", which is an emerging field of scientific inquiry (Bransford, Brown and Cocking, 2000[1]; Sawyer, 2005[2]) building on the educational science disciplines such as psychology, cognitive science and instructional technology.

The SoL-SRT was initially established in 2008 to provide a platform to bring together the diverse research efforts into learning across the university to form a collaborative cross-disciplinary community of researchers, pooling their knowledge to advance the frontiers of our understanding about human learning. Town hall meetings were organised, attracting the voluntary participation of over 60 academics from different disciplines in all of the ten faculties in the university. It was the first time such a diverse gathering of scholars as practitioners of "teaching" come together to create a community to collaborate in the quest to improve our understanding and practices of learning through scientific research.

The SRT at that time was focused on research on understanding how different pedagogical approaches, such as problem-based learning, case-based approaches and project-based learning, advance students' learning. This phase stimulated the cross-fertilisation of ideas on how teaching practices were underpinned by learning theories. It fostered collaboration among colleagues working in different disciplinary areas to address existing learning problems in new ways. For example, Speech Science colleagues were inspired by Sport Science colleagues' sharing on the implicit motor learning paradigm to apply this theory to successfully address motor speech disorders. It also fostered collaboration in tackling new problems, such as developing a focus on oral health literacy. There were also efforts to study the teaching approaches of award-winning teachers, examples include observation in geology and entrepreneurship in engineering. The studies extended to systemic efforts in assessments (e.g. evaluations of projects and group work).

The Faculty of Education, which initiated and hosted the SRT, also played an important role in supporting the systemic territory-wide school curriculum reform in Hong Kong, which started in 2000, by conceptually focusing the dissemination and discourse on learning. All in all, Phase 1 of the SRT has successfully placed learning at the centre stage of education, both within the university and influencing the larger community. It is also evident that the strong educational practice connection and commitment of the Faculty of Education, and its mission to serve and inform policies in diverse educational settings and beyond contributed much to the applied, pedagogical orientation in the SRT's Phase 1 contributions.

In reviewing the Phase 1 outcomes of the SRT, it is clear that we could go further than creating a platform for interaction and collaboration, if our goal is for the cross-disciplinary collaboration to achieve more significant contributions. There needs to be a clear research focus for interdisciplinary collaboration that addresses locally and internationally significant educational concerns that excites and leverages the network of learning-related research expertise emerging from the Phase 1 efforts.

Another strategic direction in formulating the Phase 2 work plan was to establish the role of HKU as the leading national and regional hub for learning-sciences research with broad international connections and recognition. To achieve this, the SRT should serve to facilitate the sharing of information and academic dialogue; initiate and undertake substantial and significant collaborative research; respond to issues of learning locally, nationally and internationally; and explore the implications of the collaborative activity for advancing learning in a wide range of educational contexts and beyond.

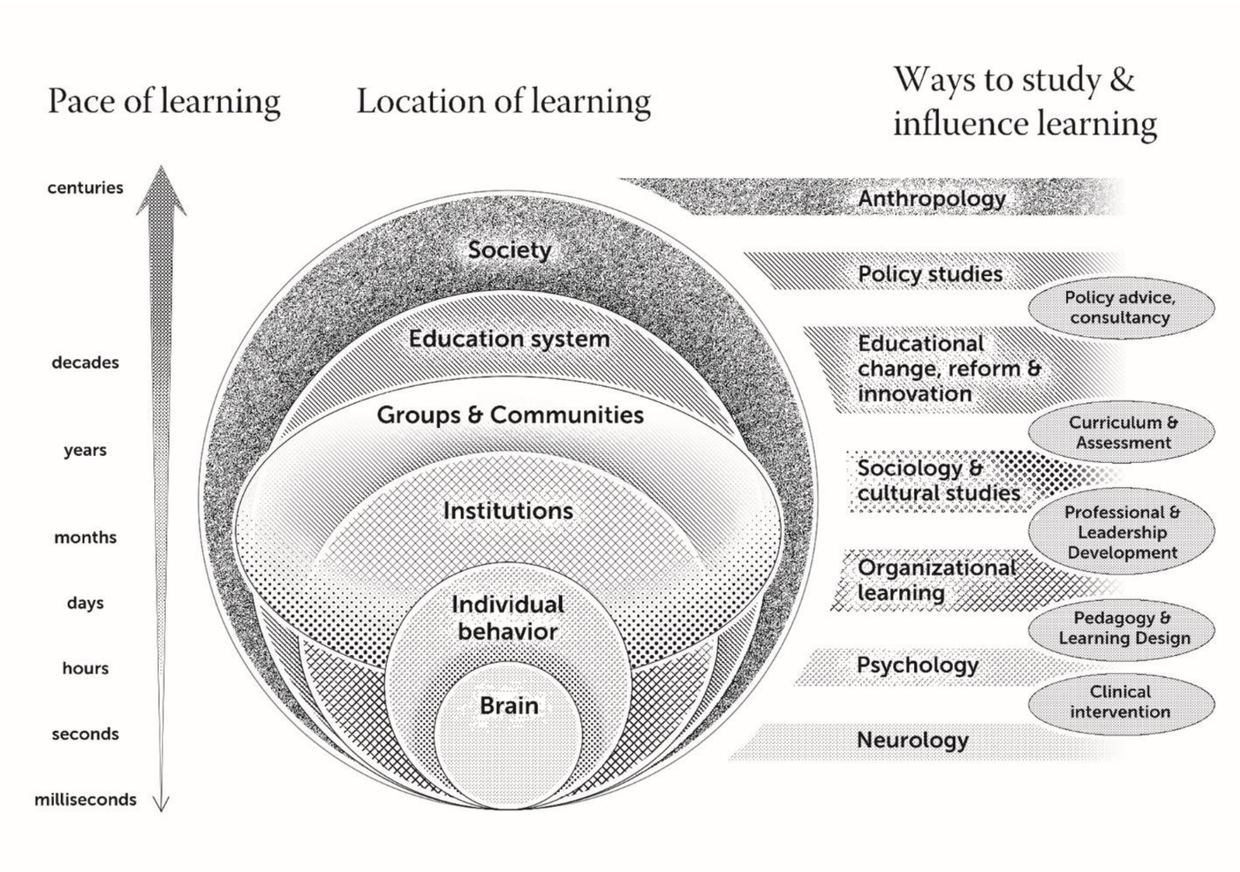
A complex system model of learning as multilevel and interconnected

The vision and mission for Phase 2 of the SRT is underpinned by a complex system model of human learning as multilevel phenomena involving interactions across hierarchically nested levels of learning, including:

- the neural level of learning in different functional areas related to learning
- cognitive and metacognitive aspects of learning at the individual level
- socio-cognitive, socio-metacognitive, socio-cultural, interactional and behavioural aspects of learning at the group level
- learning at organisational and community levels for more effective functioning and change leadership
- sociological, cultural and anthropological studies as studies of learning at the system and societal levels.

As represented in Figure 19.1, the learning taking place at each of these different levels of human learning from neural to societal has been studied using different disciplinary paradigms and research methods. The learning processes at each level takes place within different time spans, from milliseconds at the neural level to centuries at the societal level. Different disciplinary paradigms and methods have contributed to different ways of studying and influencing learning at these different levels, from clinical intervention, to policy advice. While these different disciplinary approaches have advanced our understanding of learning, a major challenge lies in the fact that learning at the different levels are not independent of each other. On the contrary, learning at each of these levels influence and feeds back on each other.

Figure 19.1. A diagrammatic representation of the multilevel hierarchically nested sites of learning and the disciplines that study them at each of these levels



By building interdisciplinary research that spans multi-levels of human learning, we have the opportunity to build explanatory models of learning that are more consilient and powerful. The overall goal for Phase 2 of the SRT is to contribute to theory building and evidence-based policies and practices related to learning through:

> *Developing focused, multilevel, multidisciplinary research programmes to support theory building and evidence-based policy and practice related to learning, building on our strengths in learning research across the University.*

This goal is to be achieved by bringing together researchers across the university from areas such as psychology, cognitive science, neuroscience, language, medicine, engineering, computer science and education.

Research subthemes building on strengths in the faculty and university

Based on the existing strength of the Faculty of Education, three subthemes have been identified as focal areas for developing research programmes and infrastructures:

Subtheme 1:

Integrating neural, cognitive and pedagogical approaches to learning research and educational intervention. This subtheme seeks to stimulate research that could focus on and advance theory, practice and policy in language learning, and building on our established strengths in research that are directly or indirectly linked to learning within a multilingual context.

Subtheme 2:

Learning and assessment. This subtheme has three inter-related foci: 1) enhancing human learning through pedagogical and technological designs that are enacted in authentic, complex learning environments; 2) developing more nuanced understanding of how people learn under different settings through the collection, analysis and visualisation of multi-faceted data of learning processes and outcomes data; and 3) developing better tools and theories of assessment on the basis of research under the above two foci that can benefit learners, parents, education practitioners, policy makers and the wider community.

Subtheme 3:

Building tools and theory for learning across levels. This emerging theme in Learning Sciences research recognises the nature of education and learning as nested, interdependent and multilevel complex phenomena, and that unless research on learning takes account of and addresses the ecological complexities involved, the impact of our research on learning, and indeed our understanding of learning, would be severely limited. Two dimensions of work in this subtheme are relatively promising given our existing strengths: 1) building hierarchical, complex system models of learning in a specific domain of learning; and 2) building models of successful strategic and policy interventions for large-scale learning improvement.

