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TEACHER-READY RESEARCH REVIEW

Improving Student Learning From Lectures

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Lecturing is a primary mode of teaching in higher education. A majority of college teachers lecture extensively, and many more lecture at least some of the time in their classes. Good lectures are viewed as well-organized presentations that stimulate student interest and maintain student attention. But, research demonstrates that lecturing is less effective than active modes of instruction. To produce better learning from lecture, educators need to promote deeper cognitive engagement with the subject matter before, during, and after lectures. This teacher-ready research review proposes strategies to help students acquire essential background knowledge before lecture, manage cognitive overload and engage in deep learning processes during lecture, and elaborate, consolidate, and retain what they learn after lecture.

Keywords: lecturing, active learning, teaching strategies, deep learning

Lecturing is deeply embedded in the culture of teaching in higher education. During the last 25 years, national surveys have documented that a majority of college teachers lecture *extensively*, and many more lecture at least some of the time in their classes. Of course, lecturing is not the sole teaching method; a majority of college teachers also incorporate other types of learning activities such as discussion and small group work in their classes (Eagan et al., 2014). Many college classes may combine lecture with other teaching strategies, but the fact remains that lecturing is still a primary mode of teaching in college classes (Stains et al., 2018; Wieman, 2017).

Good lectures are viewed as well-organized presentations that stimulate student interest and learning. But are good presentations sufficient to support robust student learning? Abundant research provides strong evidence that they are not. In a meta-analysis of 225 studies of student learning in STEM courses, researchers found that *straight lecturing* is less effective than *active* modes of teaching. Students in active learning classes scored about half a letter grade higher on examinations and concept inventories than in lecture only classes, and the failure rate in active learning classes was 22% compared to 34% in lecture only classes (Freeman et al., 2014; Wieman, 2014).

These differences in student performance reflect a significant lecture–learning gap. Given the prevalence of lecturing, college educators must be concerned about how to narrow the gap and produce better learning from lecture.

Traditional Perspectives on How to Improve Lectures: TED Talk Versus Less Talk, More Action

There are two opposing perspectives on improving lecturing. One emphasizes the development of public speaking skills. In this view, lecturing will improve to the extent that instructors present lectures that are coherent, lively, and stimulating (Burgan, 2006; Tokumitsu, 2017). The ideal lecture is exemplified by the TED Talk, in which an expert translates a complex topic into a compelling story for an audience.

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Of course, effective presentation skills are fundamental to good teaching (Bligh, 2000; Davis, 2009; Svinicki & McKeachie, 2014). Anyone who has experienced poor lectures knows how difficult it can be to make sense of disorganized material, or maintain interest when the instructor shows no enthusiasm for the subject. Good teachers do strive to prepare and deliver high quality lectures. They try to bring the most important ideas about a topic into class, organize the content carefully, provide clear explanations, stimulate student interest in the subject, and maintain student attention throughout a class period.

The second perspective is based on active learning pedagogy. In this view, lectures are inherently limited because students are passive recipients of information. To improve them, instructors should lecture less and engage students more actively in learning (Bonwell & Eison, 1991; Chickering & Gamson, 1987; Deslauriers, Schelew, & Wieman, 2011; Mazur, 2009; Menekse, Stump, Krause, & Chi, 2013b). Active learning strategies range from specific techniques and exercises that make lectures more interactive, to alternative pedagogies that minimize the use of lecture such as peer instruction and problem-based learning (Bonwell, 1996; Bruff, 2009; Crouch & Mazur, 2001; Mazur, 2009; Wieman, 2017; Wiggins, Eddy, Grunspan, & Crowe, 2017).

Missing in both of these approaches is a focus on the processes of learning, how and why students learn or do not learn from lectures. If students learn less from lectures, we should try to identify the underlying causes and then work on improving the method. Based on decades of research in the learning sciences, we know much about student learning in various contexts. This research is the foundation for a learning science perspective on how to improve learning from lectures.

