Applying Psychological Science to Higher Education: Key Findings and Open Questions

Samuel T. Moulton
The Harvard Initiative for Learning and Teaching
samuel_moulton@harvard.edu

In this document I summarize key findings and gaps in the science of learning in the hope that such a synthesis will be of use to instructors, students, researchers, and institutional leaders in higher education in general, and at Harvard in particular.

Such an effort is quite challenging, of course, in part because the scholarship of learning cuts across multiple levels of analysis (individual, interpersonal, institutional) and multiple fields (e.g., psychology, economics, educational technology), and because "learning" reflects a heterogeneity of possible changes, from changes in knowledge and behavior to changes in values and preferences. What benefits one type of learning might come at a cost to another, so the scholarship of learning depends on how one conceives of and operationalizes learning. For these reasons and more, there is not one science of learning, but many sciences of learning.

In summarizing extant literature, I focus primarily (but not exclusively) on psychological science, with learning defined in terms of long-term retention, understanding, and transfer. This emphasis is in part pragmatic: we know more about teaching for long-term retention, understanding, and transfer than teaching for creativity, citizenship, or compassion. Another reason for this emphasis is its broad relevance: insight into how individuals remember, understand, and apply knowledge to novel settings is likely relevant to any evidence-based practitioner, even those whose educational efforts are defined differently (e.g., those who teach leadership or lead institutions).

This document is guaranteed to be incomplete and flawed, and intended to facilitate discussion about our collective efforts to advance higher education. For that reason, I have also appended a summary of other researchers' attempts to synthesize the state of our knowledge about learning and teaching, all of which I used in drafting the present review. Of all the sources I've reviewed, I highly recommend John Hattie and Greg Yates's recently published book, *Visible Learning and the Science of How We Learn.*

Draft: April 16, 2014

Key findings and their practical implications

The findings below have a strong evidentiary and theoretical basis, as well as broad relevance to higher education. I have attempted to categorize these findings, in hopes that those categories begin to articulate a map that can guide future work and best practices.

Effective and active learning

Retrieval practice. Educational experiences that require individuals to recall information are more effective than those that that do not.[1,2] For example, in tests of comprehension and inference, undergraduates who read and then tried to recall textbook material learned more than those who read and then actively restudied that content by creating concept maps.[3] Students therefore should quiz themselves instead of merely reviewing course materials, and instructors should offer frequent, low-stakes "assessments for learning" instead of infrequent, high-stakes "assessments of learning".

Spaced practice. Educational experiences that are spaced out over time are generally more effective than those that are spaced closely together in time, though the optimal spacing depends on the intended retention interval.[4,5] For example, if you would like to recall something a week from now, your study sessions should be spaced one day apart; but if you would like to recall something a year from now, your study sessions should spaced be about a month apart.[6] Instructors therefore should adopt pedagogical strategies that encourage their students to space out learning experiences, such as systemically reviewing key concepts and offering cumulative exams.

Interleaved practice. Educational experiences that interleave (or "mix up") related topics or activities are generally more effective than those that segregate studying or teaching by topic or activity.[7,8] For example, in learning the painting styles of different artists, it is better to view interleaved sequences of paintings from different artists (e.g., Monet, Renoir, Monet, Renoir) than blocked sequences of paintings by the same artist (e.g., Monet, Monet, Renoir, Renoir).[9] Similarly, in learning how to calculate the volume of different types of solids, it is better to interleave tutorials and practice problems for different solids than to block tutorials and practice problems of the same solid.[10] The implications of this work are clear: students and instructors should adopt strategies to intentionally "shuffle" related topics or activities, even (or especially) if doing so makes initial learning harder.

---

1 Roediger, H. L. & Karpicke, J. D. (2006). The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science, 1,* 181-210.
2 Karpicke, J. D., & Roediger, H. L. (2008). The critical importance of retrieval for learning. *Science, 319*, 966-968
3 Karpicke, J. D., & Blunt, J. R. (2011). Retrieval practice produces more learning than elaborative studying with concept mapping. *Science, 331,* 772-775.
4 Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin, 132,* 354-380.
5 Carpenter, S. K., Cepeda, N. J., Rohrer, D., Kang, S. H., & Pashler, H. (2012). Using spacing to enhance diverse forms of learning: Review of recent research and implications for instruction. *Educational Psychology Review, 24,* 369-378.
6 Cepeda, N. J., Vul, E., Rohrer, D., Wixted, J. T., & Pashler, H. (2008). Spacing effects in learning a temporal ridgeline of optimal retention. *Psychological Science, 19,* 1095-1102.
7 Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & Willinghamd, D. T. (2013). Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest, 14*, 4-58.
8 Pashler, H., Bain, P., Bottge, B., Graesser, A., Koedinger, K., McDaniel, M., and Metcalfe, J. (2007) *Organizing Instruction and Study to Improve Student Learning* (NCER 2007-2004). Washington, DC: National Center for Education Research, Institute of Education Sciences, U.S. Department of Education. Retrieved from http://ncer.ed.gov
9 Kang, S.H.K, & Pashler, H. (2012). Learning painting styles: Spacing is advantageous when it promotes discriminative contrast. *Applied Cognitive Psychology, 26*, 97-103.
10 Rohrer, D., & Taylor, K. (2007). The shuffling of mathematics practice problems improves learning. *Instructional Science, 35,* 481-498.