Strategies to leverage international, national and local opportunities

The university and the hosting faculty provide seed funding for research themes recognised as strategic at the university level. With the Phase 2 funding, the SoL-SRT embarked on a number of strategies to realise its vision and mission. The following are the key strategies and their implementation over the past few years.

1. Connecting to and supporting pivotal high-profile international networks and events:

   One prime example of this strategy is the co-organisation of the International Convention on the Science of Learning[1] held on March 1-6, 2014 in Shanghai, in collaboration with the US National Science Foundation, OECD, UNESCO, East China Normal University and Shanghai Normal University. The first four days were an invitation only set of activities involving more than 120 participants, comprising prominent scholars, leaders of international agencies, policy makers and practitioners. We were able to solicit support from the Hong Kong SAR Government to provide funding support for a 15-member delegation to participate in the convention, which included education policy makers, scholars, principals and teacher leaders. The highlight of the convention was a two-day dialogue on "Science of Learning – How can it make a difference?" This event brought our SRT members in contact with a wide network of international and national researchers in the science of learning as well as agencies and institutions that see the contributions and potentials of science of learning research in formal and informal education. It also brought media and public attention to Science of Learning as an area of importance for national development[2]. It is also through organising this convention that the SRT decides to change the name of the SRT to Science of Learning to recognise consilience (Wilson, 1999[3]) as a strength in the multi- and interdisciplinary study of learning.

Another high-profile international event that the SRT leveraged was the opportunity to hold local versions of the Learning Analytics Summer Institutes (LASI) in conjunction with the LASI organised by the Society for Learning Analytics and Knowledge.[3] The SRT collaborated with the Centre for Information Technology in Education (CITE) in the Faculty of Education to host the 2013[4] and 2014[5] LASI-HK. These events provided important opportunities for colleagues in the Faculty of Education to connect with researchers within and outside of the university, as well as colleagues in the IT industry, working in areas related to e-learning and learning analytics.

2. Introducing important advances in research and methodologies in Science of Learning for research capacity building and knowledge exchange:

   During Phase 2, The SRT organises a major Science of Learning event every half-year: Winter Institutes (in January) and Summerfests (in June/July), during which we bring in international scholars to give keynotes, public lectures and conduct methodology workshops. These half-yearly events bring a cross-campus and community-wide focus to research on science of learning, and help to connect us with researchers and practitioners interested in the area. In addition, we take advantage of the availability of the invited scholars to facilitate "incubation workshops" around thematic research topics during which groups of colleagues across campus present their work and research ideas. These events bring together colleagues with similar research focus but may not have been connected to each other due to different disciplinary affiliations.

Brown bag seminars and meeting of the minds series

3. The brown bag seminars, later formalised in the meeting of the mind series, were held monthly to provide opportunities for informal sharing and exploration. It serves as a platform for colleagues to exchange ideas about their completed, ongoing and/or future research, and to explore common interests and opportunities for collaboration within the faculty and across faculties. Typically, each session will have 2 to 3 colleagues speaking for 10-15 minutes about their research, which may share a common theme, phenomenon of interest or methodology. These presentations then serve as stimulations for discussions among speakers and participants, which sometimes result in ideas for further collaboration.

Engaging and soliciting faculty and university leadership support to build crucial research infrastructures and human resource expertise

Given that the SoL-SRT is underpinned by a complex system conceptual framework of learning as happening in hierarchically nested multiple levels, and the aspiration to contribute towards a consilient understanding of learning, we are acutely aware that we lack theoretical and methodological expertise and infrastructure in neuroscientific methods in learning research. Our first step was to build awareness and interest within and beyond the faculty. We were fortunate to receive further funding from the university and the Faculty of Education to invite two prominent scholars from the United States to contribute to our science of learning strategic developments: Professor Laura-Ann Petitto, co-principal investigator and science director of the NSF Gallaudet University Science of Learning Center for Visual Language and Visual Learning (VL2), under the Sin Wai Kin Distinguished Visiting Professor Scheme and Professor Kevin Dunbar, Professor of Human Development and Quantitative Methodology at the University of Maryland under the University Visiting Research Professor Scheme. Both of them came for half-yearly visits from December 2014 to July 2016, each lasting about a month. These recurring visits built sustained rapport with colleagues and provided research mentoring which would not be easily achieved through one-off academic visitors.

Given the heightened awareness of the relevance and importance of neuroscientific understanding of learning to education, the faculty was keen to establish a research lab with neuroimaging equipment to support the study of learning. This was particularly opportune when the Faculty was given the opportunity to redesign and strengthen its physical infrastructure when it was relocated to new spaces as part of a campus development initiative. The Dean was successful in soliciting strategic funding support from the university to set up a neuroscience lab in 2015. Professor Petitto played a key role in providing advice to the formulation of the application, and in the subsequent design of the lab. The university's funding support included not only the construction of the physical laboratory spaces and associated neuroimaging equipment, but also the initial funding for a full professor and supporting staff to set up the Neuroscience for Education Laboratory.

What has been achieved so far

Since the launch of Phase 2 of the SoL-SRT, there have been some significant achievements, the most prominent ones include:

1. Establishment of the Neuroscience for Education Laboratory, which was described in the previous section.
2. Success in researchers in the Faculty of Education being a collaborating research partner on a tri-institutional learning design and learning analytics research and development project funded by the Innovative Technology Fund of the Hong Kong SAR Government, led by a principal investigator in the Computer Science Department of the HK University of Science and Technology, and further collaborators in the Massachusetts Institute of Technology.
3. Success in bidding for a theme-based research project on Learning and Assessment of Digital Citizenship,[6] which is the largest education related research grant ever awarded by the Hong Kong Research Grants Council. The project is an interdisciplinary research project involving researchers from the HKU and the HK University of Science and Technology, in the fields of developmental psychology, e-learning and learning technologies, journalism, paediatrics, psychometrics, computer science and computer engineering, anthropology, history, and higher education.

Looking into the future

The major driving force for the establishment of Science of Learning as a field of research at the HKU was the leadership at the Faculty of Education. The SRT was able to achieve tangible and significant outcomes within a relatively short period of time due to the SRT's successes in taking advantage of the mechanisms and incentives available at the university level to support strategic research development, and the willingness of the faculty to invest additional resources to achieve impact. However, this model of development suffers from uncertainties in securing adequate sustained support for long-term scalable development. We have made a first step in raising awareness and interest among researchers and the community, established some core infrastructure for neuroscience in education research, as well as substantial funding for a five-year project on Learning and Assessment for Digital Citizenship that builds on our established research and development strengths on technology-enhanced learning. For these efforts to achieve substantial scientific research outcomes and to contribute to advances in policy and practice requires significant sustained support at the government and institutional policy and strategy levels.

The science of learning research developments to date have also benefitted in important ways from the opportunities we had to connect with and learn from high-profile international networks and events. These have extended the conceptual and methodological reach of the SRT leadership and members, which have been pivotal to the continuing evolution of the SRT. Looking forward, this is also one area of uncertainty that will affect our further development. To date, international networking events in the Science of Learning have relied heavily on the enthusiasm and support from national and international agencies and institutions. However, there is no standing organisational infrastructure and mechanisms for establishing an explicit vision and negotiating priorities and programme for international collaboration and networking to advance research, policy and practice in the Science of Learning. There is great potential for Science of Learning in Hong Kong to develop and contribute as a national, regional and international hub if given the appropriate support, as demonstrated by the achievements made over the past few years.

Notes

[1] http://solconvention.cite.hku.hk/

[2] http://solconvention.cite.hku.hk/news/

[3] https://solaresearch.org/

[4] http://www.cite.hku.hk/news.php?id=501&category=cite

[5] http://www.cite.hku.hk/news.php?id=518&category=cite

[6] https://ecitizen.hk/

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Chapter 20. Science for Education network: The Brazilian proposal

By

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The new concept of Science for Education is proposed in this chapter, based on the 2D suggestion by Donald Stokes about the Pasteur's quadrant as the golden standard for best efficacy of scientific research. In addition, we introduce and describe the effort to constitute a network of Brazilian leading scientists who perform research translatable to education. A description of the way this network was formed, as well as its proposals and activities are offered. It is expected that the adoption of translational research inspired by education will add virtuously to other policy measures designed to push Brazil and other countries to a more developed educational level.

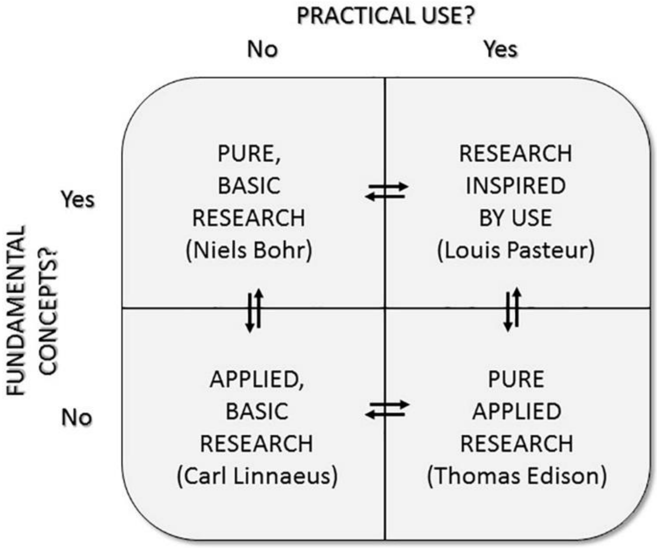
Conceptual baselines: The present

Translational science needs to target education

One of the most important advances in the world, at the transition between the 20th and 21st centuries, has been the consolidation of the concept created by Donald Stokes (Stokes, 1997[1]) on translational research inspired by use, implemented with great success in health and engineering in practically all countries of middle and high GDP. This concept, understood as a bidimensional quadrant connected both to basic, fundamental research and to innovation and development of technologies with a social insertion (Figure 20.1), stimulates the financial agents of scientific research (public and private), as well as scientists themselves, to orient their scientific efforts towards research lines framed by potential applications of social interest.