A Learning Science Perspective on How to Improve Learning From Lecture

Learning from lecture is not a matter of simply paying close attention to the instructor, being enthused about the material, or taking copious notes. Nor is it an automatic outcome of being more actively or interactively involved in class. Instead, learning depends on students' *deep cognitive engagement* with the material before, during, and after a lecture (Bransford, Brown, & Cocking, 2000; deWinstanley & Bjork, 2002; Fiorella & Mayer, 2015; Schwartz, Tsang, & Blair, 2016).

Research demonstrates that learning from lectures is limited when

- students lack the prior knowledge needed to benefit from lectures;
- students experience cognitive overload during lectures;
- students do not engage in deep learning processes during lectures; and
- after class students fail to elaborate and consolidate what they started to learn during lecture (deWinstanley & Bjork, 2002; Fiorella & Mayer, 2015; Schwartz & Bransford, 1998).

Each of these areas influences whether students learn from lecture. This review proposes strategies to help students acquire essential background knowledge before lecture, manage cognitive overload and engage in deep learning processes during lecture, and elaborate, consolidate, and retain what they learn after lecture. Because these areas encompass such a wide range of teaching strategies, it is not possible in this review to discuss their implementation in detail. Readers can find specific information about how to implement these strategies by referring to the citations both in the review and the appendix.

Help Students Acquire Essential Background Knowledge

What students know before a lecture in large part determines what they will learn during a lecture. As Mr. Davies, my junior high school math teacher, once told our class, "The more you know, the easier it is to know more." His aphorism was prophetic. Research has shown unequivocally that students' prior knowledge—what they already know and believe—affects new learning. In summarizing decades of research, Bransford et al. (2000) concluded,

> Students come to every learning situation with prior knowledge, skills, beliefs, and concepts that significantly influence what they notice about the situation, how they organize and interpret it. This affects their ability to remember, reason, solve problems, and acquire new knowledge. (p. 10)

Generally, prior knowledge facilitates new learning. However, four common prior knowledge conditions can impede learning (Ambrose, Bridges, DiPietro, Lovett, & Norman, 2010; Ambrose & Lovett, 2014):

1. Insufficient prior knowledge. When students lack relevant background knowledge, learning is likely to be fragmented and incomplete. Students will struggle to identify the meanings of new terminology, differentiate main ideas from detail, grasp how one idea relates to another, and build a coherent representation of the lecture material (Bransford et al., 2000). According to survey results, more than half of freshmen and seniors report they sometimes come to class unprepared, and an additional 19% report being unprepared often or very often (NSSE Annual Results, 2017).
2. Inaccurate prior knowledge. Student misconceptions of the subject matter are common and can interfere with new learning. Some misconceptions are minor glitches that students work out on their own; others can be tenacious, resistant to instruction, and lead to serious misinterpretations of new material (Bensley & Lilienfeld, 2017; Taylor & Kowalski, 2014; Vosniadou, 2013).
3. Inappropriate prior knowledge. Students may use inappropriate or irrelevant prior knowledge to interpret lecture material. For example, the terms *average*, *confidence*, and *random* have very different technical meanings in statistics than in common colloquial usage. Students who have the colloquial definitions in mind will be confused by a statistics lecture on these topics (Kaplan, Fisher, & Rogness, 2009).
4. Inert prior knowledge. Students may possess relevant prior knowledge but may not access it or be able to use it when needed to interpret new material. Students' inability to transfer recently acquired concepts to new contexts can be a significant obstacle to learning from lecture (Bransford & Johnson, 1972; Schwartz & Bransford, 1998; Schwartz, Chase, Oppezzo, & Chin, 2011).

