Journal of the Scholarship of Teaching and Learning, Vol. 24, No. 3, September 2024, pp.119-136.
doi: 10.14434/josotl.v24i3.35263

A Reflection on the Current State of Active Learning Research

Amedee Marchand Martella
University of California, Santa Barbara
amedeemartella@ucsb.edu

Darryl W. Schneider
Purdue University
dws@purdue.edu

Abstract: Interest in active learning continues to grow worldwide. Although the large volume of active learning research has provided a myriad of ways to implement active learning in the classroom, the construct remains underdeveloped and difficult to operationalize because of three main issues in the research literature: (a) the confusion surrounding what "active" in active learning refers to (i.e., behavioral activity, cognitive activity, or both?); (b) the variation in active learning activities in research and in practice; and (c) the dichotomy between active learning and lecture. The purpose of this reflection article is to articulate these issues so that active learning can move beyond its current status as "underdeveloped." By discussing avenues for future research that address those issues, our goal is to move the field forward by helping researchers focus on why active learning is effective, which forms of it are the most effective, how it should be implemented to maximize learning, and for whom different active learning interventions are the most effective. Just as active learning is easy to prescribe, it should also be easy to implement.

Keywords: active learning, lecture, student learning, course transformation, STEM education

The traditional lecture method continues to be the predominant mode of instruction in college courses (Stains et al., 2018). However, this method has been criticized for promoting passive learning (Deslauriers et al., 2019) and for being less effective than active learning at narrowing the achievement gap and thereby ensuring equity for underrepresented students (Theobald et al., 2020). To improve STEM education and to reduce STEM disparities, moving courses away from an environment where students receive and absorb information (typically termed *passive learning*) and toward an environment where students participate in generating and interacting with the information (typically termed *active learning*) has been encouraged through numerous university- and national-level efforts (e.g., Association of American Universities [AAU], 2017; Center for STEM Learning, 2016). With its growing research base, active learning continues to gain political and instructional interest (Hartikainen et al., 2019). As of May 1, 2022, the number of active learning articles we found for publication years 2019–2022 from five comprehensive databases (*Engineering Village* [Elsevier], *Education Research Information Center* [EBSCOhost], *Medline* [PubMed], *Web of Science Core Collection* [Clarivate], and *Dissertations & Theses Global* [ProQuest]) was nearly 14,000 after duplicates were removed. As further evidence of active learning's widespread popularity, a bibliometric analysis of articles that cited the prominent Freeman et al. (2014) meta-analysis on active learning indicated there were 925 funding sources and 90 country affiliations listed for the authors of these citing articles (Martella et al., 2021c).

Despite its increasing prominence and the high volume of active learning articles published recently, active learning remains an umbrella term (Lombardi et al., 2021) that has been described as an "easy thing to prescribe as a cure but difficult to put into practice" (Eyler, 2018, para. 5). Further, active learning has been called a "curious construct" (Lombardi et al., 2021, p. 8), and the current view of active learning has been said to be "underdeveloped" (Lombardi et al., 2021, p. 15). The uncertainty about the meaning and implementation of active learning has led to questions such as, "Are there active-learning strategies that optimize learning is some situations but not others?;" "Is lecture inherently flawed, or are there some circumstances under which students can actively learn during lecture?;" and "What characterizes effective learning processes in undergraduate STEM fields?" (Lombardi et al., 2021, p. 9). These questions reflect the current state of the active learning literature—that is, we know active learning works in general, but *why* and *for whom* it works, as well as *how* it should be implemented, are questions that remain largely unanswered.

The purpose of this reflection article is not to question active learning's effectiveness nor to present a new definition of active learning. Rather, our goal is to draw attention to critical issues in the research literature and to highlight areas in need of further research, which we hope will aid researchers studying the construct of active learning and ultimately allow them to provide clearer guidance on how to effectively implement active learning in college courses. Our reflection will focus on three main issues within the current active learning literature. The first issue is the confusion surrounding what "active" in active learning refers to (i.e., behavioral activity, cognitive activity, or both?). The second issue is the extensive variation in active learning activities that occurs in both research and practice. The third issue is the dichotomy that has been created between active learning and lecture. For each issue, we will discuss how the current research base can be strengthened by more deliberate and targeted research. Table 1 provides a summary of each issue and the accompanying research directions to address these issues.

Issue 1: The Meaning of "Active" in Active Learning

A seminal and often cited definition of active learning is "instructional activities involving students in doing things and thinking about what they are doing" (Bonwell & Eison, 1991, p. iii). This open-ended definition is unsatisfactory to many researchers, some of whom have noted the need for further operational definitions of and studies on active learning, given its range of implementations (e.g., Lombardi et al., 2021; Martella et al., 2021b; Martella et al., 2023). More recent definitions are also rather open-ended. In the meta-analysis conducted on active learning by Freeman et al. (2014), this method was defined as one that "engages students in the process of learning through activities and/or discussion in class, as opposed to passively listening to an expert. It emphasizes higher-order thinking and often involves group work" (pp. 8413–8414). This definition was established through the collection of written definitions from 338 audience members who attended biology departmental seminars on active learning at several universities throughout the United States and Canada. A similar and more recent working definition of active learning was provided by Lombardi et al. (2021): "Active learning is a classroom situation in which the instructor and instructional activities explicitly afford students agency for their learning" (p. 16). This definition was established through the combination of definitions provided by contributing discipline-based educational research (DBER) teams.

Although aspects of these definitions provide some acknowledgment of the importance of cognitive engagement for learning, active learning as an instructional method is often discussed based on the overt behaviors of students during class. For example, the Interactive Constructive Active Passive (ICAP) framework (Chi & Wylie, 2014) focuses on overt student behaviors during cognitive engagement activities. Passive engagement relates to *receiving* information such as listening to a lecture or silently reading a text. Active engagement relates to *manipulating* information such as taking notes during lecture or pausing and playing a video. Constructive engagement relates to *generating* information such as asking questions during a lecture or explaining the concepts presented in a video.

Table 1: Overview of issues in the active learning literature and future research directions to address these issues.

Issue	Crux of Issue	Future Research Directions	Example of Research Comparison(s)
Meaning of "active" in active learning	Does active learning refer to behavioral activity, cognitive activity, or both?	Design studies that focus on the two dimensions of active learning—cognitive activity and behavioral activity.	High behavioral activity / low cognitive activity vs. low behavioral activity / high cognitive activity
		Identify and implement learning strategies that encourage cognitive processing.	Lecture presentation with visual and mental imagery vs. lecture presentation without imagery
Variation in active learning activities	Which active learning activities are the most effective and how should they be combined in class?	Compare different active learning conditions with other variables isolated and controlled.	Clicker questions vs. case studies
		Combine different learning strategies to determine their paired effectiveness as compared to their individual effectiveness.	Flashcards + self-explanations vs. flashcards (alone) vs. self-explanations (alone)
Dichotomy between active learning and lecture	Should lecture be included in active learning courses?	Design studies with uncontaminated contrasts between lecture and active learning conditions.	100% lecture (0% active learning) vs. 0% lecture (100% active learning)
		Examine dosage amount, schedule, and/or order for the integration of lecture and active learning.	25% lecture / 75% active learning vs. 75% lecture / 25% active learning