In the biomedical sciences, for instance, translational research ("from bench to bedside") acquired a consistent set of players – from scientists in universities and research institutions, on one side, to the hospitals and clinics on the other side. Making the bridge between both sides there are small startup and spin-off companies, big pharmaceutical companies that make part of the health industrial complex and governmental systems that formulate public policies in this area.

Figure 20.1. The Pasteur's quadrant



Note: Bidimensional model of scientific research based on quadrants coined after representative, historical names of outstanding scientists who performed research responding to the questions displayed at the axes. Modified from Stokes (1997).

This structure has capillarised in many countries, and orients, for instance, the initiatives of the National Institutes of Health, in the United States, as well as the work of the Oswaldo Cruz Foundation, in Brazil. In general, world population health has advanced during the last decades worldwide, despite inequalities and internal difficulties of each country (WHO, 2015[2]). This evolution can be verified by the general health indicators, such as child mortality, life expectancy and the growing therapeutic possibilities developed for cancer, degenerative diseases and many infectious diseases. A similar rationale may be extended to the exact sciences (mathematics and physics, for instance) and their technological applications.

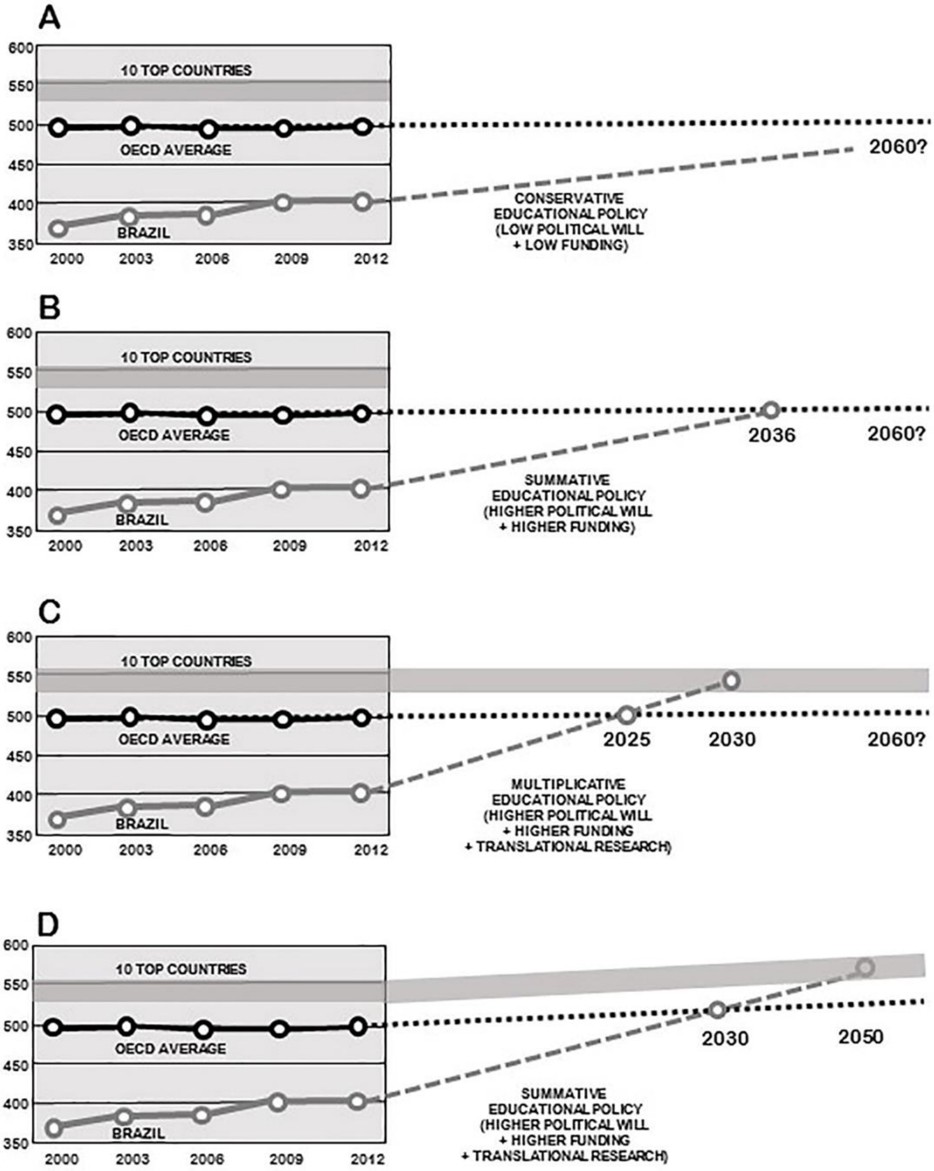
The same, however, has not occurred in education. There is still no clear perception by social agents, even in developed countries, that scientific research is already able to understand how students learn, how teachers communicate with students, which are the possible mechanisms that accelerate learning and teaching, and how this would impact on the economy and social progress of all nations. It is not perceived, as well, neither that technological innovations can be validated with populational studies to rationalise in great scale education at the classroom, nor which socio-emotional competences future citizens should have in order to become inserted in companies more and more automatised and informatised; and many other possibilities. The players who exist in health and engineering have not been connected in education ("from bench to the classroom"), and the humble attempts to link science in universities and research institutions with the schools have not succeeded as much as necessary to multiply initiatives by the public and private economic sectors, as has been the case in health. As a consequence, educational policies are either intuitive or ideological but seldom based on scientific evidence, both for the proposal of new interventions in the school system and for the evaluation of those effectively implemented.

The quality of basic education in Brazil is far below international average

Perhaps because of this omission gap, at least partially, progress of the Brazilian educational indicators has been so modest (OECD, 2013[3]), albeit positive, with maintenance of the gap relative to countries with a more aggressive stance in this particular issue, such as Finland, Poland, Singapore, South Korea and others (Figure 20.2A). In the case of health, public policies not only invest on material improvements (sanitation, hospital attendance, nutritional balance, for instance), but also in science and innovation capable of creating new options, original and competitive in the international scenario (such as new therapies for degenerative diseases and new vaccines for infectious diseases). Differently, in the case of education, investment is exclusively focused on material improvements (more schools, better salaries for teachers), which are necessary, but insufficient to accelerate the growth of Brazilian indicators at rates faster and more competitive, that would allow the country at least to reach the educational development rates of central countries in less time (Figure 20.2B-D).

Perception of this shortcoming is just starting, in Brazil as much as among the international scientific community (Meltzoff et al., 2009[4]; Sigman et al., 2014[5]) albeit just in a few countries that have created incipient initiatives in the form of Science of Learning Centers – among them the United States (NSF, n.d.[6]), Australia (SLRC, n.d.[7]) and China (Asia Society, n.d.[8]). Very recently, in February 2016, the Japanese National Science Council organised a meeting of 12 Academies of Sciences of different countries, including the Brazilian Academy of Sciences, in which one of the approved documents mentions explicitly the need to invest in this aspect of science (Statement, 2016[9]). The document was forwarded as a proposal to the G-8 meeting of international leaders that took place in May 2016 in Japan.

Figure 20.2. PISA: The Brazilian performance and the future



Note: Different prospective scenarios for Brazilian Education. Ordinates depict the PISA average indexes for reading, mathematics and sciences. In A, a conservative scenario with low investment both on educational policies and on funding (conservative educational policies). B shows a more positive scenario in which political will for new educational policies add to increased funding (summative educational policies). C depicts an even more positive scenario, on which translational Science for Education increases even more the Brazilian growth derivative (multiplicative educational policies). Finally, D takes into account the possibility that Science for Education becomes adopted more widely and implemented by most top developed countries, increasing their growth accordingly.

The potential contribution of the different scientific disciplines to education, nonetheless, is becoming undisputable. Gradually, more and more, Neuroscience manages to unravel brain connectivity and the dynamics of functional interaction between the brain, behaviour and the environment (Mišić and Sporns, 2016[10]), as well as the pathways of nervous system development and plasticity (Tovar-Moll and Lent, 2016[11]) that make the brain capable of moulding, adapting and modulating its development in response to external stimuli. Mathematics develops algorithms and models capable of describing and reproducing cognitive processing, a knowledge that transfers to computer science with an aim at creating machines that change their performance by learning from the inputs (Ghahramani, 2015[12]). Moreover, molecular and cell biology advance in understanding the interactions between molecules and cells of different organic systems, during learning and social interchange (Kandel, 2012[13]; Liu et al., 2014[14]). And developmental biology allows understanding embryogenesis and child development and their disorders (Homberg et al., 2016[15]), both their genetic and epigenetic determinants, as well as other environmental influences. This multidisciplinary development has created processes and tools that accelerate learning (especially in the area of educational applications and software of extensive social diffusion), with a high potential of use in great scale. Besides, it has stimulated the work of the Social and Economic Sciences, in the effort to unravel macro- and microeconomic determinants that may underpin public policies (Doyle et al., 2009[16]).