Desirable difficulties. Psychologically easy experiences have little educational value, and conditions that promote psychologically effortful processing tend to promote learning.[11] Relatively advanced students actually learn more when reading introductory texts that are slightly incoherent, for example, since these deliberate difficulties present challenges in initial processing that ultimately benefit long-term learning.[12] In situations where students are at risk of glossing over key content, therefore, instructors should employ countermeasures that make learning more psychologically difficult.

Deep processing. The "deeper" the level of mental processing, the greater the learning.[13] For example, in a classic laboratory experiment, participants who judged the meaning of words remembered more of those words than those who judged the sounds of those words, who in turn remembered more than those who merely judged the font of those words.[14] Instructors therefore should engage students in tasks that require them to deeply abstract, analyze, comprehend, or create instead of those that require students to superficially perceive, recognize, calculate, or reiterate.

Transfer-appropriate processing. The effectiveness of a learning experience depends on the psychological overlap between the learning context and the future context in which learning is measured or manifested.[15] For example, what people remember depends dramatically on the retrieval context, including physical location[16], mental state[17], available cues[18], and whether memory is operationalized in terms of recall, recognition,[19] familiarity, priming,[20] or preference[21]. To know whether one pedagogy, instructor, or educational technology is better than another, therefore, it is not enough to merely specify the abstract learning objectives and student population: one should also specify the future reality in which those objectives would be realized for those students.

Deliberate practice. Individuals become experts when they engage repeatedly in practice that is explicitly focused on achieving specific, challenging goals, receive objective feedback and personalized coaching, and reflect meta-cognitively on learning processes and progress.[22] In a classic study on the topic, violinists' expertise was systematically related to the amount of time they spent engaged in this sort of effortful, repetitive, and goal-directed practice.[23] Applied to education, this literature implies that the primary constraint of academic or professional expertise is motivational, and that instruction or studying conditions that promote deliberate practice promote learning.

---

[11] Bjork, R.A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe & A. Shimamura (Eds.), *Metacognition: Knowing about knowing* (pp. 185–205). Cambridge, MA: MIT Press.

[12] McNamara, D. S., Kintsch, E., Songer, N. B., & Kintsch, W. (1996). Are good texts always better? Interactions of text coherence, background knowledge, and levels of understanding in learning from text. *Cognition and Instruction, 14,* 1-43.

[13] Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*, 671-684.

[14] Craik, F. I., & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General, 104,* 268-294.

[15] Morris, C.D., Bransford, J.D., & Franks, J.J. (1977). Levels of processing versus transfer-appropriate processing. *Journal of Verbal Learning and Verbal Behavior*, 16, 519–533.

[16] Smith, S.M., Glenberg, A.M., & Bjork, R.A. (1978). Environmental context and human memory. *Memory and Cognition, 6,* 342-353.

[17] state or mood-dependent memory reference

[18] Tulving, E., & Thomson, D.M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review, 80,* 352-373.

[19] Jacoby, L. L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. *Journal of Memory and Language, 30,* 513-541.

[20] Schacter, D.L. (1987). Implicit memory: History and current status. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* 501-518.

[21] Kunst-Wilson, W. R., & Zajonc, R. B. (1980). *Affective discrimination of stimuli that cannot be recognized. Science, 207*, 557–558.

Ericsson, K. A., Charness, N., Hoffman, R. R., & Feltovich, P. J. (Eds.). (2006). *The Cambridge handbook of expertise and expert performance*. New York: Cambridge University Press

[23] Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100,* 363.

Mental architecture

Limited capacity and cognitive load theory. Our minds have severe, inherent limits on the amount of information they can consciously process at any given time[24,25,26], and this limit varies dramatically based on our experience with and strategies for processing that information[27,28]. Educational conditions that reduce the amount of extraneous information a learner must process—or, more generally, avoid overloading the learner's conscious mental resources—promote learning.[29,30] For example, in using multimedia presentations to teach students about how lighting or hydraulic brakes work, adding background music or sound effects reduces learning.[31] The fact that expert teachers "chunk" information differently from novice learners means that teachers often underestimate the cognitive burden they place on students during instruction.

Dual coding and the multimedia principle. Our conscious minds have separate processors for verbal and visual information[32,33], and students learn better from words and pictures than words alone.[34] For example, on tests of memory and creative problem-solving, students who viewed narrated animations about the mechanics of a bicycle pump learned twice as much as students who only listened to the narrations.[35] Instructors should therefore strive to create visual representations of to-be-learned content, provided such representations are relevant and do not overwhelm students' limited conscious resources.

The curse of knowledge. As humans, we are inescapably egocentric and cannot help but use our own knowledge to impute the knowledge of others.[36,37,38] For example, experience with cell phones worsened individuals' ability to predict how long novice cell phone users would take in completing voicemail tasks, even when a variety of countermeasures were employed.[39] Teachers' expertise in their domains, therefore, can actually interfere with their ability to instruct students, unless they effectively assess student knowledge and misconceptions.

