THREE COGNITIVE SCIENCE PRINCIPLES EVERY STATS TEACHER SHOULD KNOW

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Education practice continues to become more evidence-based, driving development of practices that align with research on learning and cognition. In fact, major education companies employ teams of cognitive scientists to help build their products and services according to decades of empirical research on memory, attention, and other cognitive processes. This is a welcome development, but the biggest impact on learning will come from teachers' application of cognitive science principles in their own classrooms. Thankfully, empirical research has established core principles that are both widely applicable and easy to implement. Here we review three: cognitive load management, memory retrieval practice, and metacognitive awareness. Each is summarized in nontechnical terms followed by guidelines for classroom application, including an easy-to-implement example.

INTRODUCTION

Learning statistics (or anything else) in a formal setting extends across cognitive, social, and emotional domains. We focus on the cognitive domain here and discuss three principles of cognition that, when employed by classroom teachers, can improve learning. These principles have been established through decades of cognitive science research, and the goal of this review is to provide practical summaries of these principles so that instructors might incorporate them into their teaching.

Cognitive science sits at the intersection of psychology, neuroscience, computer science, anthropology, and linguistics and is concerned with how people process sensory stimuli, allocate attention, form and retrieve memories, make decisions, comprehend language, and more. Researchers study these areas empirically through behavioral and neuroimaging techniques, cognitive ethnography, and computational modeling, and the use of experimental design and statistical analysis is widespread. Of relevance here is the line of research focused on formal learning as applied to statistics education.

The three cognitive science principles we will review are:

- *Cognitive load management*: Minimizing extraneous demands on a learner's capacity to process multiple pieces of information at once.
- *Memory retrieval practice*: Strengthening memory by attempting to recall information, as opposed to restudying presented information.
- *Metacognition*: Fostering monitoring and control of one's own cognitive processes.

COGNITIVE LOAD MANAGEMENT

Imagine attending a conference mixer and meeting a new group of people. You shake each person's hand and exchange names, only to forget each person's name as you introduce yourself to the next person. You spend the entire conversation trying to remember somebody's (anybody's!) name, which succeeds only in distracting you from the conversation. You excuse yourself from the group, remembering just one name and essentially nothing of what was said.

How can you be presented with so much information, desperately attempt to understand and remember that information, but come away with nothing? Perhaps unsurprisingly, there is a limit to how much information the human mind can process at one time (Miller, 1956). Each of us has limited *working memory* capacity, where working memory refers to the system that actively maintains information so that it can be manipulated, combined, and if necessary, encoded into *long term memory* for later retrieval, somewhat like the RAM on a computer. This system encompasses both visual and auditory sensory modalities (Baddeley, 1992) and is an emergent property of interactions between perceptual brain regions and the prefrontal cortex, which underlies cognitive control (D'Esposito, 2007). Don't feel bad about forgetting all those names; the average brain reaches its information processing capacity surprisingly easily.

Working memory burden during a cognitive task is referred to as *cognitive load*, and it has been studied extensively in the context of formal learning. Much cognitive load is intrinsic to learning, but

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learning settings or materials can induce *extraneous* cognitive load that only interferes with learning. Instructors can take steps to minimize students' cognitive load (Sweller, Ayres, & Kalyuga, 2011):

- Provide novices with worked examples and other forms of scaffolding, gradually removing such instructional supports as learners advance.
- Avoid simultaneous presentation of redundant or superfluous information (e.g., presenting a slide of text while also paraphrasing the slide aloud).
- Separate related streams of information into visual and auditory modalities when possible (e.g., describe a graph with spoken language instead of a written caption).
- Help learners integrate related information that is separated by time or space.

Example of Implementing Cognitive Load Management

We now provide an example application of the final item above: spatial integration of information. Imagine an instructor teaching students how to interpret mosaic plots. She has explained several examples and now present students with the plot in Figure 1 and ask this question: Which rating is more common in Drama movies, PG-13 or R?