A new scenario ahead: The future

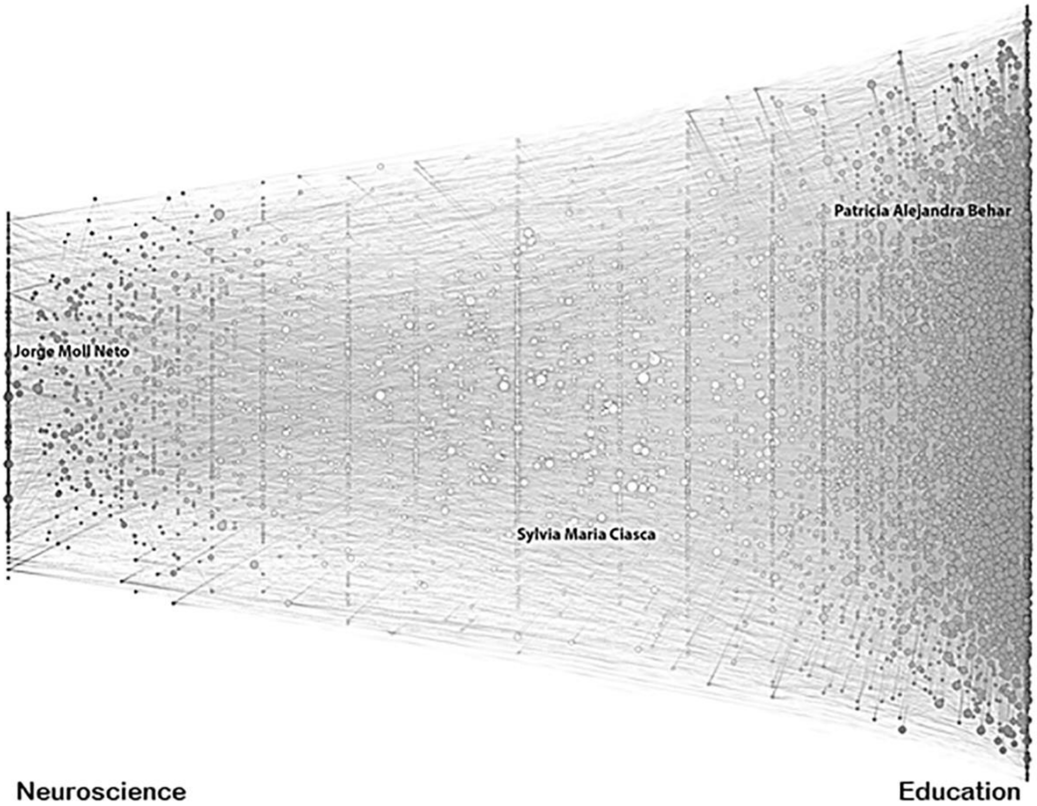
The aforementioned scenario has opened to Brazil a window of opportunity, aiming to create alternatives with this profile, with new laboratories conceived to perform research translatable to education. To give concreteness to this possibility, the proposal here offered for discussion is that new initiatives of funding by public and private agencies adopt Science for Education as a structuring axis. This term is preferred instead of Science of Learning, in order to be maximally inclusive for a broad range of disciplines and to take into consideration not only the mechanisms of learning, but also the environmental contours that facilitate learning and improve education as a social initiative. Education in the social context is a bi-univocal, interactive process, involving someone who acquires skills and/or information, and someone else (or institution) who manages to convey them to the former.

Based on these concepts, a small group of researchers founded at the end of 2014 the Brazilian Network of Science for Education (Rede CpE[1]). Due to the lack of tradition in translational research for education, mentioned above, there was no structured information available on who did – or could do – such kind of work in Brazilian universities and research institutions (Lane, 2010[17]). A survey was planned to identify research groups and researchers with this profile in the whole country, and a data mining tool was used with this purpose (Mena-Chalco and Cesar-Jr, 2009[18]). It was possible to search the Bank of PhD Theses and MSc Dissertations of the Brazilian Ministry of Education, and also the Lattes CV Platform of the Ministry of Science, Technology, Innovation and Communication, using keywords and filters to identify those scientists by their research lines, their connection to graduate programmes and their degree of seniority and productivity.

The first step was the production of keywords identifying areas of interest in Science for Education. We opted initially for 337 keywords connecting neuroscience with education, and these were first used to data mine the Bank of Theses and Dissertations, yielding 607 389 documents. Then, in order to prioritise the established research groups (qualified critical mass of senior researchers), we applied a filter to eliminate supervisors with less than five completed theses or dissertations, arriving at a figure of 7 301 researchers. Using this list, we searched the Lattes CV Platform, filtering homonymous and inactive profiles, and calculating the academic age of these researchers (time interval between the first and the most recent published paper). The resulting number was 4 165 senior researchers. This showed us that Brazil counts currently with at least a critical mass of over 4 000 senior researchers with a potential to inspire their research by educational issues.

The following step was to use algorithms to identify the degree of collaboration between these researchers, since we were interested in identifying those more articulated with their colleagues to perform multidisciplinary studies. The software Gephi was used to visualise the network structure, and to identify nodes and connectors. The resulting number totalised 1 397 names of researchers whose collaboration map, as well as their CV, can be scrutinised directly by the developed software (Figure 20.3). We then focused again on the above keywords in order to achieve an easier approach of the critical mass available. In this context, from a list of 200 research groups led by senior, experienced and productive researchers, we started inviting them to make part of the Brazilian Network of Science for Education.

Figure 20.3. Graph depicting network of Brazilian researchers



Note: A graph depicting the network relations between Brazilian researchers whose work fulfil the proposed keywords. The proof of concept of this study was performed opposing "pure" Neuroscience researchers (at left) with "pure" education investigators (at right). Intermediate dots illustrate the distribution of all others whose work associate neuroscience with education. Some names are given as examples. The same analysis, of course, can be done with different keywords to include other approaches. Modified from Botaro et al. (2016).

A research network in benefit of education

By September 2016, almost 80 groups have accepted to make part of the network. These groups work on different disciplines, namely (in alphabetical order): biochemistry, biology, computer science, economics, epidemiology, genetics, information technology, linguistics, neuropsychiatry, neuroscience, pedagogy, psychology and speech therapy. Some examples of research topics investigated by CpE members are: synaptic plasticity and sleep (Blanco et al., 2015[19]); number transcoding and phonemic awareness (Lopes-Silva et al., 2016[20]); computational modelling of synaptic plasticity (Antunes, Roque and Simoes-de-Souza, 2016[21]); reading comprehension in dyslexics (Kida, Ávila and Capellini, 2016[22]); brain representation of bilingualism (Buchweitz et al., 2012[23]); relation between school performance and future wages (Curi and Menezes-Filho, 2014[24]); machine learning (Garcia, Carvalho and Lorena, 2016[25]); biochemistry of memory (Furini et al., 2015[26]).

Besides the censitary data mining described above, different initiatives were done in the last two years, including national and international meetings (especially the International Symposium on Science for Education in July 2015, a satellite event of the IX IBRO World Congress of Neuroscience, held in Rio de Janeiro, Brazil). In addition, work documents are being prepared by groups of members about topics as literacy, learning disorders, socio-emotional competences and physiological factors that influence learning. (Lent, Buchweitz and Borges Mota, 2017[27])

The mission of the CpE network can be summarised in four main objectives: 1) to perform and foster scientific research in any discipline having a potential to impact educational policies and practices; 2) to establish a bridge between scientists and society at large, especially the educational actors (policymakers, educators, teachers), through a strong presence in communication and diffusion by the media, mainly among the young people; 3) to maintain links and partnerships with universities and research institutions, on the one hand, and the public and private sectors, on the other hand, with an aim to facilitate knowledge production translatable to educational products and processes; and 4) to form human resources of high level (scientists and educators) through university graduate programmes.

The CpE network proposes that objective 1 be implemented by a facility formed by four laboratories, forming a **National Center of Science for Education**, of multiuser characteristics: 1) laboratory of neuroimaging, using MRI and fNIRS technology; 2) laboratory of functional multi-recording, using electroencephalography, eye tracking and different physiological recording; 3) laboratory of mathematical models and digital technologies; and 4) laboratory of animal models. Steps and forms to constitute these laboratories, as well as the necessary budget, their scientific and technical personnel and organisational profiles are being negotiated with private and public sources.

Objective 2 is being fulfilled through a strong effort of science communication through media (material or virtual) created to diffuse the themes of Science for Education among the public in general[2], especially children and youngsters. It would be substantial, as well, in this context, to make the theme a pole of national and international attraction, through the organisation of events (symposia, seminars, workshops) designed to discuss the pertinent topics. In this respect, the CpE network has organised national and international meetings, some more restricted to scientists, other designed to bridge the gap between scientists and educators. In particular, special mention is deserved by the International Symposium of Science for Education, a satellite of IBRO World Congress of Neuroscience, held in July 2015 in Rio de Janeiro. Other important initiatives are work papers on important themes, which are currently being written collectively by CpE members, to be launched by the end of 2016.