Finally, interactive engagement relates to *dialoguing* information such as defending one's position to group members during lecture or answering comprehension questions with a partner while reading a text. Although the focus is on overt behaviors, the deeper purpose of these activities is to promote mental activity, as active learners are said to be engaged cognitively (Bonwell & Eison, 1991; Chi & Wylie, 2014). Indeed, active learning has been labeled "the process of keeping students mentally, and often physically, active in their learning" (Michael, 2006, p. 160). This mental activity or cognitive engagement promotes the construction of knowledge and the formation of mental models through the integration of prior knowledge and new information (Michael, 2006). Although students being cognitively active often translates into them being behaviorally active, these two dimensions of active learning (i.e., cognitive activity and behavioral activity) are distinct and not always correlated. Equating active learning (cognitive activity) with active teaching (behavioral activity) has been referred to as the *constructivist teaching fallacy* (Mayer, 2004). Therefore, it is worthwhile to discuss active learning as a learning process in addition to discussing it as an active teaching method.

As a learning process, active learning involves multiple cognitive processes (Fiorella & Mayer, 2015; Mayer, 2021). These processes include attending to the relevant material in a lesson by selecting it into working memory, mentally organizing the selected material into coherent mental representations in working memory, and integrating the incoming material with relevant knowledge activated from long-term memory. These active learning processes are guided by affect and beliefs, such as the student's positive affect during learning (Pekrun & Linnenbrink-Garcia, 2012; Pekrun & Perry, 2014) and the student's high self-efficacy beliefs during learning (Bandura, 1986; Usher & Pajares, 2008).

As an active teaching method, active learning involves engaging students in class activities that involve more than sitting and listening to a lecture. Indeed, the engagement and interaction that class activities afford represents the most common definition of active learning. For example, in a survey of 105 members of the Society for the Advancement of Biology Education Research (SABER), the most common definition of active learning related to "interacting/engagement," followed by definitions related to "not lecturing/listening" and "group work" (Driessen et al., 2020). In contrast, during lectures, students are said to be recipients of information that is passively absorbed (Prince, 2004), resulting in shallow learning (Gleason et al., 2011). Lecture is also said to "reinforce students' roles as passive learners" (Smith & Cardaciotto, 2011, p. 54). However, lecture is not necessarily always passive, at least not in the cognitive sense. Students in a class lecture may be behaviorally passive but cognitively active (Opdal, 2022). For example, an instructor may ask students to think about how the new content connects to prior content they have learned, or students may think about how to ask a question to clarify their understanding of a specific concept. Both acts are behaviorally passive but not cognitively passive. Therefore, determining whether the "active" aspect of active learning should be focused on cognitive activity, behavioral activity, or both remains an open question in the literature that, if answered, would provide insight into *why* active learning is effective.

Future Research

The simple "active learning versus lecture" contrast that is common in the literature (which we discuss later as Issue 3) focuses on the behavioral dimension but unfortunately tends to overlook the cognitive dimension. There is no question as to whether cognitive engagement is an important component of learning—it is—but there remains a question as to whether the behavioral activity of students is needed to promote deeper or greater learning. Future research could focus on the two dimensions of active learning—cognitive activity and behavioral activity—to determine whether students who are cognitively engaged during lecture (behaviorally passive) learn less than students who are cognitively engaged during active teaching (behaviorally active). One could envision four different experimental conditions in a research study (see Figure 1 in Mayer, 2004) reflecting the factorial combination of low or high behavioral activity crossed with low or high cognitive activity.

A second research direction is to "discover instructional methods that promote appropriate processing in students rather than methods that promote hands-on activity or group discussion as ends in themselves" (Mayer, 2004, p. 15). Identifying and implementing learning strategies that encourage cognitive processing could help students learn more from both lecture and active teaching (i.e., the behavioral dimension of active learning). There are many strategies that can be implemented during lecture to encourage students to be more cognitively engaged, such as using visual images and mental imagery, providing structure through outlines or knowledge maps (deWinstanley and Bjork, 2002), and using humor to help students connect classroom content to new situations (Hackathorn et al., 2011). Similarly, there are many strategies that can be implemented during active teaching to encourage students to be more cognitively engaged, such as practice testing and peer teaching (Fiorella & Mayer, 2015). Thus, the conversation surrounding active teaching and lecture may be more informative when we shift it to be about identifying strategies that are most connected to how students learn, drawing on the wealth of knowledge from cognitive and educational psychology about effective learning strategies (e.g., Ambrose et al., 2015; Karpicke, 2017; Klahr & Nigam, 2004; Mayer, 2008, 2021; Sweller et al., 2011).

Issue 2: Activity Variation in Research and in Practice

The implementation of active learning (used in the remainder of this paper to refer to active teaching methods) in college settings varies widely, both in research and in practice. The open-endedness of the definitions provided earlier lends insight into why active learning can look so different from one study to the next or from one classroom to another. However, a common thread among active learning definitions is the emphasis on the use of activities to engage students in the learning process. Indeed, numerous activities that require behavioral activity (e.g., clicker questions, group discussion, peer teaching, worksheet problems) have been implemented in classes to promote student learning. Consider that active learning college interventions in the literature vary "widely in intensity and implementation" and include "approaches as diverse as occasional group problem-solving, worksheets or tutorials completed during class, use of personal response systems with or without peer instruction, and studio or workshop course designs," as well as varying amounts of lecture (Freeman et al., 2014, p. 8410). In a recent study examining the features present in active learning courses in 57 comparison studies published in three primary DBER science journals, Martella et al. (2021a) found that the average number of active learning and other pedagogical features included in active learning college courses was five. Features identified in these studies included activity sheets, clicker questions, case studies, class projects, group tasks, purposeful tutoring (e.g., peer teaching), student presentations, tutorials and games, whole class discussions, lecture, student quizzes, learning/exam preparation, and homework (see Tables 1 and 2 in Martella et al., 2021a). How these activities and other pedagogical strategies were designed and implemented also varied across studies. Similarly, Arthurs and Kreager (2017) identified four main categories of in-class activities in their analysis of 337 articles; these included individual non-polling activities, in-class polling activities, whole-class discussions or activities, and in-class group activities. Variation in the activities themselves could also be found within these categories.

With the extensive variation in activities identified in active learning courses, it is unclear which activities are most effective (i.e., which ones promote cognitive engagement) and how these activities can be most effectively and efficiently integrated into class. Some researchers have lamented that college instructors are provided with no formal training on how to choose activities and implement them in class and yet are tasked with transitioning their courses to involve more active learning (e.g., Rhodes, 2021). When faculty were surveyed on barriers they faced for the adoption of evidence-based practices in STEM, they reported a lack of pedagogical skills or information and instructional challenges (Shadle et al., 2017). Students have been impacted by these challenges, reporting that they were not sure how the activities implemented by their instructors helped them succeed (Shekhar et al., 2020). Although the umbrella of active learning affords a myriad of activities for instructors to choose from, it also makes it more difficult for them to know which ones to choose.