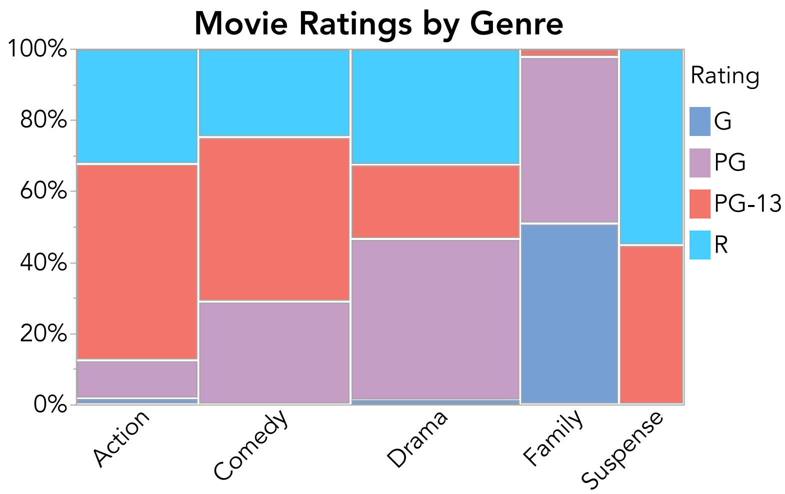

Figure 1: Example of extraneous cognitive-load due to legend placement

Answering this question simply requires comparing two plot area sizes. Yet to do so, a student must consult the legend, encode the color mapping in the visual component of working memory, shift visual attention to the plot, visually parse the plot with the same brain system that is trying to retain the color mapping information, and finally visually compare the areas of two graph regions to reach an answer (R). Doing all this may seem trivial to the instructor, but for novices still learning to interpret a mosaic plot, the extraneous cognitive load of holding the mapping in working memory may push them over their working memory capacity limit, resulting in difficulty answering a seemingly simple question.

Consider the improved mosaic plot in Figure 2, in which the rating information is overlaid on the plot. Identifying and comparing the relevant plot areas does not require the color mapping to be held in working memory, eliminating the extraneous cognitive load induced by Figure 1. Note that the process of interpreting the plot is the same; the instructor has only eliminated a working memory burden that is irrelevant to the learning objective. Simple changes like this may seem inconsequential, but they make a measurable difference in fine-grained cognitive processes that influence learning outcomes. Compounded over an entire semester (or education!), small changes can make a large impact.

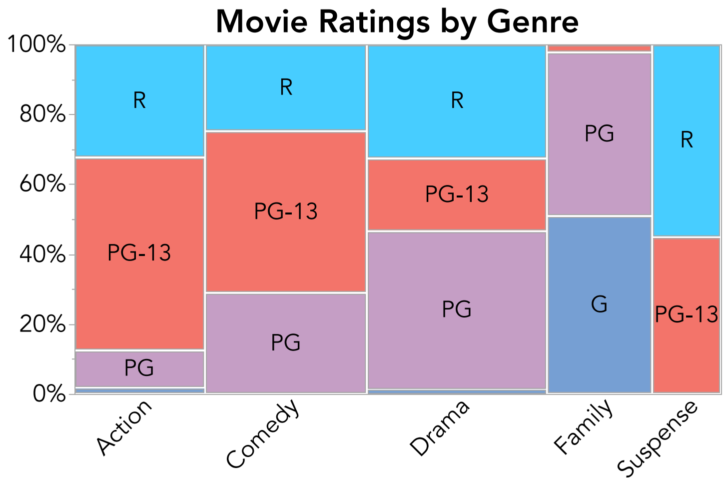

Figure 2: Example of eliminating the extraneous load in Figure 1 via spatial integration.

MEMORY RETRIEVAL PRACTICE

Consider this unfortunate (and not uncommon) scenario: A diligent student spends hours studying for an exam, only to get a poor grade. They come to office hours upset and confused, saying, "I reread the lecture notes twice and reviewed every homework problem. I felt like I understood everything perfectly. How could I do so poorly?!" You reply with advice for the next exam: "Try doing some extra practice problems from the back of the book."

According to research, this is very good advice. Many studies have shown that *retrieval practice*—actively trying to recall facts, definitions, or problem-solving procedures from memory—strengthens long-term memory and knowledge transfer more so than restudying or being re-exposed to that same information (Roediger & Butler, 2011; Roediger & Karpicke, 2006). This finding is perhaps the most widely researched and reliably replicated in the cognitive science of learning, with empirical evidence spanning a range of academic materials and student populations. Neuroimaging studies have found some evidence that the benefits of retrieval practice are associated with activation levels in brain regions underlying semantic memory encoding and information retrieval and inhibition (Van den Broek, et al., 2016). Retrieval practice may in a very general sense be like exercise for your brain.