Objective 3 will be attained by opening the above-mentioned laboratories to universities or technology developers in order to create and test products and processes of educational interest, that could be utilised in large scale both in schools and within families. The laboratories, in this case, would function as facilities for use both by university actors (basic science) and those linked to the productive sector (startups, spinoffs, big companies).

And finally, objective 4 will have to be gradually tackled, first through the involvement of established graduate programmes, then through the creation of latu sensu programmes and professional and academic graduate programmes (strictu sensu). An intensive programme to attract postdoctoral students will also represent a shorter and more efficient way of forming qualified human resources (scientists and educators).

Conclusion

Science for Education is meant as a translational approach to connect basic science in different disciplines, to educational objectives with strong and fast social repercussion. It has been seldom recognised in the global scenario, what offers a powerful window of opportunity to the countries that take the lead in this movement. It will be fundamental for Brazilian society to foster this new field of national actions in science and technology, and thus accelerate the pace to overcome the severe burden of illiteracy, low level of educational standards among the youth, and as a consequence the low social position of the people and the poor competitive power of Brazilian economy in the international scenario.

Notes

[1] CpE is the acronym of Ciência para Educação, the Portuguese equivalent of Science for Education. http://cienciaparaeducacao.org/eng.

[2] A site at the internet contains technical as well as general information on topics of Science for Education: http://cienciaparaeducacao.org.

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Chapter 21. The Australian Science of Learning Research Centre

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The Australian Science of Research Learning Centre (SLRC), established as a special initiative of the Australian Research Council in 2008, brings together neuroscientists, psychologists and educators to work collaboratively towards improving classroom outcomes. Research at the SLRC is organised into three broad themes: "understanding learning", which focusses on the basic neurophysiological and psychological processes involved in learning; "measuring learning", which aims to develop novel techniques to quantify learning as it occurs dynamically in the classroom; and "promoting learning", which takes the insights of the other themes to formulate novel strategies to improve learning outcomes. SLRC projects have examined such phenomena as mathematics anxiety, the role of feedback and Bayesian approaches to learning and the brain. The chapter also addresses recent scepticism about the utility of using neuroscientific insights to improve classroom learning.

Introduction

The Australian Science of Learning Research Centre (SLRC) was established in 2013 with a mission to investigate how advances in our basic understanding of the neural and psychological processes underlying learning and memory can help improve educational outcomes in the classroom. This is an attractive project from a governmental perspective: it co-opts high profile, state of the art neuroscientific research (e.g. brain imaging, etc.) in the service of addressing a bread and butter concern for every family, i.e. schooling. Several voices, however, have expressed scepticism about whether this political enthusiasm for educational neuroscience will be matched by any tangible benefits, (Bowers, 2016[1]; Bruer, 1997[2]; Cubelli, 2009[3]). This chapter will examine the historical context and the specific aims and achievements of the SLRC. It will also address the sceptical challenges that have been raised to the application of neuroscientific findings to classroom teaching, and attempt to outline how the collaboration between neuroscience, psychology and education can be both productive and mutually beneficial.

History of educational research

While academic interest in teaching methods date back at least as far as the Socratic elenchus (Plato, 1980[4]), modern scientific approaches to pedagogy date from the establishment of education departments in American universities at the end of the 19th century. The pioneers of psychological research into learning – Ebbinghaus (1885[5]), Thorndike (1976[6]), Pavlov (1927[7]) and Skinner (1938[8]) – had a profound effect on scientific approaches to education. However, despite the adoption of these scientific methods from psychology, educational research has been widely criticised for significant conceptual and methodological problems (Higgins and Simpson, 2011[9]; Kaestle, 1993[10]; Lagemann, 1997[11]; Vinovskis, Kaestle and Glennan, 2000[12]). Lagemann (1997[11]), in a wide-ranging review, suggested that "new, more collegial patterns of cooperation" should be encouraged between "scholars of education, scholars in other fields and disciplines, school administrators and teachers" to foster "knowledge-based reform in education". It was in this historical context that initiatives to bring neuroscientific insights to education were first instituted.

The international "Brain and Learning" project at the OECD's Centre for Educational Research (OECD, 2002[13]) involving various international institutions, including the Sackler Institute (United States), University of Granada (Spain), RIKEN Brain Science Institute (Japan) National Science Foundation (United States), the Lifelong Learning Institute (United Kingdom) and INSERM (France), brought together neuroscientists, psychologists and educationalists to foster collaboration in improving teaching and learning. The success of the OECD Brain and Learning project led to the creation of dedicated multi-institutional centres for educational neuroscience in Cambridge (2005) and London (2008). The Australian Science of Learning Centre (SLRC) was established in 2013 as a special initiative of the Australian Research Council.

Australian SLRC

Administered by the University of Queensland, and in partnership with three state education departments and four international universities, the SLRC involves a collaboration between the University of Melbourne, the University of New England, Macquarie University, Flinders University, Deakin University, Curtin University and the Australian Council for Educational Research (ACER). Facilities available at the SLRC include the Educational Neuroscience Classroom at the University of Queensland, which allows electroencephalography (EEG), eye tracking and other psychophysiological measurements on multiple subjects during learning sessions, and the Learning Interaction Classroom at the University of Melbourne which can accommodate 30 students in a conventionally structured classroom equipped with multiple channels of high definition video capture and the ability to collect psychophysiological data from wireless devices. Research at the SLRC is organised into three broad themes: understanding learning, measuring learning and promoting learning. The understanding learning theme focuses on exploring fundamental neurophysiological and psychological processes underlying learning and memory; the measuring learning theme focusses on developing novel techniques to measure learning dynamically, as it is happening, in classrooms and digital learning environments; finally, the promoting learning theme aims to develop novel strategies, on the basis of insights gained in the other themes, to improve learning outcomes.

Minding the gap

Despite the founding of organisations, such as the SLRC, and increasing political and academic interest in educational neuroscience, there has also been notable criticism of this new discipline. Bruer (1997[2]) argues that the conceptual gap between neuroscience and education is "a bridge too far", and that neuroscientific findings cannot make a meaningful contribution to classroom practice. Cubelli (2009[3]) agrees that the aim of educational neuroscience is misguided and proposes that advances in psychology rather than neuroscience are potentially useful to classroom teaching. Nineteen years after Bruer's article (1997[2]), Bowers (2016[1]) reinforces and amplifies its sceptical argument, concluding that that "there is no reason to assume that neuroscience will add any new insights relevant to teaching" and that neuroscience "is (and always likely will be) irrelevant to the task of designing or evaluating instruction". These criticisms, which clearly question the entire raison d'être of the SLRC and educational neuroscience in general, are addressed in detail in the remainder of this chapter, using examples of research from the SLRC and other groups.

One project in the SLRC's measuring learning theme is investigating mathematics anxiety and its effect on high school students (Buckley et al., 2016[14]). Students with mathematics anxiety have previously been shown to have greater activation of the amygdala, a region of the brain strongly implicated in emotional processing, particularly fear learning and memory (Young, Wu and Menon, 2012[15]). The neural circuitry underlying fear conditioning (aversive Pavlovian conditioning) is also a principal focus of research in the SLRC's understanding learning theme. A potential role for the amygdala in mathematics anxiety might be considered a good example, therefore, of how neuroscientific knowledge can contribute to teaching practice. Bowers (2016[1]), however, rejects claims that neuroscientific insights into the role of the amygdala are of any benefit to educational practice: he states that "everyone knows that stressed and fearful students make poor learners", and that therefore information concerning the underlying neural circuitry is "trivial" and can contribute nothing to classroom teaching. This conclusion, however, ignores the fact that improving our understanding of amygdala function may also transform the way we conceptualise interactions between emotion and learning at a psychological level. This new conceptual framework might then facilitate the development of novel techniques to mitigate mathematical anxiety that might not otherwise have become apparent without the neuroscientific input.

Another SLRC project is investigating the partial reinforcement extinction effect (PREE), a paradoxical phenomenon in which the unexpected omission of reinforcement during conditioning leads to persistence of conditioned responding in extinction (Amsel, 1962[16]; Capaldi, 1966[17]). The PREE can therefore be seen as a model for enhanced memory retention. The SLRC PREE project is using immunohistochemistry, in vivo electrophysiology in animal subjects and electroencephalography (EEG) in human subjects during partially reinforced fear conditioning, to identify and characterise the neural responses and brain circuitry mediating the PREE, particularly in the hippocampus and amygdala (Morris, 2015[18]). Although the PREE is difficult to reconcile with standard associative learning models (Rescorla and Wagner, 1972[19]), it is predicted by Bayesian models, which emphasise the role of uncertainty and surprise in learning (Courville, Daw and Touretzky, 2006[20]). The application of Bayesian models of brain function in an educational context has been advocated by several authors (Fischer, 2009[21]). Critics, however, have explicitly rejected the idea that a Bayesian approach to the role of surprise and uncertainty in learning can be usefully applied to classroom teaching. Bowers (2016[1]) states that "the link between Bayesian models of cortical computation and education is hard to see". However, several current classroom projects at the SLRC do indeed lend themselves to a Bayesian interpretation, indicating, therefore, that such criticism is narrow and short-sighted.