Future Research

To advance the field's knowledge surrounding how to most effectively implement activities in the classroom, we will discuss two primary research directions to be considered. The first research direction relates to disentangling the effectiveness of different activities and controlling variables. The second research direction relates to combining different learning strategies to determine their paired effectiveness. Both of these research directions would provide clarity as to *why* and *how* active learning as a teaching method can be effective.

Disentangling the Effectiveness of Activities and Controlling Variables

Active learning courses often involve several activities used to engage students in the learning process (Martella et al., 2021a). Examples of the activities provided in three active learning courses are: (a) pre-class reading and video assignments, pre-class quizzes, clicker questions, in-class problem sets, weekly self-tests, and practice problems and practice exams (the course also included Socratic lecture; in Crimmins & Midkiff, 2017); (b) worksheets, group work, clicker questions, assignment review, teaching assistant help during group problems/assignments (the course also included lecture; in Rissanen, 2018); and (c) worksheet activities, group work, homework problems to solve during class, and quizzes (the course also included online videos to watch as well as "catch-up days" with instructor-led problem solving; in Collins, 2019). An issue with each of these examples is that the concurrent implementation of multiple activities in a course does not allow one to determine the relative effectiveness of the various activities, both in isolation and in conjunction with one another. Considering that many activities differ not only on a surface level (e.g., clicker questions are visibly different than group worksheets) but also may differ on a deeper level (e.g., in the cognitive processes involved, as discussed later), there is likely a range in their effectiveness. If one desires to optimize an active learning course by retaining the most effective activities and discarding the least effective ones, then it is critical to disentangle the effectiveness of different activities.

One approach to disentanglement is to compare different active learning interventions or courses. However, given the array of activities provided in many courses, it may be unsurprising that the comparison conditions in studies on active learning often differ on more than one feature (Martella et al., 2021a). For example, in one study comparing two active learning courses (Connell et al., 2016), the first active learning course involved 160 minutes of class per week consisting of lecture (120 minutes per week), think-pair-share activities, real-time writing, reflective pauses, and reading guides, whereas the second active learning course involved 160 minutes of class per week consisting of online lectures, group quizzes with immediate feedback technique scratch cards, just-in-time lectures, activity sheets, 2-minute writes, cooperative learning, think-pair-share activities, content summaries, reading assignments, reading and watching guides, real-time writing, reflective pauses, and an online discussion board. The second active learning course was clearly more interactive and did lead to higher student performance than the first active learning course did. However, what specifically led the second course to outperform the first course remains unclear because it is not possible to disentangle the effectiveness of the various activities, thereby making it difficult to know how they impacted student learning. Was there synergy among features in the second course that led to higher learning gains? Or was there a specific activity within the second course that was most responsible for improving student learning? These questions reflect the importance of isolating and controlling variables when conducting experiments on what makes active learning effective.

To make valid inferences from the outcomes of experiments, the conditions in the experiments need to be unconfounded. An important strategy for scientific reasoning is the control-of-variables strategy, where a single contrast is made between conditions and any confounds that hinder making valid conclusions are identified (Chen & Klahr, 1999). In the context of studying active learning, applying this strategy would involve comparing one active learning activity to a different activity, with no other differences between the conditions being compared. Unfortunately, this is rarely done in the active learning literature (Martella et al., 2021a), making it difficult to determine why certain conditions resulted in higher (or lower) performance than the comparison condition(s). Without identifying what aspect of an intervention resulted in higher learning gains, providing practical advice and guidance to instructors is difficult. Thus, specific recommendations that are validated in experiments that disentangle the effectiveness of different activities and control for variables across conditions are needed to help instructors transform their courses to be more evidence-based.

Combining Different Learning Strategies

We alluded earlier to the fact that activities can differ based on their surface features, such as the materials involved and students' overt behavior. For example, a multiple-choice quiz looks quite different and evokes visibly different behavior than providing students with a concept map where they make a diagram of the relationships between or among concepts. However, activities can also differ on a deeper level where they engage different cognitive processes (reflecting active learning as a learning process). For example, numerous active learning activities incorporate learning strategies that encourage elaborative or retrieval-based cognitive processes. These processes have been found to be effective in promoting student learning and retention. Elaboration (also termed elaborative rehearsal) involves integrating prior knowledge with new knowledge and results in higher recall (e.g., Gallimore et al., 1977; Shaughnessy, 1981), higher delayed recognition accuracy (e.g., Benjamin & Bjork, 2000), and better conscious recollection (e.g., Gardiner et al., 1994) than simply repeating information (termed maintenance rehearsal). Several activities can promote elaboration such as making concept maps, engaging in self-explanations, summarizing/paraphrasing content, serving as a peer teacher, and participating in elaborative interrogation (i.e., generating an explanation or using *why* and *how* questioning strategies). With regard to encouraging the retrieval of information, the testing effect is the phenomenon that occurs where taking memory tests enhances later retention (Roediger & Karpicke, 2006). Other forms of retrieval practice include taking quizzes, solving worksheet problems without notes, and using flashcards to deliberately recall information.

When compared to elaborative practice, retrieval practice often leads to higher retention (e.g., Goossens et al., 2014; Karpicke & Blunt, 2011; Karpicke & Smith, 2012; O'Day & Karpicke, 2021). Although elaboration does enhance initial encoding, it may not provide additional memory benefits after successful retrieval (Karpicke & Smith, 2012). One direction for further research is to systematically investigate the effects of combining activities that include different learning strategies, such as combining elaborative encoding activities with retrieval activities (Karpicke & O'Day, in press; O'Day & Karpicke, 2021). It may be the case that elaborative and retrieval activities have additive or multiplicative effects when used in combination; alternatively, their combination may offer little or no advantage over using just one of them. In one recent study that begins to fill this research gap, the effects of combining retrieval practice (in the form of practice testing) with concept mapping were examined; interestingly, the combination of the two activities did not lead to greater benefits than when retrieval practice was implemented on its own (O'Day & Karpicke, 2021). Therefore, only the retrieval activity was needed to improve student performance.

The study by O'Day and Karpicke (2021) highlights the importance of assessing whether different types of activities that draw on different learning strategies lead to differences in retention when used in combination. As in their study, it may be the case that activities that are entirely retrieval-based promote greater retention than activities that involve a mix of elaborative-based strategies and retrieval-based strategies. Similar research questions could be applied to the ICAP framework, asking whether a particular combination of active, constructive, and/or interactive activities could lead to more, less, or equivalent learning than when each activity is used on its own. From a practical standpoint, systematically studying the combination of different types of activities could help instructors refine how they select specific activities to use in their courses and could help them determine how and whether to combine different types of activities to promote student learning.

Issue 3: The Dichotomy Between Active Learning and Lecture

Research on active learning commonly presents active learning as an alternative to lecture (Zakrajsek, 2018). For example, in the Freeman et al. (2014) and Theobald et al. (2020) meta-analyses on active learning, two categories of instructional methods were compared—active learning and lecture—creating a dichotomy by making it appear as an either/or choice. However, active learning versus lecture is not necessarily a simple dichotomy (Bernstein, 2018; Evans & Dietrich, 2022; Richardson, 2008; Zakrajsek, 2018) and contrasting the two methods can lead to overlooking aspects of lecture that promote learning (Lombardi et al., 2021) and are cognitively engaging. In this section, we address the dichotomy between active learning and lecture by considering whether lecture can be (and should be) included in active learning courses.