Mind wandering. Humans are limited in our ability to sustain attention over time to any given task and we frequently "mind wander" when trying to do so;[40,41] moreover, such lapses of attention are particularly

---

[24] Miller, G.A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *63*, 81.
[25] Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral And Brain Sciences, 24*, 87-185
[26] Simon, H.A. (1974). How big is a chunk. *Science, 183*, 482-488.
[27] Luria, A. R. (1968). *The mind of a mnemonist: A little book about a vast memory*. Harvard University Press.
[28] Anders Ericsson, K. (2003). Exceptional memorizers: made, not born. *Trends in Cognitive Sciences, 7,* 233-235.
[29] Sweller, J., Van Merrienboer, J. J., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10,* 251-296.
[30] Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist, 38*, 43-52.
[31] Moreno, R., & Mayer, R. E. (2000). A coherence effect in multimedia learning: The case for minimizing irrelevant sounds in the design of multimedia instructional messages. *Journal of Educational Psychology, 92,* 117.
[32] Clark, J. M., & Paivio, A. (1991). Dual coding theory and education. Educational psychology review, 3(3), 149-210.
[33] Baddeley, A. (1992). Working memory. *Science, 255*, 556-559.
[34] Mayer, R. E. (2009). *Multimedia learning*. New York: Cambridge University Press.
[35] Mayer, R. E., & Anderson, R. B. (1992). The instructive animation: Helping students build connections between words and pictures in multimedia learning. *Journal of Educational Psychology, 84*, 444.
[36] Nickerson, R. S. (1999). How we know—and sometimes misjudge—what others know: Imputing one's own knowledge to others. *Psychological Bulletin, 125,* 737-759.
[37] Camerer, C., Loewenstein, G., & Weber, M. (1989). The curse of knowledge in economic settings: An experimental analysis. *The Journal of Political Economy, 97,* 1232-1254.
[38] Birch, S. A., & Bloom, P. (2004). Understanding children's and adults' limitations in mental state reasoning. *Trends in Cognitive Sciences, 8,* 255-260.
[39] Hinds, P. J. (1999). The curse of expertise: The effects of expertise and debiasing methods on prediction of novice performance. *Journal of Experimental Psychology: Applied, 5,* 205-221.
[40] Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science, 315*, 393-395.
[41] Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*, 946.

prevalent during passive classroom instruction, and likely increase in frequency over the course of lectures.[42] For example, undergraduates probed at various points during psychology lectures reported mind wandering one third of the time.[43] Some evidence suggests that instructors can encourage student attention by interspersing period of lecturing with brief quizzes, activities, or discussion.[44,45]

Limited self-control. Willpower can be an exhaustible resource, such that efforts to control behavior or impulses in one domain temporarily deplete individuals' ability to do so in another domain (an effect known as "ego depletion").[46] For example, students given a difficult essay-writing task were more likely to cheat on a subsequent, unrelated task, compared to students given an easier essay-writing task.[47] Although an essential and desirable part of teaching is to challenge students, this research implies that instructors should avoid putting students in situations that require prolonged period of self-control without explicitly helping student develop effective coping strategies.

Planning fallacy. People tend to underestimate how long they will take to complete a task.[48,49] For example, undergraduates asked to estimate how long it would take them to complete their senior theses estimated that it would take approximately half as long as it actually took.[50] To the extent possible, students and instructors should therefore undertake countermeasures against the planning fallacy, e.g., mentally simulating all the component steps necessary to complete a given task.[51]

Overconfidence. Humans are chronically overconfident: on the average, we think that we far better than the average on a multitude of personal, academic, and professional qualities.[52] For example, college students asked to estimate their exam scores immediately after taking an exam overestimated their performance to the extent that the worst performers thought they were above-average.[53] Since domains in which objective feedback is frequent (e.g., athletics) show relatively little overconfidence, one implication of this research is that instructors should provide students with frequent opportunities for such feedback, perhaps in conjunction with self-assessments.

Motivation and persistence

Achievement motivation. People are more intrinsically motivated, face challenge better, enjoy themselves more, and sometimes perform better when they have mastery (or learning) goals compared to when they

---

[42] Szpunar, K. K., Moulton, S. T., & Schacter, D. L. (2013). Mind wandering and education: from the classroom to online learning. *Frontiers in Psychology*, 4, 1-7.
[43] Lindquist, S. I., & McLean, J. P. (2011). Daydreaming and its correlates in an educational environment. *Learning and Individual Differences, 21*, 158-167.
[44] Szpunar, K. K., Khan, N. Y., & Schacter, D. L. (2013). Interpolated memory tests reduce mind wandering and improve learning of online lectures. *Proceedings of the National Academy of Sciences, 110*, 6313-6317.
[45] Killingsworth, M. A., & Gilbert, D. T. (2010). *A wandering mind is an unhappy mind. Science, 330*, 932-932.
[46] Baumeister, R. F., Bratslavsky, E., Muraven, M., & Tice, D. M. (1998). Ego depletion: is the active self a limited resource? *Journal of Personality and Social Psychology, 74,* 1252.
[47] Mead, N. L., Baumeister, R. F., Gino, F., Schweitzer, M. E., & Ariely, D. (2009). Too tired to tell the truth: Self-control resource depletion and dishonesty. *Journal of Experimental Social Psychology, 45,* 594-597.
[48] Kahneman, D., & Tversky, A. (1979). Intuitive prediction: Biases and corrective procedures. *Management Science, 12,* 313–327.
[49] Bueler, R., Griffin, D., & Ross, M. (2002). Inside the planning fallacy: The causes and consequences of optimistic time predictions. In T. Gilovich, D. Griffin, & D. Kahneman (Eds.), Heuristics and biases: The psychology of intuitive judgment (pp. 250-270). Cambridge: Cambridge University Press.
[50] Buehler, R., Griffin, D., & Ross, M. (1994). Exploring the "planning fallacy": Why people underestimate their task completion times. *Journal of Personality and Social Psychology, 67,* 366.
[51] Taylor, S. E., Pham, L. B., Rivkin, I. D., & Armor, D. A. (1998). Harnessing the imagination: Mental simulation, self-regulation, and coping. *American Psychologist, 53,* 429.
[52] Dunning, D., Heath, C., & Suls, J. M. (2004). Flawed self-assessment implications for health, education, and the workplace. *Psychological Science in the Public Interest, 5,* 69-106.
[53] Ehrlinger, J., Johnson, K., Banner, M., Dunning, D., & Kruger, J. (2008). Why the unskilled are unaware: Further explorations of (absent) self-insight among the incompetent. *Organizational Behavior and Human Decision Processes, 105,* 98-121.