On any class day, a significant number of students may not benefit from lectures because they lack some combination of sufficient, accurate, relevant, or usable background knowledge. To help students acquire essential background knowledge, teachers can use prior knowledge assignments that target the facts and skills students need in order to benefit from the upcoming lecture (Ambrose et al., 2010). To illustrate, suppose an instructor plans to lecture about the language development theories of Piaget and Vygotsky. If her goal is for students to become familiar with the key concepts of these theories, a reasonable assignment would be for students to read relevant course material and complete an online quiz about the concepts before class. Low-stakes quizzes and practice tests are effective ways to support student learning of factual material (Pyc, Agarwal, & Roediger, 2014).

However, if the learning goal is for students to be able to analyze and evaluate the theories, a more appropriate assignment would be for students to practice these activities. One approach is to use a graphical matrix to support student analysis or evaluation. For example, a matrix could list different features of language acquisition theories, for example, roles of maturation and experience in language acquisition and the course of early language development. Students read the chapter and complete the matrix by describing how each theory explains the role of maturation and experience and the sequence of language development. Or, a matrix could list criteria used to evaluate language acquisition theories, and involve students in evaluating the theories on each criterion (Kauffman & Kiewra, 2010; Kiewra, 2012).

Another type of prior knowledge assignment is based on studies in which students explore the problems or phenomena related to the lecture topic before class (Schwartz & Bransford, 1998). Instead of reading about the topic, students analyze topic-related contrasting cases, data sets, or scenarios as preparation for lecture. In the language development example, students could try to explain language samples from naturalistic observations or laboratory studies, for example, egocentric speech, overgeneralization of word meanings, examples of babbling, and one-word utterances. Research has shown that experience with the phenomena before class enables students to interpret the teacher's explanation better than students who read about and summarize the topic before class (Alfieri, Nokes-Malach, & Schunn, 2013; Chin, Chi, & Schwartz, 2016; Schwartz & Bransford, 1998; Schwartz et al., 2016).

These prior knowledge assignments are based on the premise that instructional techniques should align with the learning goal of the lecture, and target specific declarative and procedural knowledge to help students benefit from the instructor's lecture. To illustrate further, suppose students have significant misconceptions about an upcoming lecture topic. Quizzes or graphical matrices may not address the underlying misconceptions. In such a case, a strategy designed to promote conceptual change would be more suitable, for example, refutational teaching (Taylor & Kowalski, 2014).

Prior knowledge assignments also provide timely feedback about the "state" of students' knowledge, which instructors can use to plan their lectures. For example, they can reveal lingering knowledge gaps and misconceptions that may interfere with students' understanding. Using prior knowledge assignments for formative assessment can help instructors prepare a lecture to meet the exigencies of students' thinking (Ambrose et al., 2010; Bransford et al., 2000).

From a learning science perspective, the effectiveness of prior knowledge assignments depends on whether the tasks target and support the development of knowledge and skills essential to help students learn new material in lecture (Schwartz & Bransford, 1998). The tasks also provide feedback instructors can use to identify persistent knowledge gaps and misconceptions, and to guide decisions about the objectives, organization, and content of the lecture.

Manage and Reduce Cognitive Load During Lecture

Lectures make considerable cognitive demands on students, who must select and focus on relevant information, ignore distractions and irrelevant information, organize and integrate new material with relevant prior knowledge, make inferences about how new ideas are related to one another, decide which ideas are important and which are less so, interpret the meaning of graphics, such as pictures, charts, and diagrams, and reconcile those with the instructor's oral explanations. As students are doing all this, they also make decisions about what information to record in their notes, and what to do about information they do not understand or completely missed.

This view depicts students not as passive recipients of information, but as actively trying to coordinate multiple mental tasks. A major threat to learning during lecture is cognitive *overload*, which occurs when the cognitive demands of the situation exceed students' cognitive capacities (Chandler & Sweller, 1991). Because of limited working memory capacity, students may experience episodes when they are not able to attend to and process the material effectively. The challenge for teachers is to manage or reduce unnecessary cognitive load so that students can make best use of their capacities to learn the material during lecture.