Can active learning courses contain lecture or are they mutually exclusive? The "lecture versus active learning" dichotomy pits the two against each other, making it appear as though instructors need to choose one or the other to implement in their courses. The sentiment that lecture should be significantly reduced or completely eliminated from college courses is ubiquitous across the United States and in other countries. For example, there are numerous department and university-wide initiatives focused on active learning course transformations where faculty are supported and/or incentivized to make changes to their courses to actively engage students (e.g., AAU, 2017; Center for STEM Learning, 2016). In 2015, Vice-Chancellor Warren Bebbington at the University of Adelaide in Australia was working to phase out lectures in favor of flipped classrooms (which still often contain lecture in the form of at-home videos or recorded lectures; see Lawson et al., 2019 for a discussion of designing effective flipped courses) and other active learning course formats (Dawson, 2015). However, some researchers say that there should not be "a monolithic stance about lecture or no lecture" as "there are still times when lectures will be needed" (Noah Finkelstein quoted in Bajak, 2014, para. 7) and that the answer to the question "How do we best get our students to learn—by facilitating for student activity or by lecturing?" is "a matter of *both*, not one or the other" (Opdal, 2022, p. 86).

When looking to the research literature to determine whether lecture should be abolished, the question becomes more muddled for two reasons. First, despite laments that lecture is ineffective, the research base on direct instruction (e.g., lectures, demonstrations, modeling) is vast and includes a variety of instructional topics, intervention durations, assessment measures, and student ages and skill levels, among other factors (e.g., Alfieri et al., 2011; Chen & Klahr, 1999; Klahr & Nigam, 2004; Kruit et al., 2018; Lorch et al., 2010; Morgan et al., 2015). This research base has revealed benefits of direct instruction linked to reducing the burden on students' working memory by removing the discovery/trial-and-error process (Clark et al., 2012; Sweller et al., 2011) and ensuring the knowledge that students acquire is not incorrect, disjointed, or incomplete (Rosenshine, 1995). Consequently, it seems questionable to advocate for the outright elimination of an instructional method that research shows can be effective in helping students learn. Second, most empirical studies on active learning compare the continuous exposition of lecture to interactive lecture rather than to pure (i.e., lecture-free) active learning (Zakrajsek, 2018). For example, when examining the active learning courses from 57 comparison studies, Martella et al. (2021a) found that most active learning courses contained a significant lecture component, with 72.4% of the active learning college courses devoting at least 20%

of the main class session to lecture. Often, courses that were flipped also contained lecture in the form of at-home videos or recorded lectures. Further, in the Freeman et al. (2014) meta-analysis, active learning college courses could contain up to 90% lecture and still be deemed active learning courses. Therefore, the "lecture versus active learning" dichotomy in the literature does not capture the true comparison of "lecture versus lecture+activities" that is actually occurring in these studies (Zakrajsek, 2018), making it difficult to gauge the effectiveness of lecture and to know whether lecture is necessary.

Future Research

To move the field forward in terms of understanding how much, if any, lecture should be included in college courses, it is important to disentangle lecture and active learning while also investigating their combination. The research directions described below relate to the question of *how* active learning should be implemented. Echoing our earlier discussion about assessing the effectiveness of various active learning activities, the conditions in experiments comparing lecture and active learning need to be unconfounded, such that a pure lecture condition is compared with a pure active learning condition. This uncontaminated contrast between conditions would enable researchers to draw conclusions about which instructional method is more effective (if that is their goal). However, the combination of lecture and active learning—which is what is actually represented in "active learning" conditions in many research studies—is also important to investigate to provide clarity as to how active learning should be implemented, which introduces *dosage amount* (or *intensity*—see, for example, Bernstein, 2018) as a factor that should be systematically studied.

Dosage Amount

The amount of time instructors should dedicate to active learning and lecture is referred to as *dosage amount*, which can range between the extremes of 0% active learning activities (100% lecture) to 100% active learning activities (0% lecture). Comparing those extremes would represent the pure contrast between active learning and lecture that tends to be missing from the literature. Between those extremes, one can explore variations in relative dosage amounts. For example, a researcher or an instructor could decide to (a) emphasize active learning activities and implement dosage amounts of approximately 25% lecture and 75% active learning activities; (b) emphasize lecture and implement dosage amounts of approximately 75% lecture and 25% active learning activities; or (c) emphasize the two equally and implement dosage amounts of approximately 50% lecture and 50% active learning activities.

Dosage Schedule and Dosage Order

Once the percentage of class time dedicated to active learning activities and lecture is established, an important consideration is how to integrate the two approaches, which introduces *dosage schedule* and *dosage order* as factors. Dosage schedule refers to how lecture and student activities are organized in a structured manner, such as blocked or interspersed during a class session. In a *blocked schedule*, students are presented with a full lecture over multiple concepts and a full active learning activity over these concepts, but the instructional methods are not alternated. In an *interspersed schedule*, students receive a mini-lecture and a mini-learning activity over the first concept, followed by a mini-lecture and mini-learning activity over the second concept, and so on. Therefore, the two instructional methods are alternated or interspersed in class. Research on the spacing effect suggests that breaking the lecture into segments (each accompanied by corresponding learning activities before or after) should be more effective than presenting the lecture as a continuous unit (accompanied by corresponding learning activities before or after), thereby supporting implementation of an interspersed schedule. The spacing effect is the finding that learning is often better when it occurs distributed or spaced over time rather than massed (Bahrick et al., 1993; Carpenter, 2017; Dunlosky et al., 2013; Karpicke, 2017; Weinstein et al., 2018). It has been theorized that spacing is beneficial because it allows unique features to be added to contextual representations during learning; these different contexts can help in the search process during future memory retrieval attempts (Karpicke, 2017; Karpicke et al., 2014; Mayer & Fiorella, 2022).

Dosage order refers to whether instructors lecture on the content before students engage in activities relating to the content (*lecture-then-activity*) or whether students explore the content through activities first and then receive a lecture over the content (*activity-then-lecture*). According to the cognitive load hypothesis (de Jong, 2010; Sweller et al., 1998; Sweller et al., 2019), learning activities should be more effective when implemented after lecture, particularly for students who do not have high relevant prior knowledge. *Cognitive load* refers to how much of a demand is imposed on working memory during a task (Sweller et al., 1998). Given that working memory is limited in capacity (e.g., see Cowan et al., 2012; Miller, 1956), having to discover the solution to a problem can lead to a long trial-and-error process that places a high demand on working memory (Sweller, 2004). Strong initial guidance could therefore be particularly important for students from underrepresented groups who may be more likely to be underprepared for college due to economic and educational disparities (see U.S. Department of Education, 2017; Theobald et al., 2020). For example, Salehi et al. (2019) found that differences in incoming preparation were associated with performance differences in introductory physics courses. On the other hand, according to the productive failure hypothesis (Kapur, 2008, Kapur & Bielaczyc, 2012), learning activities should be more effective when implemented before the lecture. It is theorized that the struggle and unsuccessful outputs of students will familiarize them with elements of the problem sets; when guidance is ultimately provided, this familiarization can help make their procedural and conceptual understanding more meaningful and better encoded (Kapur, 2008; Matlen & Klahr, 2013). Given that the cognitive load and productive failure hypotheses support implementing different dosage orders, future research should take dosage order into account to test these hypotheses when combining active learning and lecture interventions.