have performance (or outcome) goals.[54] For example, individuals given feedback while playing a pinball game reported and demonstrated more motivation to play the game when that feedback was framed as an opportunity to learn as opposed to an opportunity to perform.[55] To encourage such mindset and goals, instructors can adopt a range of strategy, from framing feedback in terms of learning to allowing students more control over their coursework.

Social conditions that affect motivation and well-being. The degree to which individuals are intrinsically motivated and flourish psychologically depends on the degree to which their social conditions promote feelings of competence, autonomy, and connectedness.[56] In one study, for example, students' interest in word games was reduced when the researchers' imposed an external deadline on the task.[57] To the extent possible, therefore, instructors should promote students learning and well-being by promoting their sense of competence, autonomy, and social connection.

Setting and specifying goals. The presence and specificity of individuals' goals can help motivate, direct, and sustain a variety of desirable behaviors, including those that advance learning and teaching.[58] Generally speaking, instructors design courses and assignments more effectively when they set specific instructional goals from the outset ("backward design"),[59] and students learn more, regulate their learning more, and enjoy learning more when they possess specific goals.[60] For example, undergraduates were three times as likely to follow through on their intention to complete a difficult project (e.g., write a term paper) over the winter holiday break when they also specified a plan for completing that project.[61] Although there are likely other attributes of effective goals (most notably: measurable, meaningful, proximal, challenging), the research is clear that students learn more when they or their instructors specify the intended outcomes of educational experiences.

We value what we own or create. People tend to more highly value products that they invest effort to create (the "IKEA effect") or that they possess (the "endowment effect"), compared to identical products they do not create or possess.[62,63] For example, participants who constructed boxes or origami were willing to pay two to three times as much for those items than those who did not construct them.[64] Because students value work that they effortfully create or consider their own, instructors should consider designing experiences that capitalize on these effects in ways that promote motivation and learning (e.g., student projects with multiple opportunities for feedback).

Social learning. Humans are fundamentally social beings whose learning is motivated and guided by other people. [65,66] The most powerful demonstrations of the social nature of academic motivation come from work

---

[54] Grant, H., & Dweck, C. S. (2003). Clarifying achievement goals and their impact. *Journal of Personality and Social Psychology, 85,* 541-553.
[55] Elliot, A. J., & Harackiewicz, J. (1994). *Goal setting, achievement orientation, and intrinsic motivation: A mediational analysis. Journal of Personality and Social Psychology, 66,* 968-980.
[56] Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist, 55,* 68-78.
[57] Amabile, T. M., DeJong, W., & Lepper, M. R. (1976). Effects of externally imposed deadlines on subsequent intrinsic motivation. Journal of Personality and Social Psychology, 34, 92-98.
[58] Locke, E. A., & Latham, G. P. (2002). Building a practically useful theory of goal setting and task motivation: A 35-year odyssey. *American Psychologist, 57*, 705–717.
[59] Wiggins, G. & McTighe, J. (1998). *Understanding by design.* Alexandria, VA: Association of Supervision and Curriculum Development.
[60] Locke, E. A., Shaw, K. N., Saari, L. M., & Latham, G. P. (1981). Goal setting and task performance: 1969–1980. *Psychological Bulletin, 90,* 125-152.
[61] Gollwitzer, P. M., & Brandstätter, V. (1997). Implementation intentions and effective goal pursuit. *Journal of Personality and Social Psychology, 73,* 186.
[62] Ariely, D. (2010). *The Upside of Irrationality: The Unexpected Benefits of Defying Logic at Work and at Home.* New York: Harper
[63] Norton, M., Mochon, D., & Ariely, D. (2012). The IKEA effect: When labor leads to love. *Journal of Consumer Psychology, 22*, 453-460.
[64] Morewedge, C. K., Shu, L. L., Gilbert, D. T., & Wilson, T. D. (2009). Bad riddance or good rubbish? Ownership and not loss aversion causes the endowment effect. *Journal of Experimental Social Psychology, 45*, 947-951.
[65] Dunbar, R.I.M. (1998). The social brain hypothesis. *Evolutionary Anthropology, 6,* 178–190.
[66] Tomasello, M. (2009). The cultural origins of human cognition. Harvard University Press.