The sheer volume of new information in lectures is a common cause of overload. As Schwartz et al. (2016) reported,

> By far the most common problem is that lectures contain too much information. One count has it that an average engineering lecture introduces a new equation every 2.5 min and a new variable every 45 seconds (Blikstein & Wilensky, 2010). Imagine sitting through that for an hour! (p. 124)

Cognitive load also increases when the material is unfamiliar, the presentation is fast-paced or disorganized, and when there are frequent distractions (Mayer, 2011). To manage and reduce unnecessary cognitive load, teachers can try to monitor their presentation pace, improve coherence, reduce distractions, and reduce extraneous processing associated with multimedia.

- Monitor and adapt presentation pace. Lecture information is transient; there is no pause button to allow more time to process the information. If students miss an idea, it's gone. Studies show that a typical speaking rate is 2–3 words per second, and people write at a rate of .2–.3 words per second (Piolat, Olive, & Kellogg, 2005). Trying to think about the instructor's talk while deciding what notes to write is challenging. Studies indicate that students' lecture notes include less than half of the main ideas from the class period (Armbruster, 2009; Kiewra, 2002; King, 1992). Instructors can monitor and adjust their pace by using student feedback to indicate when the presentation is moving too quickly, for example, ask a few students each class period to use clickers to signal when the pace is too fast, or hand in a tally sheet after class with the number of overload episodes during the lecture.

Given the variation in students' background knowledge and note-taking skills, it is unlikely that one presentation pace will suit all students. To help moderate the pace instructors can build in pauses during lectures to allow students to catch up, ask questions, and process the material more completely.

- Improve coherence. Well-organized, coherent information is easier to comprehend and remember than poorly organized information (Bransford, 1979; Mayer & Fiorella, 2014). Teachers can improve coherence by making the organization of their lectures explicit, building on prior knowledge, identifying connections among topics throughout the lecture, segmenting the material into manageable and meaningful chunks, and eliminating extraneous material (Ambrose et al., 2010). For example, an effective technique to make lecture organization explicit is to provide students with a schematic outline of the lecture, which lists major headings, concepts, or questions. Students can use the outline to identify how the topics fit together and organize their note taking (Bui & McDaniel, 2015; Kiewra, 2002).
- Reduce distractions. Extraneous stimulation or activities that interrupt students' attention from the task at hand can derail learning. Distractions split students' attention; they stop thinking about the lecture and shift their attention to the source of the distraction. During these momentary shifts they lose their place and miss whatever took place while their attention was elsewhere (Ravizza, Uitvlugt, & Fenn, 2017). A source of significant distraction in the college classroom involves the nonacademic use of electronic devices (McCoy, 2016). Chronic use of smartphones and other devices splits attention and subverts learning (Kraushaar & Novak, 2010; Ravizza et al., 2017; Stothart, Mitchum, & Yehnert, 2015). For example, nonacademic use of a laptop in lecture distracts not only the student user, but also students sitting nearby who can see the screen (Fried, 2008; Sana, Weston, & Cepeda, 2013). To reduce these distractions, many instructors adopt course policies that restrict the use of phones and other devices (Weimer, 2018).
- Use multimedia learning principles to reduce extraneous load. Extensive research by Mayer and associates has established multimedia learning principles for reducing extraneous processing in multimedia materials such as lecture slides (Mayer, 2014; Mayer & Fiorella, 2014; Mayer, Heiser, & Lonn, 2001). Even small changes in slide design, such as deleting interesting but extraneous graphics and organizing bullet point text into a table format, can have a positive effect on student learning (Issa et al., 2011; Mayer, 2014; Overson, 2014; Rey, 2012).