Retrieval practice can take many forms, including multiple-choice or short answer quizzes, practice problems, flash cards, concept diagramming, or anything else requiring a learner to retrieve information from memory, as opposed to be re-exposed to that information in some external form. Note that retrieval practice extends beyond rote recollection of facts to include problem-solving, which requires learners to retrieve and use both conceptual and procedural memories. Whichever form of retrieval practice you implement, following several guidelines will help maximize the learning benefit. For a helpful summary of these guidelines, see www.retrievalpractice.org (no affiliation with the author). Retrieval practice should:

- be moderately difficult. Trivially easy retrieval provides no added benefit to learning.
- interleave different concepts or topics. Switch concepts or procedures from question-to-question instead of practicing the same concept or procedure multiple times in succession.
- be spaced out in time. Teach a concept or topic, then provide retrieval practice for it repeatedly throughout the remainder of the term.
- be low-stakes, preferably ungraded. The focus should be on learning, not assessment.
- followed by correct answer feedback. Feedback helps retrieval practice confer a benefit even if the memory retrieval itself was unsuccessful (i.e., the student answers incorrectly).

Example of Implementing Memory Retrieval Practice

Recall that retrieval practice can take many different forms. Choose those that best suit your course, students, and learning goals. In this example, an instructor ends each lesson with a short, ungraded multiple-choice quiz. She periodically reiterates the value of retrieval practice to the learners and that these quizzes are purely learning activities. Today's lesson covered measures of central tendency and when to use each. The instructor presents the multiple-choice question in Figure 3 and asks students to register their responses in some fashion (e.g., via web app).

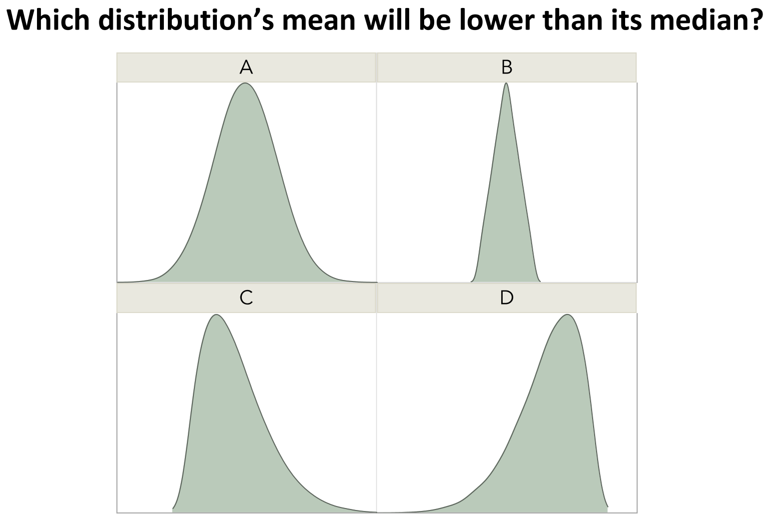

Figure 3: Example retrieval practice prompt

Answering the question in Figure 3 requires successfully recalling several important concepts and their relationships: mean, median, and skew. It may be somewhat difficult for a number of students, but the benefits of retrieval practice depend on a degree of difficulty. After students have submitted their answers, the instructor provides the correct answer and an explanation. After this question, she presents two more questions, one targeting an important concept from earlier in the week, and another targeting one from the beginning of the course. This allows her to space out retrieval practice across the term and to interleave different concepts in a single quiz. All of this takes valuable minutes at the end of each class, but the instructor can be confident that the learning gains are worth the sacrifice.

METACOGNITITION

Consider again that student who did poorly on an exam despite feeling like they understood everything perfectly. This overestimation of knowledge–often called the *illusion of knowing*–is a common contributor to learning shortcomings (Bjork, Dunlosky, & Kornell, 2013). After all, why keep working at something if you believe you've already achieved your goal? Here, the student reread content and experienced the subjective feeling of understanding, but he then failed to realize that this understanding might not extend to successful problem-solving on an exam. We shouldn't completely fault this student, though: he at least attempted to gauge his own understanding. This "thinking about thinking" is called *metacognition* (Flavell, 1979), and it is critical to successful learning.