on sense of belonging, the basic human motivation to feel socially connected. Student motivation and performance can be derailed by *belongingness uncertainty,* a state this is particularly common in stigmatized groups (e.g., racial minorities). Thus, creating a sense of belonging can increase academic motivation and achievement (grades), especially for minority students. [67] Even minimal cues to social connectedness (e.g., the belief that a task will provide opportunities for positive social interaction) can enhance achievement motivation. [68]

Myths and misconceptions

Finally, it's worth noting that our intuitions or common beliefs about learning and teaching are oftentimes wrong (and oftentimes for revealing reasons). For example, here are some counter-intuitive but compelling conclusions from educational psychology:

- There is no evidence that teachers should design instruction based on students' learning styles.[69]
- Pure discovery learning—in which students are given little to no guidance or direct instruction—is ineffective.[70]
- Expertise is largely the product of effort and motivation, as opposed to giftedness.[71]
- Expertise is extremely domain-specific, e.g., chess experts are not any better at checkers, and vice versa.[72]
- The notion that instruction in one academic discipline (e.g., Latin) confers students with a general cognitive benefit—i.e., the concept of "far transfer," or the doctrine of formal discipline—is highly suspect.[73]
- Despite abundant experience as students, our judgments about effective methods of studying and instruction are frequently wrong, particularly when we use ease of processing to infer learning.[74]
- With some exceptions for elementary and special education, neuroscience adds very little value to our practical understanding of learning and teaching.[75,76]
- As indirect measures of learning, student ratings of instruction are neither worthless nor particularly useful.[77]

---

[67] Walton, G. M., & Cohen, G. L. (2007). A question of belonging: Race, social fit, and achievement. *Journal of Personality and Social Psychology, 92,* 82-96.
[68] Walton, G. M., Cohen, G. L., Cwir, D., & Spencer, S. J. (2012). Mere belonging: The power of social connections. *Journal of Personality and Social Psychology, 102,* 513-532.
[69] Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning styles concepts and evidence. *Psychological Science in the Public Interest, 9,* 105-119.
[70] Mayer, R. E. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist, 59*, 14.
[71] Howe, M. J., Davidson, J. W., & Sloboda, J. A. (1998). Innate talents: Reality or myth? *Behavioral and brain sciences, 21,* 399-407.
[72] Ericsson, K. A., Charness, N., Hoffman, R. R., & Feltovich, P. J. (Eds.). (2006). *The Cambridge handbook of expertise and expert performance.* New York: Cambridge University Press.
[73] Barnett, S.M., & Ceci, S.J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. Psychological Bulletin, 128, 612–637.
[74] Bjork, R.A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe & A. Shimamura (Eds.), *Metacognition: Knowing about knowing* (pp. 185–205). Cambridge, MA: MIT Press.
[75] Bruer, J. T. (1997). Education and the brain: A bridge too far. *Educational Researcher, 26,* 4-16.
[76] Willingham, D. (2012, Nov 26). Neuroscience applied to education: Mostly unimpressive. http://www.danielwillingham.com/1/post/2012/11/neuroscience-applied-to-education-mostly-unimpressive.html
[77] Moulton, S.T.. (2012). The science of student ratings. http://vimeo.com/45665193

Open questions and knowledge gaps

Gaps in our knowledge of learning and teaching exist for different reasons. Some research questions remain open in spite of evidence. Although dozens or even hundreds of articles have been published on such topics, those collective research efforts have failed in terms of theoretical coherence, methodological rigor, or empirical convergence. For example, in spite of over one thousand recent studies on the relative effectiveness of online, blended, and face-to-face instruction, the lack of experimental control, small sample sizes, and potential experimenter biases in this literature limits meta-analysts from making strong inferences.[78]

Other research questions—or the contexts in which they are evaluated—are relatively new, and therefore remain open for lack of evidence. Example topics here include the effectiveness of machine-graded essay feedback, interventions that enhance self-regulated learning, and the nature of students' learning objectives.

Of the limitless set of open research questions, how can we decide which ones to invest in? Three criteria which I have found helpful in prioritizing research questions are:

I. ***Impact.*** In terms of generalizability (across populations and contexts), relevance (to current questions and efforts), practicality (to learners and teachers), and credibility (to researchers and scholars), how might the research impact how people think about and practice education?

II. ***Tractability***. Can we address the research question with available data sources, research methods, and resources?

III. ***Enhanced interdependence***. Does the proposed research benefit greatly from input across multiple disciplines, perspectives, or levels of analysis and, by doing so, enhance our research community's interdependence?

With this said, here are some topics and questions that stand out for me as both substantially unresolved and worth researching:

Foundational challenges

Authentic measures of learning and teaching (This set of problems is perhaps the hardest and most important, in that our ability to conduct research depends on our ability to authentically measure outcomes.)

- How can we authentically and effectively measure student learning, preferably using methods of assessments that both measure and promote learning, generalize across content and context, and are scalable?
- To what degree can well-established measures of conceptual knowledge and expert-like thinking in the physical sciences inform assessment for other disciplines, particularly interpretative or humanistic ones?
- Are there more valid, useful, and empirically-grounded alternatives to Bloom's Taxonomy for conceiving of and measuring learning objectives? If so, how can such a framework be used to design instruction and assessment, and to measure learning outcomes?
- How can we improve course evaluations?