As experts, it can be difficult for teachers to see their own lectures through the eyes of students, and identify the obstacles that interfere with learning. However, students can point out specific trouble spots. For example, graduate students in a course on science teaching identified more than 30 ways to reduce *unnecessary mental load* related to lecture organization, slides and graphics, the instructor's projected notes, and the classroom atmosphere and pace, for example, "Leave slides up long enough for students to absorb and/or record the information. Remember, this takes much longer when one is seeing them for the first time"; "Avoid peripheral information and seductive details"; "Find ways to make material interesting that is directly linked to the desired learning objectives" (Carl Wieman Science Education Initiative, 2014).

Students also recommended that instructors periodically solicit student feedback about their lecturing, for example,

> When I am lecturing, what do you usually look at or focus on? In general, are you able to read everything and understand what is on the slide? Do you feel you have enough time, too much time, or too little time to process new information that is presented and take necessary notes. (Carl Wieman Science Education Initiative, 2014)

From a cognitive load perspective, good lectures are well organized, clearly presented, and reduce unnecessary mental load. They make complex ideas more accessible, clearing away extraneous information so that students can use more of their mental horsepower to make sense of the information and build knowledge. Nevertheless, students must still do the heavy lifting of learning the material. The teaching challenge then is how to promote deeper cognitive engagement during lecture (deWinstanley & Bjork, 2002).

Induce Deep Learning Processes During Lecture

Researchers distinguish between shallow and deep processing in learning (Craik & Lockhart, 1972). Shallow processing involves attending to surface features of information, and trying to learn material through rote memorization, repetition, rereading, and highlighting. These activities re-expose students to the material but often result in superficial learning (Chi, 2009). Deeper processing involves *trying to make sense* of the material by

- connecting new information to prior knowledge;
- looking for patterns, themes, organizing principles; and
- exploring the implications or consequences of the new information (Mayer, 2011).

Deep processing activities tend to produce better understanding and retention than shallow processing, and instructors can prompt deeper processing during lectures (Chi & Wylie, 2014; deWinstanley & Bjork, 2002).

To illustrate, suppose an instructor's goal is for students to be able to explain two models of human memory. In lecture, he introduces a new model and compares it to one the class has already studied, and then moves on to cover the remainder of the lecture material. The teacher's explanation may be coherent and well presented, but may not prompt deep processing of the explanation (Hrepic, Zollman, & Rebello, 2007).

Alternatively, the teacher could start by explaining the new model, and then ask students to compare it to the one they had learned previously. They write a short response and then share their ideas with a classmate. During the episode students identify characteristics of both models, judge their similarities and differences, make connections between prior knowledge and new information, and identify gaps in their understanding. Their explanations may not be fully developed, but the goal is for students to try to make sense of the material by thinking through the similarities and differences between the models (Bisra, Liu, Nesbit, Salimi, & Winne, 2018; Chi, 2017; Chiu & Chi, 2014). Moreover, after students work on their own, the instructor could ask the class to list the key differences between the models, and then give targeted feedback to elaborate on and highlight important points (Ambrose et al., 2010).

This is one example of how to structure and facilitate students' deep processing of the subject matter. Below are three additional strategies that involve deeper processing during lectures:

- Retrieval practice. Retrieval of information from memory is a potent learning strategy. Instructors can use a short low-stakes quiz at the start of class to strengthen and activate students' prior knowledge of the lecture topic for that day (Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013; Karpicke & Blunt, 2011; Khanna, 2015; Pyc et al., 2014).
- Explain and elaborate the lecture material. The acts of *explaining* and *elaborating* are powerful learning strategies in which students make connections between new and prior knowledge, and notice gaps in their own understanding (Chiu & Chi, 2014; Fiorella & Mayer, 2015; Fonseca & Chi, 2011). Instructors can pause after explaining a concept, and ask students to explain it in their own words in writing or explain the concept to a classmate. In large classes, instructors can use explanation-focused clicker questions to promote deeper thinking about the material (Bruff, 2009; Carl Wieman Science Education Initiative, 2009; Landrum, 2015).
- Predict and explain the outcomes of an experiment, demonstration, or scenario. Before doing a demonstration in class, describe what is about to happen and ask students to predict and explain the outcome. After observing the demonstration, students reconcile their predictions with the actual outcome. Students who predict the outcome of a demonstration are much

more likely to discern how the demonstration illustrates a specific concept or principle compared to students who simply view the demonstration (Brod, Hasselhorn, & Bunge, 2018; Crouch, Fagen, Callan, & Mazur, 2004).