Metacognition can be broken down into two distinct phases: monitoring cognitive processes and subsequently controlling further cognition and action appropriately (Lai, 2011). A student who engages in *self-regulated learning* is one who demonstrates both facets of metacognition. Neuroimaging studies suggest that metacognitive activities engage prefrontal cortical regions associated with high-order representations of the thoughts of one-self and others (Vaccaro & Fleming, 2018), and research in schools has demonstrated that metacognition is teachable and associated with improved learning outcomes (Dignath & Büttner, 2008; Lundie & Goldner, 2019).

For many students, successful metacognition doesn't simply happen on its own. There are numerous ways in which educators can promote metacognition (Lai, 2011):

- Explicitly teach metacognitive strategies, when to use them, and why they work.
- Model metacognitive awareness and strategies by "thinking aloud" while problem solving.
- Use prompting to encourage cognitive monitoring and control. For example, "What was your thought process?" or "What concept do you think you should study more?"

- Use exercises, such as concept mapping, that force students to be explicit about their conceptual understandings.
- Use collaborative or cooperative learning exercises that include metacognitive discussion prompts to expose students to each other's thinking.

Example of Fostering Metacognition

Nearly any learning activity can have a metacognitive component added to it. Consider the retrieval practice quiz discussed with respect to Figure 3. To add a metacognitive component, the instructor could ask students to register their responses individually, then turn to a neighbor and explain why they chose the answer they did. This collaborative exercise encourages each student to introspect into their own reasoning and exposes them to their peers' thought processes, potentially surfacing gaps in understanding or, more fundamentally, demonstrating what awareness of one's own thought processes even looks like. (With respect to the latter: It is important for the instructor to verbalize their own thought processes so that all students are sure to be exposed to good examples.) This peer discussion prompt addresses the monitoring component of metacognition; to address control, the teacher could end each quiz by asking each student to, according to their quiz performance, write down one concept they understand well and one they should study more. Adding such prompts takes only a few minutes of class time while helping students engage in metacognition and learn metacognitive strategies they can use to achieve self-regulated learning on their own.

CONCLUSION

The three cognitive science principles detailed here are evidence-based, applicable across the curriculum, and relatively easy to implement. These are not the only principles of cognition that are important to learning, nor is cognition the only facet of learning that matters. (In fact, many would argue that without motivation and social support, the cognitive side of learning is moot.) Still, adding a little cognitive load management, memory retrieval practice, and metacognitive support to classroom teaching can improve learning outcomes with relatively little effort on behalf of the instructor.

REFERENCES

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556-559.

Bjork, R. A., Dunlosky, J., & Kornell, N. (2013). Self-regulated learning: Beliefs, techniques, and illusions. *Annual Review of Psychology*, *64*, 417-444.

D'Esposito, M. (2007). From cognitive to neural models of working memory. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1481), 761-772.

Dignath, C., & Büttner, G. (2008). Components of fostering self-regulated learning among students. A meta-analysis on intervention studies at primary and secondary school level. *Metacognition and Learning*, *3*, 231-264.

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive–developmental inquiry. *American Psychologist*, *34*(10), 906.

Jarrold, C., & Towse, J. N. (2006). Individual differences in working memory. *Neuroscience, 139*(1), 39-50.

Lai, E. R. (2011). Metacognition: A literature review. *Always Learning: Pearson Research Report, 24,* 1-40.

Perry, J., Lundie, D., & Golder, G. (2019). Metacognition in schools: what does the literature suggest about the effectiveness of teaching metacognition in schools?. *Educational Review*, *71*(4), 483-500.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81.

Roediger, H. L., & Butler, A. C. (2011). The critical role of retrieval practice in long-term retention. *Trends in Cognitive Sciences*, *15*(1), 20-27.

Roediger III, H. L., & Karpicke, J. D. (2006). The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science*, *1*(3), 181-210.

Sweller, J., Ayers, P. & Kalyuga, S. (2011). *Cognitive Load Theory*. New York: Springer.

Vaccaro, A. G., & Fleming, S. M. (2018). Thinking about thinking: A coordinate-based meta-analysis of neuroimaging studies of metacognitive judgements. *Brain and Neuroscience Advances*, *2*, 1-14.

Van den Broek, G., Takashima, A., Wiklund-Hörnqvist, C., Wirebring, L. K., Segers, E., Verhoeven, L., & Nyberg, L. (2016). Neurocognitive mechanisms of the "testing effect": A review. *Trends in Neuroscience and Education*, *5*(2), 52-66.