---

78 Means, B., Toyama, Y., Murphy, R., Bakia, M., & Jones, K. (2009). Evaluation of evidence-based practices in online learning: A meta-analysis and review of online learning studies. *U.S. Department of Education Office of Planning, Evaluation, and Policy Development*. http://www2.ed.gov/rschstat/eval/tech/evidence-based-practices/finalreport.pdf

Translating science into practice

- How can students and instructors systemically integrate and implement evidence-based practices? For example, in designing large lecture courses, how can faculty jointly incorporate the benefits of retrieval practice, spaced practice, and interleaved practice?
- For any principle of learning or evidence-based practice, what are the boundary conditions or moderating variables? For example, how should assessment strategies depend on learning objectives?
- In students and instructors, what individual differences matter for learning and teaching? In what ways do students' perceptions of or reactions to failure or frustration, for example, determine their academic behavior?
- What are other educational implications of foundational findings and principles from the social sciences? For example, how can notions from evolutionary dynamics (e.g., principles and models underlying cooperation) inform learning and teaching?

Extending studies of learning beyond knowledge acquisition and application

- For outcomes that go beyond memory, comprehension, performance, and transfer, what practices and principles can guide instruction and studying? How can we help students gain insight into their own intellectual or professional interests, for example?
- To what extent is learning implicit, and how should instruction, studying, or assessment depend on whether intended learning is explicit or implicit?

Instructional methods and modalities

Distinctive value of different modes of instruction

- What is the distinctive value of residential education, what is the distinctive value of online education, and how can these two educational paradigms be blended together to optimize student learning?
- What sort of material can be best delivered through pre-recorded videos or other online media, and how can instructors best take advantage of in-class time?
- What instructional methods or student behaviors are optimal for the long-term retention of knowledge, and how do they depend on instructional paradigm (e.g., MOOC vs seminar)?

Unintended consequences of various modes of teaching and grading

- By making certain things much easier, like watching lectures at a later date, does technology have unexpected adverse effects on student learning? Put differently, is there a tradeoff between technological ease and "desirable difficulty"?
- How does teaching to broader audiences impact instruction and learning?
- How do various assessment practices or properties (e.g., absolute versus relative grading, test difficulty, amount of feedback provided) interact with the effectiveness of instruction and student motivation?

Student engagement, motivation, and behavior

The "nudge" variables that most increase and decrease student engagement

- How do we use game design principles to create engaging online and offline learning experiences?

- Does increasing students' sense of social presence and sense of belonging increase their motivation and engagement?
- How and when does feedback increase student engagement?
- In what ways does student engagement depend on the live nature of instruction? For example, are students more engaged when they are led to believe that an online video is live (as opposed to pre-recorded)?

Ways to effectively track student engagement and learning over time

- To what extent we infer students' engagement or motivation from their interactions with online course materials or platforms, their patterns of course performance, their out-of-class behavior, or their classroom behavior?
- How can we systematically measure students' physical and mental presence during instruction, and how do such measure predict learning?
- How can we measure student behavior over longer periods of time than one course (or even one degree)?

Effective ways to leverage social/group dynamics

- How can social forces be leveraged to increase both the productivity and ethicality of student behavior?
- How do the social experiences of students, both inside and outside the classroom, affect their academic motivation and mindset? For example, does the experience of collaborating, or the experience of being a leader, change whether a student views his or her learning experience as competitive or cooperative, whether they see the class as a unified group pursuing a common goal?
- From the perspective of learning and teaching, when is competitiveness pernicious and when helpful?
- What social activities outside the classroom that have a measurable impact on learning and how can they be better supported or encouraged?
- Does the actual or perceived presence of other students affect engagement? For example, are students able to sustain attention better during instruction in the synchronous presence (physical or virtual) of others?

Influences on studying and academic decision-making

- When are students' actual behaviors inconsistent with their desired behavior (e.g., procrastination, cramming), and what can be done to align the two?
- How can study behaviors and self-regulated learning be improved?
- How and how well are students making academic decisions? For example, does the availability of course difficulty ratings lead students to select courses that they ultimately find less satisfying?
- How do students spend their time outside of class, and how does their allocation of time relate to their academic goals, behaviors, decisions, and outcomes?

What specific tools or technologies increase student engagement and effective study behaviors

- Which tools or technologies help students regulate their learning, and which disrupt learning?
- Can we use technology to test the effectiveness of self-regulatory activities, such as setting and using assignment reminders, tracking one's own learning progress, and peer accountability systems?