A third project is investigating how "confusion" can paradoxically enhance learning by evoking greater engagement with the material to be learned (D'Mello and Graesser, 2014[22]; Pachman et al., 2016[23]). Behavioural responses (e.g. facial expression, facial EMG, eye fixation, posture, learner-computer interactions, etc.) and physiological responses (e.g. skin conductance, heart rate, pupillometry, brain imaging, etc.) are being investigated as potential measures of confusion to help the development of predictive models for real world learning situations (Pachman et al., 2016[23]). Theoretical accounts of confusion relate it to cognitive disequilibrium or dissonance, a psychological theory that proposes that individuals try to minimise conflicts that arise between new information and their existing beliefs (Festinger, 1957[24]). In this view, as a result of the conflict, incoming information undergoes enhanced processing, and the new information is either rejected or incorporated into a revised set of beliefs (i.e. learned). This effect of "confusion" also lends itself very readily to a Bayesian interpretation: according to the Bayesian brain hypothesis, the brain is essentially a statistical prediction machine, continually predicting stimulus events according to a "world model" or "prior beliefs" (Courville, Daw and Touretzky, 2006[20]). Unexpected or surprising events lead to an update of these prior beliefs according to Bayes' rule (Courville, Daw and Touretzky, 2006[20]). Bayesian models could provide, therefore, a unified account of uncertainty and surprise at the neural and psychological level, and of confusion at the classroom teaching level. This account can then drive changes in the response to when students are confused. The key is to be aware of when confusion is apparent and respond accordingly.

In the classroom, it has been apparent for many years that a key determinant of effective learning is feedback (Hattie and Donoghue, 2016[25]). The role of feedback in computer-based, intelligent learning environments (ILEs) is also being investigated at the SLRC, (Holland and Schiffino, 2016[26]; Timms, DeVelle and Lay, 2016[27]). Physiological measures such as heart rate and skin conductance, as well as eye tracking, pupillometry and EEG are being used to dynamically assess and optimise the role of feedback in ILEs. The role of feedback in learning is informed by the psychological and neuroscientific concept of prediction error (Timms, DeVelle and Lay, 2016[27]). Influential models of learning propose that the prediction error "mismatch" between expected and actual outcomes is the primary driver of learning (Rescorla and Wagner, 1972[19]). This role of feedback in learning can again be very easily accommodated by a Bayesian account of the updating of prior beliefs (Courville, Daw and Touretzky, 2006[20]). The conceptual convergence between confusion, cognitive dissonance, feedback, prediction error and the PREE presents an opportunity for the development of novel teaching methods (and teacher feedback), and models to advance our understanding of these learning processes, e.g. using partial reinforcement to elicit or enhance confusion or using feedback to elicit surprise. The multidisciplinary nature of the SLRC allows such potentially convergent models to be studied from the single neuron level (e.g. animal electrophysiology) to the classroom.

Another phenomenon with the prospect of a productive collaboration between education and neuroscience is the testing effect, which refers to the improvement in memory retention that arises from substituting free recall tests for study time during learning (Roediger and Karpicke, 2006[28]). The testing effect has parallels with the neurophysiological phenomenon of reconsolidation, in which retention of conditioned responding can be enhanced or degraded by the unpredictable presentation of unreinforced conditioned stimuli which are hypothesised to return the memory trace to a labile state (Lee, 2008[29]; Pedreira, Pérez-Cuesta and Maldonado, 2004[30]). Critics, however, have rejected claims of parallels (Carew and Magsamen, 2010[31]) between reconsolidation and "the testing effect", arguing that the neurophysiological processes of consolidation and reconsolidation can make no contribution to understanding the effect or its implementation in the classroom (Bowers, 2016[1]). This criticism ignores the fact that reconsolidation is an active area of current research, not only concerning the underlying neural mechanisms, but also the specific protocols and boundary conditions with which it is expressed. For example, labilisation-reconsolidation has been shown to strengthen declarative memory in humans, but only when two or more reactivations are used, and only when cues alone and not cues and responses are used for reactivation (Forcato, Rodríguez and Pedreira, 2011[32]). The possibility for such neuroscientific findings to directly inform classroom practice is clear from this example. It is also quite possible that novel behavioural findings from classroom studies may guide hypotheses and research at the molecular and cellular level. This potentially productive "two-way street" belies Bowers (2016[1]) contention that neuroscientific findings can never make a positive contribution to education.

Another research area receiving increasing interest from educational neuroscience is the parallel between experimental protocols that induce long-term potentiation (LTP) and the spacing effect (Kornmeier and Sosic-Vasic, 2012[33]). LTP is widely regarded as the most promising cellular model of long-term memory storage (Bliss and Lomo, 1973[34]). Experimental studies across a range of species has identified the critical importance of the distributed timing of stimuli in the optimisation of LTP (Scharf et al., 2002[35]). The psychological "spacing effect", which describes the positive effect of distributed practice often over days or weeks on memory retention (Ebbinghaus, 1885[5]), has therefore an obvious parallel with optimal LTP timing (Kornmeier and Sosic-Vasic, 2012[33]). Taking into account the optimal timing parameters required for LTP, Kelley and Whatson (Kelly and Whatson, 2013[36]) conducted an innovative classroom study with high school science students in which traditional lesson structures were replaced with "Spaced Learning". Intensive 20-minute learning periods were separated by 10-minute periods of distractor physical activities, such as juggling or clay modelling. Learning content was repeated after each 10-minute "stimulus-free" gap in order to match the optimal conditions for establishing LTP (Scharf et al., 2002[35]). Kelley and Whatson (2013[36]) report significantly increased learning rates with the LTP-inspired teaching programme, and significantly higher test scores with Spaced Learning compared to traditional methods in a review of course content. The development of the Spaced Learning programme took place over seven years, and crucially involved neuroscientists and psychologists working directly with classroom teachers.

The Spaced Learning project (Kelly and Whatson, 2013[36]) demonstrates how neuroscientific insights into cellular and molecular mechanisms of learning can drive developments in education practice and make a direct and positive impact on classroom teaching. Conversely, insights gained in the classroom application of spaced learning may help to inform future neurophysiological studies of learning, completing a rich and productive "two-way street" of collaboration. For example, significant effects in the classroom relating to the use of multiple stimulus modalities, motivational and emotional manipulations, diurnal and sleep patterns, individual (genetically based) differences in response, etc., could also be studied in animal models. Insights from these studies could then in turn, inform classroom practice, perhaps by suggesting novel approaches or optimal parameters. The multidisciplinary and collaborative structure of organisations such as the SLRC can facilitate this dynamic "two-way street" of communication by bringing together neuroscientists, psychologists and educationalists on common projects.

Critics of educational neuroscience typically rely on creating a sharp divide between psychology and neuroscience. Bowers (2016[1]) argues that psychology has made and will continue to make important contributions to education, principally because it deals in behavioural outcomes, but that neuroscience cannot make a similar contribution since it only deals with neural activity: "changes in brain states are irrelevant for evaluating the efficacy of an instruction". However, such an argument represents a very blinkered and inflexible approach to levels of understanding in science. Bowers (2016[1]) argues that psychological constructs, such as "episodic memory", "semantic memory", "attention", "phonological processing", etc., are valid and useful for improving educational practice. Neuroscience not only attempts to describe the neural circuitry and processes underlying these psychological concepts, but by relating them to neurophysiological phenomena such as LTP, consolidation, reconsolidation, oscillatory coherence, etc., offers the real prospect of radically transforming the psychological concepts themselves. Just as advances in biomedical science have transformed ancient terms such as "humours", "jaundice" and "consumption" allowing more precise medical diagnoses and treatments, so neuroscientifically transformed psychological concepts may facilitate improvements in teaching and learning outcomes.

Conclusion

This chapter has examined in detail a convergence of ideas and projects between single neurons, animal models and the classroom: fear conditioning and mathematics anxiety; uncertainty-dependent PREE and confusion; reconsolidation and the testing effect; and LTP and spaced learning. The Australian SLRC, by bringing together neuroscientists, psychologists and educationalists in collaborative projects, appears well placed to facilitate and exploit these convergences, which offer the prospect not only of improving classroom teaching through novel procedures and materials, but also of providing behavioural data to guide and inform research at the cellular and molecular level. Indeed, learning principals emerging from the SLRC are now being implemented in classrooms in Australia, and longitudinal evaluation of these trials will provide validation. The claim of several critics that this promise is illusory and that neuroscience can never hope to inform educational practice often appears as a narrow and blinkered exercise in circular reasoning, i.e.

neuroscientific data is strictly relevant only to neural activity, and therefore can never be applied to classroom teaching.

An analogy between clinical genetics and educational neuroscience can help to refute the claim that basic neuroscience can never be of relevance for classroom teaching. The discovery of the structure of DNA, or even the determining of the human genome, did not immediately change medical practice. The identification of a particular sequence of DNA base pairs, in isolation, cannot improve the clinical care of a patients. However, determining that a particular DNA sequence codes for a protein that alters the susceptibility for a certain disease can dramatically alter classification, diagnosis, prognosis and treatment (Kelly and Whatson, 2013[36]). Importantly, such advances occur when information about a DNA sequence is directly related to a clinical outcome, i.e. in a cross-disciplinary project. There is every reason to expect, therefore, pace Bruer (Bruer, 1997[2]); Cubelli (Cubelli, 2009[3]) and Bowers (Bowers, 2016[1]), that just as molecular genetics is now revolutionising medical practice, so advances in our understanding of the neural basis of learning and memory will also be able to transform educational practice.

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Chapter 22. Does the science of learning matter?