These deep processing examples resemble widely used active learning techniques such as think-pair-share (Lyman, 1987), minute papers (Angelo & Cross, 1993), and peer instruction (Mazur, 1997). On a cautionary note—not all active learning techniques engender deep processing. For example, discussion, which is widely viewed as active learning, can be unfocused and ineffective. Turning discussion into a deeper learning experience involves structuring the interaction so that it prompts deeper learning processes (Chi & Wylie, 2014; DeLozier & Rhodes, 2017; Menekse, Stump, Krause, & Chi, 2013a; Wieman, 2017). Instead of asking students to talk to each other or discuss an idea, the instructor could present a task in which students compare and contrast, analyze, evaluate, hypothesize, draw a diagram, or weigh evidence. Students then work with a partner to develop a "best" answer based on their individual ideas. Rather than simply exchange information, students are more likely to integrate ideas and build new knowledge (Scardamalia & Bereiter, 2006).

Ultimately, support for student learning during lectures involves more than giving well-organized, enthusiastic presentations. To the extent possible, teachers need to manage the cognitive challenge of their lectures. Students are likely to flounder if they experience too much unfamiliar, complex information too quickly, and if they must cope with unnecessary mental load. Equally important, teachers should engage students in the kind of deep processing that produces robust learning. This involves creating opportunities during lecture for students to explain, elaborate, analyze, evaluate, and integrate the subject matter.

Help Students Consolidate and Retain Material After Lecture

Results from national surveys indicate that about one third of college students do not review their notes or summarize important material regularly after class (NSSE Annual Results, 2017). Unless students *do something* to consolidate and retain newly acquired information, they are likely to forget it quickly. What can teachers do to support students' post-lecture learning?

At the end of the class period, set aside a few minutes for students to catch up, organize their thoughts, identify gaps in their understanding, reflect, and ask questions. Students could

- work with a few classmates to review, organize, elaborate on the lecture material, and check their understanding (Chi, 2017; Luo, Kiewra, & Samuelson, 2016).
- write a minute paper or muddiest point exercise. For example, explain what you think are the most important ideas from the lecture. What concepts from the lecture are still confusing? (Angelo & Cross, 1993; Chi, 2017; Mosteller, 1989; Wilson, 1986)
- take a short quiz based on major concepts from the lecture (Butler, 2010; Khanna, 2015).
- apply the lecture material to a new question or problem (Ambrose et al., 2010; Bassok, 1990).
- review a worked example of a problem or scenario (Renkl, 2014; Yeo & Fazio, 2018).

These strategies engage students in trying to remember key points from the lecture, thinking about how concepts are related to one another, and identifying what they know and do not know. They also provide feedback to the instructor about students' immediate understanding of the lecture.

Instructors can further support student learning with post-lecture assignments that involve deep learning activities such as retrieval practice and explaining. Simple techniques include low-stakes quizzes (Pyc et al., 2014), journal responses in which students submit questions after reviewing their lecture notes (Miyatsu, Nguyen, & McDaniel, 2018), and studying worked examples (Renkl, 2014). Moreover, to support long-term retention, post-lecture questions can be repeated on subsequent practice quizzes and exams during the term. These successive relearning activities help students' deepen their grasp of the material, and prepare them for subsequent lectures (Bisra et al., 2018; Butler, 2010; Dunlosky & Rawson, 2015).