Appendix A: Twenty-five heuristics for promoting learning

Contiguity effects	Ideas that need to be associated should be presented contiguously in space and time.
Perceptual-motor grounding	Concepts benefit from being grounded in perceptual motor experiences, particularly at early stages of learning.
Dual code and multimedia effects	Materials presented in verbal, visual, and multimedia form richer representations than a single medium.
Testing effect	Testing enhances learning, particularly when the tests are aligned with important content.
Spacing effect	Spaced schedules of studying and testing produce better long-term retention than a single study session or test.
Exam expectations	Students benefit more from repeated testing when they expect a final exam.
Generation effect	Learning is enhanced when learners produce answers compared to having them recognize answers.
Organization effects	Outlining, integrating, and synthesizing information produces better learning than rereading materials or other more passive strategies.
Coherence effect	Materials and multimedia should explicitly link related ideas and minimize distracting irrelevant material.
Stories and example cases	Stories and example cases tend to be remembered better than didactic facts and abstract principles.
Multiple examples	An understanding of an abstract concept improves with multiple and varied examples.
Feedback effects	Students benefit from feedback on their performance in a learning task, but the timing of the feedback depends on the task.
Negative suggestion effects	Learning wrong information can be reduced when feedback is immediate.
Desirable difficulties	Challenges make learning and retrieval effortful and thereby have positive effects on long-term retention.
Manageable cognitive load	The information presented to the learner should not overload working memory.
Segmentation principle	A complex lesson should be broken down into manageable subparts.
Explanation effects	Students benefit more from constructing deep coherent explanations (mental models) of the material than memorizing shallow isolated facts.
Deep questions	Students benefit more from asking and answering deep questions that elicit explanations (e.g., why, why not, how, what-if) than shallow questions (e.g., who, what, when, where).

Cognitive disequilibrium	Deep reasoning and learning is stimulated by problems that create cognitive disequilibrium, such as obstacles to goals, contradictions, conflict, and anomalies.
Cognitive flexibility	Cognitive flexibility improves with multiple viewpoints that link facts, skills, procedures, and deep conceptual principles.
Goldilocks principle	Assignments should not be too hard or too easy, but at the right level of difficulty for the student's level of skill or prior knowledge.
Imperfect metacognition	Students rarely have an accurate knowledge of their cognition, so their ability to calibrate their comprehension, learning, and memory should not be trusted.
Discovery learning	Most students have trouble discovering important principles on their own, without careful guidance, scaffolding, or materials with well-crafted affordances.
Self-regulated learning	Most students need training in how to self-regulate their learning and other cognitive processes.
Anchored learning	Learning is deeper and students are more motivated when the materials and skills are anchored in real-world problems that matter to the learner.

Reproduced from Winne, P. H., & Nesbit, J. C. (2010). The psychology of academic achievement. *Annual Review of Psychology, 61*, 653-678. http://www.annualreviews.org.ezp-prod1.hul.harvard.edu/doi/pdf/10.1146/annurev.psych.093008.100348

Appendix B: Hattie & Yates' (2014) Nine Principles of Learning

1. Explanations of human learning in terms of native ability, talent, or intelligence are severely constrained by one consistent and persistent finding: that substantial investments of time, energy, structured tuition, and personal effort are all required in order to develop mastery in all knowledge domains investigated. Notions such as talent, ability, and intelligence exist as useful descriptive terms. But they are not sufficient to explain learning or achievement.

2. We naturally learn from exposure to information detected by our senses. But to increase our knowledge base, this information has to possess a level of organization which matches how our minds are structured and organized—and our minds change in how we structure and organize as we age.

3. Our mind has severe and inherent limitations, as built-in characteristics. When these limitations are reached, through experiences or depletion, deep and meaningful processing becomes impossible, and only shallow learning will occur from that point.

4. Human learners benefit enormously from social examples, from directed instruction, and from corrective feedback. Learning from exposure to the information provided by other people represents a fundamental aspect underpinning human adjustment and evolution; the more expert these 'other people' are in understanding the progression of learning, the more effective is the learning.

5. We will exert strong efforts to perform at a high level, calling upon hidden and guarded reserves of effort, once we become confident that worthwhile goals are achievable in the short term.

6. Short-term goals are highly motivating. But they may exist in conflict with other long-term values we harbor. Hence, one of the key aspects of personal development and happiness involving learning and activating strategies that enable us to control impulses and delay gratification.

7. Leaners possess human traits requiring a consistent level of maintenance. These include ego esteem needs, as well as the need to synchronize actions with other people within the immediate social context.

8. Neurologically, we possess a remarkably social brain. This evolved organ becomes a tool enabling us to react to the physical presence of others, to learn from information they dispense, and to become familiar with the characteristics of up to 150 individuals within our wilder social world.

9. Within both public and professional domains, fallacious ideas of human learning continue to be promoted despite being contradicted by available scientific opinion and evidence. Many such fallacies are potentially destructive and driven by false promises, pecuniary interests, or an over-reliance on anecdotes.

Reproduced from Hattie, J., & Yates, G.C.R. (2014). *Visible learning and the science of how we learn*. Routledge: London and New York. http://books.google.com/books?id=VdhAAQAAQBAJ

Appendix C: Ambrose et al.'s (2010) Seven Principles of Learning

1. Student's prior knowledge can help or hinder learning.

2. How students organize knowledge influences how they learn and apply what they know.

3. Students' motivation determines, directs, and sustains what they do to learn.

4. To develop mastery, students must acquire component skills, practice integrating them, and know when to apply what they have learned.

5. Goal-directed practice coupled with targeted feedback enhances the quality of students' learning.

6. Students' current level of development interacts with the social, emotional, and intellectual climate of the course to impact learning.