By

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Society has changed. The change is fundamental, that young people are facing a VUCA future, volatile, uncertain, complex and ambiguous. The conventional role of education, which prepares people for lifelong credentials towards definitive jobs, is being challenged. Young people have to learn to learn, in order to adapt to ever changing circumstances, to survive and thrive, but then we have to know much more about learning, hence the Science of Learning. Meanwhile, the development of non-traditional modes of learning has also placed urgent demands on the understanding of learning. Nonetheless, principles established by Science of Learning have to be made simple and available to teachers and parents.

The foregoing chapters, written by scientists who specialise in the science of learning, have provided many ideas about the newest findings and their implications for policy. In this chapter, I write not as an expert on learning science, or the science of learning, but as a person focused on education policies and reforms. My goal is to fill the gap between macro policies and micro activities on the educational frontline.

Science of learning: Why now?

I regard learning as the core business of education. Yet educators know little about how human learning works. People often ask, “Do we need a science of learning? What difference would it make?”

I believe that learning is a human instinct, but education is not. Education is what adults design for the younger generation to produce systematic learning. As a human design, education inevitably bears with it the economic, social, cultural, political and/or religious inclinations of the time and place the design is made.

The education systems we have today, represented by contemporary schools, started only in the mid-19th Century. There is a common notion that schools as a national system started in 1870 at the enactment of the British Education Act.

It does not mean that there were no schools before that. I have seen Buddhist schools, with hundreds of years of history, in Myanmar, Laos and Cambodia, where children attended as novice monks, and could choose to stay in the monasteries after a certain period of study. The primary activity in the Buddhist schools was memorising and chanting Buddhist scripts. However, contemporary Buddhist schools also teach a full syllabus – Language, Mathematics, Science, English – not very different from any other school. However, one major difference from other schools is that their primary concern is the development of the child. People believe that Buddhist schools are where young people are purified, often seen as an essential stage of personal growth. Young people live under strict discipline and modest living conditions, as a way of training them to be a “good person”.

I have also seen Madrasa by the side of Mosques in Central Asia and other Muslim countries, where students reside and study. Koran is basic to their study, but their curriculum includes Local Language, Arabic, Mathematics, Science and sometimes English. The curriculum is not very different from any other modern school, but the primary aim of the schools is to cultivate a close relationship between the students and Ala.

With different religious accents, in both the Buddhist schools and the Madrasa, the focus is on people. This is rather different from the modern schools. I was inspired by the school in Sturbridge, Massachusetts, in the United States, supposedly a tourist site, where people live the life of 1836. It was among the first schools in the United States. I played a student, attended the class and chatted with the teacher. “Why did young people come to the schools?” I asked. “Oh, they wanted to find a job in Boston. Therefore, they had to learn: to read and write and calculate” was the answer. This is perhaps how contemporary schools were established – for knowledge and skills to fit available jobs in the workforce.

Ever since, education policies in most countries, with only rare exceptions, are formulated as part of an economic discourse. Up until now, people related the development of education to GDP growth and global competitiveness at the national level, and employability at the individual level.

What is wrong with this? The economic discourse perhaps is a perfect match to an industrial society. A typical industrial society prospers on mass production. With the principles of division of labour, by way of carefully designed systems of bureaucracy (i.e. layers and departments in the organisation), people work in departments and tiers. The lowest tier hires labourers where knowledge is not necessary, and they have to handle only very simple skills. Through meticulous designs, the production lines integrate all these simple skills and come up with a very sophisticated product, which then are produced in mass quantities. It is an efficient pyramidal structure of manpower.

The pyramidal model of the organisation also shapes society, which is also a pyramid, and forms a pyramid of knowledge. The army of frontline workers may have little knowledge, but over the tiers, the upper layers require more knowledge. The chief engineer, who designs whole systems, should be the most knowledgeable.

This idea has also shaped the education system. Classification, ranking, screening, selection, have become the social objective of the education system. In a way, the education system, with no shame, is a mechanism that turns human beings into human resources. A more cynical way to say this is: Students are tortured until they confess to the labour market!

It is therefore understandable that people often take schooling for education. In our parts of the world, where population density is high and school choices are plenty, people compete for admissions into the "best" kindergartens, then to the "best" primary schools, "best" secondary schools, then to "good" universities, until they secure a "good" job. Hence, the call for "school readiness" for kindergarten, "college readiness" for high school, all the way to regard colleges for "career readiness".

I have taken a long path of argument in order to delineate a picture of a typical industrial pyramid, but also to illustrate that this kind of pyramid approach is fading away.

In 1999, when Hong Kong launched an overhauling education reform, I decided to look at the workplace in which our students would end up. I did this with the overall belief that the primary aim of education is to prepare young people for their future. I was shocked to find that the workplace has changed so much that it is no longer recognisable. Further tracing the changes, I believe that the change is comprehensive, irreversible and global.

There is no intention to elaborate the changes here, but I will mention the dimensions. First, the economy has changed. Instead of producing for demands, industries now compete to create demands (or, more accurately, to create desire). Second, in doing that, and in the general context of oversupplying, production aims at "less of more" – less quantity, more variety – and produce customised, tailor-made, personalised products and services. Third, in that context, large bureaucracies are gradually giving way to "one-stop" small units; organisations are therefore becoming smaller, flatter, looser and more fragile. Fourth, Individuals are now working under very different conditions. Frontline workers have to face clients, make decisions, design products or solutions. They have to innovate, to shoulder personal responsibility, to run risks, to face ethical challenges, and so forth.

Education versus learning

In other words, people are no longer protected by the organisation. Unlike in a typical industrial society, credentials prepared a young person for a job, and he or she could be in that job for ever. Now, individuals are largely on their own. Credentials no longer give them lifelong guarantees. Overall, obtaining a credential, which is more or less what schools are about, is no longer sufficient preparation for life.

Meanwhile, individuals face all kinds of changes. They change jobs and occupations much more frequently. Even in the same job, the organisation can change or disappear. The product, the clients, the market, the technologies, can all change, and change very rapidly. With the challenge of rapid change, individuals have to survive, to succeed, if not to lead.

They have to learn! They have to learn continuously! And here comes learning!

This is how the overhauling reform in Hong Kong's education came about at the turn of the Century. This is also the line of thinking that underpins noticeable education developments in jurisdictions such as Singapore and Shanghai, and also in systems such as Ontario, Canada. Two elements are essential to make education reforms meaningful – awareness of the change in society and focused attention to learning.

Example 1 – Learning Chinese

I had the opportunity to encounter the Science of Learning, and tried to compare it with practices in education, and I was again shocked. I have come to understand that education, as we have traditionally known it, is not always conducive to learning. At times, what is practiced in education may even hinder learning.

Let me spend some time and explain an example of reform in Chinese language learning, attributable to my colleague Professor Brian Tse. It is not difficult to know that learning of Chinese characters, the rare species of ideographic script in the world, is not easy. One of the typical practices in teaching the Chinese characters is dictation – the teacher gives the students a passage of, say, 100 characters, students are asked to practice and memorise them, for example overnight, and dictate these characters the next day.

Tse queried such a practice in which students rote-learn the passage. The motivation for students is to get high scores from the teacher. This is not how people effectively learn. Instead, Tse used "creative dictation". Each student is given a large piece of white paper, with a theme written in the centre of the paper, such as the word "SPRING" for a second grader (7-8 year-olds). Students are asked to write, around the central theme, words relevant to "Spring". There is no limit to how many they write, but they are expected to produce at least six. Each word (often comprises two to three characters) will be given three marks, and there is no punishment for mistakes or errors. Students are encouraged to identify these words in whatever way they can – from books, from newspapers, from parents – as long as they are relevant, or even remotely associated.

In the end, a student may produce a few dozen words. The example shows a student's work of 53 words, involving over 100 characters. The work the student produces actually represents a mental lexicon, where the characters are mutually associated in meaning.

In the whole exercise, the students are active learners. They compete to do more, and find interest in their work. It is their creation. They own the learning. They learn the characters in context, with meaning. The lexicons are constructed by individual brains and they reflect individual undertaking. Diversity is not only allowed, but also cherished. All these features echo the principles of the Science of Learning described in this book.

Teachers may be sceptical of the method, because there is no control over what characters students will learn. However, clever teachers capitalise on the diversity and ask students to work in groups of five, for example, and select from the five papers, say 30 characters to be recommended to the whole class. The process gives the students the opportunity to examine the total number of characters in a group, and learn from additional numbers from other groups' recommendations, and so on.

The process takes much longer than just a few minutes in traditional dictation, but students are rewarded by their very fruitful learning of a large number of characters. More importantly, they are masters of such a learning process. The most important thing is that their attention is focused on the characters, rather than whether or not they fit the teacher's expectations, and get high scores.

This is an illustration of the power of the Science of Learning when compared with the traditional way of teaching Chinese. There has been basically an analytic paradigm. Students are taught to start with characters, which are building blocks of sentences. And in order to learn characters, they have to start with characters of fewer strokes. However, some of the characters with fewer strokes could be rather remote from children's lives. Yet, some of the characters with many strokes, which are difficult to write, are easy to recognise as a picture, which makes much more sense to the children. Hence the analytic approach goes against students' effective learning processes.

Brian Tse's "creative approach" to learning Chinese extends to reading (starting from stories rather than from simple words) and writing (starting with diaries), with small kids in their very early years of schooling. In the end, children under this approach can master about 2 500 characters, which is sufficient to read newspapers by the end of Grade 2. By Grade 5, they are ready to read thick novels in Chinese.