Summary and Conclusions

Lecturing is a primary mode of instruction in higher education. Learning from lectures depends on deep cognitive engagement with the subject matter before, during, and after the actual presentation. To produce better learning from lectures, teachers need to help students

- develop sufficient, accurate, and appropriate prior knowledge as a basis for making sense of new lecture material;
- manage the cognitive challenges of lecture presentations;
- process the lecture material deeply by selecting, organizing, and integrating new information with prior knowledge during lecture; and
- elaborate on the material to consolidate and remember it after the lecture.

This perspective emphasizes using evidence of how students learn as a basis for improving teaching. That evidence can tell us where and how students are likely to have difficulty. As we get a better understanding of their difficulties, we can adopt teaching practices accordingly. The strategies and techniques proposed here are neither new nor sure-fire remedies. However, they can be used to diagnose and address a broad range of problems students experience in learning from lecture.

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Appendix

Research on Applications of Teaching Strategies

Strategy	Supporting Research and Practical Applications
Analyze contrasting cases, data, problems, scenarios, vignettes	Alfieri, Nokes-Malach, & Schunn, 2013; Chi, 2017; Schwartz & Bransford, 1998; Schwartz et al., 2011; Schwartz, Tsang, & Blair, 2016
Matrix organizer	Fiorella & Mayer, 2015; Kauffman & Kiewra, 2010; Kiewra, 2012
Refutational teaching (revise misconceptions)	Taylor & Kowalski, 2014
Diagnose prior knowledge	Ambrose, Bridges, DiPietro, Lovett, & Norman, 2010; Bransford, Brown, & Cocking, 2000
Schematic outline	Bui & McDaniel, 2015; Kiewra, 2002
Increase coherence	Bransford, 1979; Mayer, 2014; Mayer & Fiorella, 2014
Reduce unnecessary cognitive load	Carl Wieman Science Education Initiative, 2014; Holstead, 2015; Issa et al., 2011; Mayer, 2014; Overson, 2014
Monitor and adjust rate of speaking	Piolat, Olive, & Kellogg, 2005; Carl Wieman Science Education Initiative, 2014
Segment into meaningful chunks	Ambrose et al., 2010
Course policies about non-academic use of electronic devises in class	Weimer, 2018
Use multimedia learning principles to reduce extraneous load	Issa et al., 2011; Mayer et al., 2001; Mayer, 2014; Mayer & Fiorella, 2014; Overson, 2014; Rey, 2012
Explanation (to self or others)	Bisra, Liu, Nesbit, Salimi, & Winne, 2018; Chiu & Chi, 2014; Fiorella & Mayer, 2015; Fonseca & Chi, 2011; Wieman & Perkins, 2005
Clickers (activate prior knowledge, retrieval practice, explanation)	Bruff, 2009; Landrum, 2015; Carl Wieman Science Education Initiative, 2009
Retrieval practice; low stakes quizzes and practice tests	Butler, 2010; Butler & Roediger, 2007; Dunlosky et al., 2013; Dunlosky & Rawson, 2015; Karpicke & Blunt, 2011; Khanna, 2015; Pyc, Agarwal, & Roediger, 2014
Prediction and explanation	Brod, Hasselhorn, & Bunge, 2018; Crouch & Mazur, 2001
Review, reorganize, revise class notes	Armbruster, 2009; Cohen, Kim, Tan, & Winkelmes, 2013; Kiewra, 2002; King, 1992; Luo, Kiewra, & Samuelson, 2016; Miyatsu et al., 2018; Reed, Rimel, & Hallett, 2016
Minute paper (summarize)	Angelo & Cross, 1993; Fiorella & Mayer, 2015
Muddiest point (comprehension monitoring and explanation)	Angelo & Cross, 1993; Chi, 2017
Apply lecture material to a new question or problem	Ambrose et al., 2010; Bassok, 1990
Study worked examples	Mayer et al., 2001; Renkl, 2014; Schwartz et al., 2016; Yeo & Fazio, 2018

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