Prior Research on Dosage Amount, Schedule, and Order

Initial insight into whether and how dosage amount, dosage schedule, and/or dosage order affect student learning has been provided by Theobald et al. (2020) and Martella et al. (2024). In Theobald et al.'s meta-analysis examining how active learning versus traditional lecture affected the achievement gap for underrepresented students, they conducted a separate analysis on active learning intensity. They found that high-intensity active learning (dosage amount of 67–100%) was the most effective at narrowing the achievement gap for underrepresented groups. Unfortunately, the studies on which this analysis were based also differed on several other factors, such as the activities implemented in class and where lecture was implemented during the class period, preventing conclusions that can be tied unequivocally to dosage amount.

Martella et al. (2024) conducted two experiments to examine the impact of manipulating the dosage amount and dosage schedule of active learning and lecture. In the first experiment, college students received either an 18-minute lecture over a scientific topic (dosage amount: 100% lecture / 0% active learning) or an 18-minute active learning activity (a matching game) over that same topic (dosage amount: 0% lecture / 100% active learning). There were no other differences between conditions, following the control-of-variables strategy discussed earlier. Overall, students in the pure lecture condition outperformed their peers in the pure active learning condition on a test about the topic. In the second experiment, college students received one of the following: (a) an 18-minute lecture over a scientific topic (dosage amount: 100% lecture / 0% active learning); (b) a 9-minute lecture and a 9-minute active learning activity (a matching game) that were blocked (9-minute lecture → 9-minute activity; dosage amount: 50% lecture / 50% active learning); or (c) a 9-minute lecture and a 9-minute active learning activity (a matching game) that were interspersed (3-minute lecture → 3-minute activity → 3-minute lecture → 3-minute activity → 3-minute lecture → 3-minute activity; dosage amount: 50% lecture / 50% active learning). There were no other differences between conditions. Overall, students in the interspersed condition outperformed their peers in the pure lecture and blocked conditions on a test about the topic; however, students in the blocked condition did not, on average, outperform their peers in the pure lecture condition. Therefore, integrating lecture and active learning maximized student learning, but only when this integration occurred with an interspersed schedule. This study provides an example of how experiments can be designed to investigate dosage amount and dosage schedule in future research on active learning.

Moderating Variables

As a final note, there are many moderating variables that should also be systematically studied to determine whether there are any boundary conditions for certain active learning interventions. Two of these variables will be discussed in detail: relevant-knowledge level and demographics (e.g., sex, race/ethnicity). However, there are many other variables to also think about, including but not limited to, class size (e.g., <25 students, >250 students); course focus (e.g., conceptual knowledge, procedural knowledge); course discipline (e.g., engineering, physics); course topic difficulty (e.g., easy, hard); course format (e.g., online, face-to-face); and classroom setup (e.g., lecture hall, room with grouped tables).

Relevant-Knowledge Level

Whether students are novice, intermediate, or expert learners is important to examine in the context of active learning research because explicit instruction can be quite effective for more novice learners. As noted by Clark et al. (2012, p. 10), "if the learner has no relevant concepts in long-term memory, the only thing to do is blindly search for solutions. Novices can engage in problem solving for extended periods and learn almost nothing." Once students have developed a solid knowledge base, minimal guidance may be useful for reinforcing student learning (Archer & Hughes, 2011; Clark et al., 2012). For these more expert learners, actively taking part in generating information can lead to better long-term retention for this information than if students had been simply provided with it—a finding called the *generation effect* (deWinstanley & Bjork, 2004; Slamecka & Graf, 1978). Therefore, answers to questions about the optimal dosage amount, schedule, and order of lecture and active learning could be qualified by students' prior knowledge. For example, novice learners might need more lecture than expert learners and they might also need lecture to come first rather than second. This prior knowledge consideration also relates to the level of a class. For example, lecture may be more necessary in an introductory course where students are more likely to be more novice learners or with foundational content early in an instructional sequence.

Demographics

Some researchers have found that different implementations and intensities of active learning in the classroom have led to differences in the reduction of the achievement gap (Theobald et al., 2020). For example, in an investigation of society's educational debts, Nissen et al. (2022) found that collaborative learning did not help in closing the gap for first-generation Black and Hispanic women, continuing-generation Black women, and first-generation Black men. Further, a gender performance difference was found in inquiry-oriented courses but not in other courses (Johnson et al., 2020). Unfortunately, active learning "is not a silver bullet for mitigating achievement gaps" (Theobald et al., 2020, p. 6479). Of concern, certain instantiations of active learning have resulted in women reporting more stereotype threat as well as lower self-efficacy (Aguillon et al., 2020), and non-White first-generation college students reporting decreases in academic self-efficacy (Hood et al., 2020). Therefore, the research directions we have discussed for the three main issues in the active learning literature should also include a consideration of potential moderating variables, thereby providing insight into how active learning interventions can be tailored appropriately for different students. Consideration of moderating variables would provide clarity about *for whom* active learning works as well as *how* it should be implemented for different populations of students.

Conclusion

The growth of active learning research and the interest in transforming college courses to improve STEM education is encouraging. Researchers and practitioners alike care that students receive evidence-based practices in the classroom. The current active learning literature has provided a large platform from which deeper and more targeted research can stem. The purpose of this reflection article is to provide insight into areas within the literature that can be further developed so that active learning can move beyond its current status as "underdeveloped." By articulating three major issues and providing a discussion of avenues for future research to address them (see Table 1), our goal is to facilitate more insight into why active learning is effective, which forms of it are the most effective, how it should be implemented to maximize learning, and for whom different active learning interventions are the most effective. These research directions will provide mechanistic information in addition to practical information that can move the field forward. It is time for recommendations from the active learning literature to move beyond the general advice of "try active learning in your courses" to providing specific recommendations supported by appropriate empirical evidence and based on individual and group needs.

Acknowledgements

The authors would like to thank Richard Mayer for helpful feedback on an earlier draft of this article. The first author acknowledges support from the National Science Foundation Graduate Research Fellowship Program under grant number DGE-1842166 and the National Science Foundation Postdoctoral Research Fellowship Program under grant number 2222208. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Aguillon, S. M., Siegmund, G. F., Petipas, R. H., Drake, A. G., Cotner, S., & Ballen, C. J. (2020). Gender differences in student participation in an active-learning classroom. *CBE—Life Sciences Education, 19*(2), article 12. https://doi.org/10.1187/cbe.19-03-0048

Alfieri, L., Brooks, P. J., Aldrich, N. J., & Tenenbaum, H. R. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology*, *103*(1), 1–18. http://doi.org/10.1037/a0021017

Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., & Norman, M. K. (2010). *How learning works: Seven research-based principles for smart teaching.* Jossey-Bass.