Tse's method was supported by the Education Bureau and was implemented fully. In the end, Hong Kong's performance in PIRLS – an international comparison of reading literacy – escalated from the world's 14th in 2001 to 2nd in 2005. This further reinforces the government support of the approach. Brian Tse has since become a consultant to governments such as Singapore, Taiwan and Korea.

Example 2 – Teaching of Tort Law

There is another example in higher education, the teaching of Tort Law. The conventional way of teaching a law course is to start with theories, followed by cases, overseas and local, which help to illustrate the theories. My colleague in law, Professor Rick Rofcheski, took a different approach. Rofcheski starts by introducing students to the basic concerns of Tort, and asks them, from the very beginning, to (a) scan newspaper stories, and to do a brief trial analysis of three such stories wherever they found them relevant to Tort, and (b) walk around the city and take photos of whatever they see as relevant to Tort.

This produces a fundamental difference in students' learning. First, they pay attention to local news and local society, which is basic to professionalism in law. Second, they start with a notion that knowledge of law does not start from the book or from the professor, but from social reality.

Rofcheski chooses some cases for illustrative analyses in class. As the course proceeds, students are asked to do more in-depth and elaborate analysis of cases, again on newspapers. Students select a few such analyses for submission as assignment at the end of the course.

People would think such practices are possible only with intensive resources in small classes. To everybody's amazement, the class is with 250 students. A typical scene is students, in groups of five, work together in an assembly hall. With the help of a digital platform, all students are exposed to hundreds of cases analyses, from their own experience, with the teacher's analysis as guidance.

Rofcheski is not keen to mark and correct each and every one of the students' work. He marks only the minimum required for scoring purposes. The final examination is again a real case. The real case may be open to diverse analyses, and there are cases where there is no perfect solution. "The students should always work in reality", Rofcheski emphasised.

The drama surrounding the examination, which is a traditional sit-down examination, as required, is that he opens up discussion of the cases immediately after the examination, right on the spot.

Students love the course. They learn in a lively way and they learn deeply. All the way, through the eight-month course, despite the workload and constant group work, students develop insights into Tort Law, creating views that are sometimes beyond Rofcheski's original thinking.

Again, here, students are the masters of their own learning. Based on their respective observations of social reality, they produce diverse cases for analyses. That way, the concepts (or theories) they learn transcend individual cases. They learn in groups. And, they are assessed not by what they know, but by what they can do.

Gist of learning

So, what is learning? Learning is often taken for granted. People often take education, learning, and even study as interchangeable synonyms. The above two cases refer to education or study in areas that are common in the education system. However, they depart from the teaching conventions in a number of ways.

First, these practices put students into the position of active learners. Second, students learn by creation, producing the mental lexicon and the case analyses. That is, they form concepts or knowledge during the process of creation. These are processes of knowledge construction. Third, they position student learning in real life applications, hence they provide students with fertile soil for self-motivated learning. Fourth, they trust students, tolerate and embrace diversity, and believe that nitty-gritty rights and wrongs are not the major concern. Fifth, they have therefore distracted students from scores and marks, and hence developed learning targets which is not due to teachers' expectations. Sixth, they all emphasise group work.

As I made clear from the outset, I am not a scientist of learning. However, I believe that if learning is the core business of education, then policy workers should also have a sound knowledge of learning. Until now, there are relatively few examples of study on the genuine outcomes of student learning. A large percentage of research on "teaching and learning" often lead to examination scores as proxies of learning. While the notion of "learning outcomes" looms high, measurements about learning outcomes are often based on very narrow concepts defined by formal examinations and scores. The actual learning process, about what goes on in the learner's brain remains a black-box.

There are often subtle assumptions which are not based on any scientific exploration, but are commonly believed. For example, there is still a belief that knowledge is transmitted, like a liquid, into students' heads. There are still TV advertisements where babies would "absorb knowledge like a sponge". There is still the belief that theories should precede practice. Hence, even science teachers may think lessons are for students to learn the theory, and experiments are just to verify theories.

There are also assumptions that go without challenge. For example, asking learners to follow analytical procedures in order to achieve, or, to believe that schools should be "pure" institutions "clean" from social reality, with real experience in society coming after schooling. As a third example, even when group work is introduced in some of the learning sessions, assessments are still based on individual tests.

The foregoing observations do not fall into anyone's specific territory. It is not typical for scientists of learning to detect the deep paradigms that dictate educational practice. It is even more difficult for teachers to reveal what has become part of a culture in education, previously unchallenged and unquestioned.

This has led me to try to summarise what I understand, albeit constrained by my limited knowledge about the Science of Learning. Running the risk of over-simplification or distortion, I have settled on the following general principles:

1. The fundamental
    - Human brains are plastic.
    - Human activities shape the development of human brains.
2. Learning as sense-making and knowledge construction
    - Learning is making sense of the world external to human beings. A new-born girl sees all and hears all, but these impressions make no sense to her. Only after her interactions with others does she begin to form a concept of things she sees and hears. Thereby human beings construct their knowledge.

    Corollaries:

    - Learning happens in individuals' brains, not due to transmission of knowledge from outside.

    Implications for education:

    - Students have to be active learners. They do not learn as passive receivers.
    - Teaching is the act of inducing or facilitating learning.
    - Emphasis should always be on students' learning rather than teachers' teaching.
3. Learning is an individual undertaking.
    - Different people learn differently.
    - Even when facing the same environments and engaging in the same activities, different people learn differently.

    Corollaries:

    - Respect diversity in learning.
    - The same learning processes may yield different learning outcomes.

    Implications for education:

    - The same learning processes may yield different learning outcomes.
    - It is unreasonable to expect uniform learning outcomes from students.
    - Students should be at least given choices of learning paths.
    - Programmes should be so designed to allow maximal personalised learning.
    - Technologies should help create customised learning opportunities.
    - Assessment of learning should move from testing "what students know" to "what students can do".
4. Experience is of critical importance to learning.

- Experiences are activities in which human beings learn. Experiences allow human learning.

Corollaries:

- Human beings learn through diverse experiences.
- Human beings also learn from other people's experience, indirect learning.

Implications for education:

- Students experience should not be confined to listening, writing and responding.
- Students deserve the widest range of diverse experiences.
- Students deserve experiences in classrooms, outside classrooms, beyond schools, in nature, beyond geographic boundaries, and in the cyber space.
- Students deserve experiences in cognitive, affective as well as motor domains.

5. Understanding and application are intertwined.

   - Understanding and application are two sides of the same coin. Knowledge is constructed during practice.

   Corollaries:

   - Understanding and application happen at the same time.
   - Theory and practice are not separate stages of learning.
   - The best learning occurs in context, i.e. with meaningful activities.

   Implications for education:

   - We learn by doing.
   - Students learn not only by knowing, but also by using.
   - Memorising and imitation are essential initial stages of learning, but they are lower levels of learning.
   - Students should be expected to experience real life nature and society as early as possible during the school years.

6. Learning is a holistic process

   - Learning happens as a comprehensive and integrated process. Learning takes place embracing multiple integrated dimensions all happen at the same time.

   Corollaries:

   - Learning does not take place as clear-cut segments of analytic pieces.
   - Intended and unintended, planned and unplanned learning often come together.
   - Implicit learning is commonplace in human life.

   Implications for education:

   - Exploit the wonders of implicit learning.
   - Rigid programmes should be replaced by accommodating platforms of learning.
   - Turn assessment into opportunities of holistic creation by students.
   - Education should induce innovations which are often holistic in nature.

7. Learning is best in groups

- Learning is a matter of social cognition. Human brains echo one another and have multiplying effects on learning.

Corollaries:

- Challenging the basic assumption that the best learning happens among isolated individuals.

Implications for education:

- Discussion is essential at all stages of education.
- Classes should become learning communities, rather than "necessary evils".
- Create all possible opportunities for collaborative work.
- Use technology to enable more extensive and sophisticated collaborative learning.
- Create new ways of looking at "learning outcomes" and "assessments" in view of group work.

Concluding: Scaling up

The question typically facing policy-makers is: Can these practices at the grassroots and at the micro-level be extended to scale? In other words, can the Science of Learning be applied to change a whole system of education?

Hong Kong has tried. In the education reform that was launched in 1999, curriculum reform took centre stage. In a nutshell, the essence of the reform was to totally change the discourse about curriculum, from "subjects" to "Key Learning Areas". "Subjects" are infiltrations of university's academic disciplines, "Key Learning Areas" refer to learning experiences that students deserve. The net results compress the traditional subjects, and create room for new experiences, such as Liberal Studies (which involves broad discussions about society and life), Applied Learning (experience in the workplace) and Other Learning Experiences.

Such changes have to meet challenges from conventions about schooling, about university admissions, and sometimes even parents' expectations. The change in the curriculum touches upon fundamental assumptions about education. Nevertheless, the reform stays on, basically because teachers have undergone a movement from an industrial discourse to a learning discourse about education. However, for real change to mature, this is just the very beginning of a long journey.

Before I end this chapter, I cannot help mentioning the more urgent needs of understanding human learning. They come from many angles. Students learn much more outside the formal school curriculum, and of that we know little. Many emerging technologies meant for student learning are designed by technologists who are not informed by how students learn. Students develop their ideas, norms and beliefs often from the social media, from "consensus" within confined groups, i.e. group-think. Just to mention a few. There are enormous expectations on the Science of Learning.

Presentation of the editors

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