7. To become self-directed learners, students must learn how to monitor and adjust their approaches to learning.

Reproduced from Ambrose, S.A., Bridges, M.W., DiPietro, M., Lovett, M.C., & Norman, M.K. *How learning works: Seven research-based principles for smart teaching*. John Wiley & Sons, Inc: San Francisco. http://books.google.com/books?id=_mjNjwEACAAJ

Appendix D: Institute of Education Sciences' Practice Recommendations

Space learning over time

- Identify key concepts, terms, and skills to be taught and learned.
- Arrange for students to be exposed to each main element of material on at least two occasions, separated by a period of at least several weeks—and preferably several months.
- Arrange homework, quizzes, and exams in a way that promotes delayed reviewing of important course content.

Interleave worked example solutions with problem-solving exercises

- Have students alternate between reading already worked solutions and trying to solve problems on their own.
- As students develop greater expertise, reduce the number of worked examples provided and increase the number of problems that students solve independently.

Combine graphics with verbal descriptions.

- Use graphical presentations (e.g., graphs, figures) that illustrate key processes and procedures. This integration leads to better learning than simply presenting text alone.
- When possible, present the verbal description in an audio format rather than as written text. Students can then use visual and auditory processing capacities of the brain separately rather than potentially overloading the visual processing capacity by viewing both the visualization and the written text.
- Connect and integrate abstract and concrete representations of concepts.
- Connect and integrate abstract and concrete representations of concepts, making sure to highlight the relevant features across all forms of the representation.

Use quizzing to promote learning

- Prepare pre-questions, and require students to answer the questions, before introducing a new topic.
- Use quizzes for retrieval practice and spaced exposure, thereby reducing forgetting.
- Use game-like quizzes as a fun way to provide additional exposure to material.

Help students allocate study time efficiently

- Conduct regular study sessions where students are taught how to judge whether or not they have learned key concepts in order to promote effective study habits.
- Teach students that the best time to figure out if they have learned something is not immediately after they have finished studying, but rather after a delay. Only after some time away from the material will they be able to determine if the key concepts are well learned or require further study.
- Remind students to complete judgments of learning without the answers in front of them.
- Teach students how to use these delayed judgments of learning techniques after completing assigned reading materials, as well as when they are studying for tests.
- Use quizzes to alert learners to which items are not well learned.
- Provide corrective feedback to students, or show students where to find the answers to questions, when they are not able to generate correct answers independently.

Ask deep explanatory questions

- Encourage students to "think aloud" in speaking or writing their explanations as they study; feedback is beneficial.
- Ask deep questions when teaching, and provide students with opportunities to answer deep questions, such as: What caused Y? How did X occur? What if? How does X compare to Y?
- Challenge students with problems that stimulate thought, encourage explanations, and support the consideration of deep questions

Reproduced from Pashler, H., Bain, P., Bottge, B., Graesser, A., Koedinger, K., McDaniel, M., and Metcalfe, J. (2007) *Organizing Instruction and Study to Improve Student Learning* (NCER 2007-2004). Washington, DC: National Center for Education Research, Institute of Education Sciences, U.S. Department of Education. http://ncer.ed.gov.

Appendix E: Utility of Major Learning Techniques

Technique	Utility	Description
Practice testing	High	Self-testing or taking practice tests over to-be-learned material
Distributed practice	High	Implementing a schedule of practice that spreads out study activities over time
Interleaved practice	Moderate	Implementing a schedule of practice that mixes different kinds of problems, or a schedule of study that mixes different kinds of material, within a single study session
Elaborative interrogation	Moderate	Generating an explanation for why an explicitly stated fact or concept is true
Self-explanation	Moderate	Explaining how new information is related to known information, or explaining steps taken during problem solving
Summarization	Low	Writing summaries (of various lengths) of to-be-learned texts
Highlighting/underlining	Low	Marking potentially important portions of to-be-learned materials while reading
Keyword mnemonic	Low	Using keywords and mental imagery to associate verbal materials
Imagery for text	Low	Attempting to form mental images of text materials while reading or listening
Rereading	Low	Restudying text material again after an initial reading

Reproduced from Dunlosky, J., Rawson, K.A., Marsh, E.J., Nathan, M.J., and Willingham, D.T. (2013). Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest, 14*, 4-58. http://www.psychologicalscience.org/index.php/publications/journals/pspi/learning-techniques.html

Appendix F: Mayer's Principles for the Design of Multimedia Instruction

Goal	Principle	Definition
To reduce extraneous processing	Coherence	Reduce extraneous material
	Signaling	Highlight essential material
	Redundancy	Do not add on-screen text to narrated animation
	Spatial contiguity	Place printed words next to corresponding graphics
	Temporal contiguity	Present corresponding narration and animation at the same time
To manage essential processing	Segmenting	Present animation in learner-paced segments
	Pretraining	Provide pretraining in the name, location, and characteristics of key components
	Modality	Present words as spoken text rather than printed text
To foster generative processing	Multimedia	Present words and pictures rather than words alone
	Personalization	Present words in a conversational styles rather than a formal style

Reproduced from Mayer, R. E. (2008). Applying the science of learning: evidence-based principles for the design of multimedia instruction. American Psychologist, 63(8), 760. http://ezp-prod1.hul.harvard.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=pdh&AN=2008-15778-032&site=ehost-live&scope=site