Arthurs, L. A., & Kreager, B. A. (2017). An integrative review of in-class activities that enable active learning in college science classroom settings. *International Journal of Science Education, 39*(15), 2073–2091. https://doi.org/10.1080/09500693.2017.1363925

Association of American Universities (AAU). (2017). *Progress toward achieving systemic change: A five-year status report on the AAU undergraduate STEM education initiative.* https://www.aau.edu/sites/default/files/AAU-Files/STEM-Education-Initiative/STEM-Status-Report.pdf

Bahrick, H. P., Bahrick, L. E., Bahrick, A. S., & Bahrick, P. E. (1993). Maintenance of foreign language vocabulary and the spacing effect. *Psychological Science*, *4*(5), 316–321. https://doi.org/10.1111%2Fj.1467-9280.1993.tb00571.x

Bajak, A. (2014, May 12). Lectures aren't just boring, they're ineffective, too, study finds. *Science.* https://www.science.org/content/article/lectures-arent-just-boring-theyre-ineffective-too-study-finds

Bandura, A. (1986). *Social foundations of thought and action: A social cognitive theory*. Prentice-Hall.

Benjamin, A. S., & Bjork, R. A. (2000). On the relationship between recognition speed and accuracy for words rehearsed via rote versus elaborative rehearsal. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(3), 638–648. https://doi.org/10.1037//0278-7393.26.3.638

Bernstein, D. A. (2018). Does active learning work? A goof question, but not the right one. *Scholarship of Teaching and Learning in Psychology, 4*(4), 290–307. https://doi.org/10.1037/stl0000124

Bonwell, C. C., & Eison, J. A. (1991). *Active learning: Creating excitement in the classroom* (ED336049). ERIC. http://files.eric.ed.gov/fulltext/ED336049.pdf

Carpenter, S. K. (2017). Spacing effects on learning and memory. In J. T. Wixted (Ed.), *Cognitive psychology of memory, Vol. 2 of Learning and memory: A comprehensive reference (J. H. Byrne, Series Ed.)* (pp. 465–485). Academic Press. http://doi.org/10.1016/B978-0-12-809324-5.21054-7

Center for STEM Learning. (2016). *TRESTLE mini seed grant proposals: Transforming education, supporting teaching and learning excellence.* University of Colorado Boulder. https://www.colorado.edu/csl/sites/default/files/attached-files/trestle_rfp-_minigrant_0.pdf

Chen, Z., & Klahr, D. (1999). All other things being equal: Acquisition and transfer of the control of variables strategy. *Child Development*, *70*(5), 1098–1120. https://doi.org/10.1111/1467-8624.00081

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823

Clark, R. E., Kirschner, P. A., & Sweller, J. (2012). Putting students on the path to learning: The case for fully guided instruction. *American Educator*, *36*(1), 6–11. https://files.eric.ed.gov/fulltext/EJ971752.pdf

Collins, B. V. C. (2019). Flipping the precalculus classroom. *International Journal of Mathematical Education in Science and Technology, 50*(5), 728–746. https://doi.org/10.1080/0020739X.2018.1535098

Connell, G. L., Donovan, D. A., & Chambers, T. G. (2016). Increasing the use of student-centered pedagogies from moderate to high improves student learning and attitudes about Biology. *CBE—Life Sciences Education, 15*(1), Article 3. https://doi.org/10.1187/cbe.15-03-0062

Cowan, N., Rouder, J. N., Blume, C. L., & Saults, J. S. (2012). Models of verbal working memory capacity: What does it take to make them work? *Psychological Review*, *119*, 480–499. https://doi.org/1037/a0027791

Crimmins, M. T., & Midkiff, B. (2017). High structure active learning pedagogy for the teaching of organic chemistry: Assessing the impact on academic outcomes. *Journal of Chemical Education, 94,* 429–438. https://doi.org/10.1021/acs.jchemed.6b00663

Dawson, P. (2015, July 2). Will the University of Adelaide's lecture phase-out be a flop? *The Conversation*. https://theconversation.com/will-the-university-of-adelaides-lecture-phase-out-be-a-flop-44074

de Jong, T. (2010). Cognitive load theory, educational research, and instructional design: Some food for thought. *Instructional Science, 38*(2), 105-134. https://doi.org/10.1007/s11251-009-9110-0

Deslauriers, L., McCarty, L. S., Miller, K., Callaghan, K., & Kestin, G. (2019). Measuring actual learning versus feeling of learning in response to being actively engaged in the classroom. *Proceedings of the National Academy of Sciences, 116*(39), 19251–19257. www.pnas.org/cgi/doi/10.1073/pnas.1821936116

deWinstanley, P. A., & Bjork, E. L. (2002). Successful lecturing: Presenting information in ways that engage effective processing. New Directions for Teaching & Learning, 2002*(89),* 19–31. https://doi.org/10.1002/tl.44

deWinstanley, P. A., & Bjork, E. L. (2004). Processing strategies and the generation effect: Implications for making a better reader. *Memory & Cognition*, *32*(6), 945–955. https://doi.org/10.3758/BF03196872

Driessen, E. P., Knight, J. K., Smith, M. K., Ballen, C. J. (2020). Demystifying the meaning of active learning in postsecondary biology education. *CBE—Life Sciences Education, 19*(4), 1–9. https://doi.org/10.1187/cbe.20-04-0068

Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & 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*(1), 4–58. http://doi.org/10.1177/1529100612453266

Evans, T., & Dietrich, H. (2022). *Inquiry-based mathematics education: A call for reform in tertiary education seems unjustified.* arXiv. https://arxiv.org/abs/2206.12149

Eyler, J. (2018). *"Active Learning" has become a buzzword (and why that matters).* Rice University Center for Teaching Excellence. Retrieved from https://cte.rice.edu/blogarchive/2018/7/16/active-learning-has-become-a-buzz-word

Fiorella, L., & Mayer, R. E. (2015). *Learning as a generative activity: Eight learning strategies that promote understanding.* Cambridge University Press. https://doi.org/10.1017/CBO9781107707085

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences, 111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Gallimore, R., Lam, D. J., Speidel, G. E., & Tharp, R. G. (1977). The effects of elaboration and rehearsal on long-term retention of shape names by kindergarteners. *American Educational Research Journal*, *14*(4), 471–483. https://doi.org/10.2307/1162344

Gardiner, J. M., Gawlik, B., & Richardson-Klavehn, A. (1994). Maintenance rehearsal affects knowing, not remembering; elaborative rehearsal affects remembering, not knowing. *Psychonomic Bulletin & Review*, *1*, 107–110. https://doi.org/10.3758/BF03200764

Gleason, B. L., Peeters, M. J., Resman-Targoff, B. H., Karr, S., McBane, S., Kelley, K., Thomas, T., & Denetclaw, T. H. (2011). An active-learning strategies primer for achieving ability-based educational outcomes. *American Journal of Pharmaceutical Education, 75*(9), 1–12. https://doi.org/10.5688/ajpe759186

Goossens, N. A. M. C., Camp, G., Verkoeijen, P. P. J. L., Tabbers, H. K., & Zwaan, R. A. (2014). The benefit of retrieval practice over elaborative restudy in primary school vocabulary learning. *Journal of Applied Research in Memory and Cognition*, *3*(3), 177-182. https://doi.org/10.1016/j.jarmac.2014.05.003

Hackathorn, J., Garczynski, A. M., Blankmeyer, K., Tennial, R. D., & Solomon, E. D. (2011). All kidding aside: Humor increases learning at knowledge and comprehension levels. *Journal of the Scholarship of Teaching and Learning, 11*(4), 116–123. https://eric.ed.gov/?id=EJ956757

Hartikainen, S., Rintala, H., Pylväs, L., & Nokelainen, P. (2019). The concept of active learning and the measurement of learning outcomes: A review of research in engineering higher education. *Education Sciences, 9*(4), 1–19. https://doi.org/10.3390/educsci9040276

Hood, S., Barrickman, N., Djerdjian, N., Farr, M., Gerrits, R. J., Lawford, H., Magner, S., Ott, B., Ross, K., Roychowdury, H., Page, O., Stowe, S., Jensen, M., & Hull, K. (2020). Some believe, not all achieve: The role of active learning practices in anxiety and academic self-efficacy in first-generation college students. *Journal of Microbiology & Biology Education, 21*(1), 1–11. https://doi.org/10.1128/jmbe.v21i1.2075

Johnson, E., Andrews-Larson, C., Keene, K., Melhuish, K., Keller, R., & Fortune, N. (2020). Inquiry and gender inequity in the undergraduate mathematics classroom. *Journal for Research in Mathematics Education, 51*(4), 504–516. https://doi.org/10.5951/jresematheduc-2020-0043

Kapur, M. (2008). Productive failure. *Cognition and Instruction, 26*(3), 379–424. https://doi.org/10.1080/07370000802212669

Kapur, M., & Bielaczyc, K. (2012). Designing for productive failure. *Journal of the Learning Sciences, 21*(1), 45–83. https://doi.org/10.1080/10508406.2011.591717

Karpicke, J. D. (2017). Retrieval-based learning: A decade of process. In J. T. Wixted (Ed.), *Cognitive psychology of memory, Vol. 2 of learning and memory: A comprehensive reference* (J. H. Byrne, Series Ed.) (pp. 487–514). Oxford: Academic Press. https://doi.org/10.1016/B978-0-12-809324-5.21055-9

Karpicke, J. D., & Blunt, J. R. (2011). Retrieval practice produces more learning than elaborative *Science, 331*(6018), 772–775. https://doi.org/10.1126/science.1199327

Karpicke, J. D., Lehman, M., & Aue, W. R. (2014). Retrieval-based learning: An episodic context account. In B. H. Ross (Ed.), *Psychology of learning and motivation, Vol. 61* (pp. 237–284). Academic Press. https://psycnet.apa.org/record/2014-12777-007

Karpicke, J. D., & O'Day, G. M. (in press). Elements of effective learning. In M. J. Kahana & A. D. Wagner (Eds.), *Oxford handbook of human memory* (Vol. 2). Oxford University Press.

Karpicke, J. D., & Smith, M. A. (2012). Separate mnemonic effects of retrieval practice and elaborative encoding. *Journal of Memory and Language, 67,* 17–29. https://doi.org/10.1016/j.jml.2012.02.004

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effects of direct instruction and discovery learning. *Psychological Science, 15*(10)*,* 661–667. https://doi.org/10.1111/j.0956-7976.2004.00737.x

Kruit, P. M., Oostdam, R. J., van den Berg, E., & Schuitema, J. A. (2018). Effects of explicit instruction on the acquisition of students' science inquiry skills in grades 5 and 6 of primary education. *International Journal of Science Education*, *40*(4), 421–441. https://doi.org/10.1080/09500693.2018.1428777

Lawson, A. P., Davis, C. R., & Son, J. Y. (2019). Not all flipped classes are the same: Using learning science to design flipped classrooms. *Journal of the Scholarship of Teaching and Learning, 19*(5), 77–104. https://doi.org/10.14434/josotl.v19i5.25856

Lombardi, D., Shipley, T. F., Astronomy Team, Biology Team, Chemistry Team, Engineering Team, Geography Team, Geoscience Team, & Physics Team. (2021). The curious construct of active learning. *Psychological Science in the Public Interest, 22*(1), 8–43. https://doi.org/10.1177/1529100620973974

Lorch, R. F., Lorch, E. P., Calderhead, W. J., Dunlap, E. E., Hodell, E. C., & Freer, B. D. (2010). Learning the control of variables strategy in higher and lower achieving classrooms: Contributions of explicit instruction and experimentation. *Journal of Educational Psychology*, *102*(1), 90–101. https://doi.org/10.1037/a0017972

Martella, A. M., Lovett, M., & Ramsay, L. (2021a). Implementing active learning: A critical examination of sources of variation in active learning science courses. *Journal on Excellence in College, 32*(1), 67–96.

Martella, A. M., Yatcilla, J., Martella, R. C., Marchand-Martella, N. E., Karatas, T., Ozen, Z., Park, H., Simpson, A., & Karpicke, J. D. (2021b). Quotation accuracy matters: An examination of how an influential meta-analysis on active learning has been cited. *Review of Educational Research*, *9*(2), 272–308. https://doi.org/10.3102/0034654321991228

Martella, A. M., Yatcilla, J., Park, H., Marchand-Martella, N. E., & Martella, R. C. (2021c). Investigating the active learning research landscape through a bibliometric analysis of an influential meta-analysis on active learning. *SN Social Sciences*, *1*, Article 228. https://doi.org/10.1007/s43545-021-00235-1

Martella, A. M., Martella, R. C., Yatcilla, J. K., Newson, A., Shannon, E. N., & Voorhis, C. (2023). How rigorous is active learning research in STEM education? An examination of key internal validity controls in intervention studies. *Educational Psychology Review*, *35*(4), Article 107. https://doi.org/10.1007/s10648-023-09826-1

Martella, A. M., Schneider, D. W., O'Day, G. M., & Karpicke, J. D. (2024). Investigating the intensity and integration of active learning and lecture. *Journal of Applied Research in Memory and Cognition.* Advance online publication. https://doi.org/10.1037/mac0000160

Matlen, B. J., & Klahr, D. (2013). Sequential effects of high and low instructional guidance on children's acquisition of experimentation skills: Is it all in the timing? *Instructional Science, 41*(3)*,* 621–634. https://doi.org/10.1007/s11251-012-9248-z

Mayer, R. E. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist, 59*(1), 14–19. https://doi.org/10.1037/0003-066X.59.1.14

Mayer, R. E. (2008). Applying the science of learning: Evidence-based principles for the design of multimedia instruction. *American Psychologist, 63*(8), 760–769. https://doi.org/10.1037/0003-066X.63.8.760

Mayer, R. E. (2021). *Multimedia learning* (3rd ed). Cambridge University Press.

Mayer, R. E., & Fiorella, L. (2022). Principles for managing essential processing in multimedia learning: Segmenting, pre-training, and modality principles. In R. E. Mayer & L. Fiorella

(Eds.), *The Cambridge handbook of multimedia learning* (3rd ed., pp. 243-260). Cambridge University Press.

Michael, J. (2006). Where's the evidence that active learning works? *Advances in Physiology Education*, *30*(4), 159–167. https://doi.org/10.1152/advan.00053.2006

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*(2), 81–97. https://doi.org/10.1037/h0043158

Morgan, P. L., Farkas, G., & Maczuga, S. (2015). Which instructional practices most help first-grade students with and without mathematics difficulties? *Educational Evaluation and Policy Analysis, 37*(2), 184–205. https://doi.org/10.3102/0162373714536608

Nissen, J., Van Dusen, B., & Kukday, S. (2022). *A QuantCrit investigation of society's educational debts due to racism, sexism, and classism in biology student learning.* bioRxiv. https://www.biorxiv.org/content/10.1101/2022.05.05.490808v1.full

O'Day, G. M., & Karpicke, J. D. (2021). Comparing and combining retrieval practice and concept mapping. *Journal of Educational Psychology,* 113(5), 986–997. https://doi.org/10.1037/edu0000486

Opdal, P. A. (2022). To do or to listen? Student active learning vs. the lecture. *Studies in Philosophy and Education, 41,* 71–89. https://doi.org/10.1007/s11217-021-09796-3

Pekrun, R., & Linnenbrink-Garcia, L. (2012). Academic emotions and student engagement. In S. L. Christenson, A. L. Reschly, & C. Wylie (Eds.), *Handbook of research on student engagement* (pp. 259–282). Springer Science + Business Media. https://doi.org/10.1007/978-1-4614-2018-7_12

Pekrun, R., & Perry, R. P. (2014). Control-value theory of achievement emotions. In R. Pekrun & L. Linnenbrink-Garcia (Eds.), *International handbook of emotions in education* (pp. 120–141). Taylor & Francis.

Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education, 93*(3), 223–231. https://doi.org/10.1002/j.2168-9830.2004.tb00809.x

Rhodes, A. (2021). Lowering barriers to active learning: A novel approach for online instructional environments. *Advances in Physiology Education, 45*(3)*,* 547–553. https://doi.org/10.1152/advan.00009.2021

Richardson, D. (2008). Don't dump the didactic lecture; fix it. *Advances in Physiology Education, 32*(1)*,* 23–24. https://doi.org/10.1152/advan.00048.2007

Rissanen, A. (2018). Student engagement in large classroom: The effect on grades, attendance and student experiences in an undergraduate biology course. Canadian *Journal of Science, Mathematics and Technology Education, 18*(2)*,* 136–153. https://doi.org/10.1007/s42330-018-0015-2

Roediger, H. L., & Karpicke, J. D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science, 17*(3), 249–255. https://doi.org/10.1111/j.1467-9280.2006.01693.x

Rosenshine, B. (1995). Advances in research on instruction. *The Journal of Educational Research, 88*(5), 262–268. https://doi.org/10.1080/00220671.1995.9941309

Salehi, S., Burkholder, E., Lepage, G. P., Pollock, S., & Wieman, C. (2019). Demographic gaps or preparation on performance of students in introductory physics. *Physical Review Physics Education Research, 15*(2), Article 020114. https://doi.org/10.1103/PhysRevPhysEducRes.15.020114

Shadle, S. E., Marker, A., & Earl, B. (2017). Faculty drivers and barriers: Laying the groundwork for undergraduate STEM education reform in academic departments. *International Journal of STEM Education, 4*(1), Article 8. https://doi.org/10.1186/s40594-017-0062-7

Shaughnessy, J. J. (1981). Memory monitoring accuracy and modification of rehearsal strategies. *Journal of Verbal Learning and Verbal Behavior*, *20*(2), 216-230. https://doi.org/10.1016/S0022-5371(81)90389-3

Shekhar, P., Borrego, M., DeMonbrun, M., Finelli, C., Crockett, C., & Nguyen, K. (2020). Negative student response to active learning in STEM classrooms: A systematic review of underlying reasons. *Journal of College Science Teaching, 49*(6), 45–54. https://www.nsta.org/journal-college-science-teaching/journal-college-science-teaching-julyaugust-2020/negative-student

Slamecka, N. J., & Graf, P. (1978). The generation effect: Delineation of a phenomenon. *Journal of Experimental Psychology: Human Learning and Memory*, *4*, 592–604. https://doi.org/10.1037/0278-7393.4.6.592

Smith, C. V., & Cardaciotto, L. (2011). Is active learning like broccoli? Student perceptions of active learning in large lecture classes. *Journal of the Scholarship of Teaching and Learning, 11*(1), 53–61. https://eric.ed.gov/?id=EJ915923

Stains, M., Harshman, J., Barker, M. K., Chasteen, S. V., Cole, R., DeChenne-Peters, S. E., Eagan, M. K., Esson, J. M., Knight, J. K., Laski, F. A., Levis-Fitzgerald, M., Lee, C. J., Lo, S. M., McDonnell, L. M., McKay, T. A., Michelotti, N., Musgrove, A., Palmer, M.S., Plank, K. M., Rodela, T. M., … & Young, A. M. (2018). Anatomy of STEM teaching in North American universities: Lecture is prominent, but practices vary. *Science, 359*(6383), 1468–1470. http://chemistry.as.virginia.edu/sites/chemistry.as.virginia.edu/files/2018-Stains%20et%20al-Science-%20COPUS%20profiles.pdf

Sweller, J. (2004). Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science, 32*(1-2), 9–31. https://doi.org/10.1023/B:TRUC.0000021808.72598.4d

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. Springer.

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, *10*(3), 251–296. https://doi.org/10.1023/a:1022193728205

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review*, *31*, 261–292. https://doi.org/10.1007/s10648-019-09465-5

Theobald, E. J., Hill, M. J., Tran, E., Agrawal, S., Arroyo, E. N., Behling, S., Chambwe, N., Cintrón D. L., Cooper, J. D., Dunster, G., Grummer, J. A., Hennessey, K., Hsiao, J., Iranon, N., Jones, L., Jordt, H., Keller, M., Lacey, M. E., Littlefield, C. E., … Freeman, S. (2020). Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. *Proceedings of the National Academy of Sciences*, *117*(12), 6476–6483. https://doi.org/10.1073/pnas.1916903117

U.S. Department of Education. (2017). *Developmental education. Challenges and strategies for reform*. https://www2.ed.gov/about/offices/list/opepd/education-strategies.pdf

Usher, E. L., & Pajares, F. (2008). Sources of self-efficacy in school: Critical review of the literature and future directions. *Review of Educational Research*, *78*(4), 751-796. https://doi.org/10.3102/0034654308321456

Weinstein, Y., Madan, C. R., & Sumeracki, M. A. (2018). Teaching the science of learning. *Cognitive Research: Principles and Implications*, *3*(2), 1–17. https://doi.org/10.1186/s41235-017-0087-y

Zakrajsek, T. (2018). Reframing the lecture versus active learning debate: Suggestions for a new way forward. *Education in the Health Professions, 1*(1), 1–3. https://doi.org/10.4103/EHP.EHP_14_18