Mathematics Education Research Journal (2022) 34:911–931
https://doi.org/10.1007/s13394-021-00369-8

ORIGINAL ARTICLE

The use of lecture capture in university mathematics education: a systematic review of the research literature

Euan Lindsay[1] · **Tanya Evans**[1]

Received: 29 July 2020 / Revised: 26 January 2021 / Accepted: 27 January 2021 /
Published online: 15 February 2021

Abstract

Lecture capture (LC), the process of recording face-to-face lectures for future viewing, has become a common technology in Western universities in the twenty-first century, yet research on its effectiveness has lagged behind its implementation. Despite the rapid, widespread implementation, research regarding the impact LC has on pedagogy and student attainment is limited and not conclusive in its findings. It is still unclear if there is a causal or a correlated relationship between attainment and usage of LC. This systematic review sought to collate and compare the current literature on the efficacy of LC in tertiary mathematics education and provide practical advice for institutions that use or plan to use LC. The literature is consistent in the opinion that students and administrators positively view LC for its utility and flexibility despite the moderately strong evidence that most institutions face attendance drops. However, most students do tend to see attending lectures/watching recordings as an "either-or." The literature predominantly reports a negative association between attainment and the use of LC as a substitute to live lectures. The proportion of students who choose to skip live lectures has steadily increased over the last decade as the student campus culture adjusts to LC. Within this group, LC is used imperfectly, providing false benefits and promoting surface learning strategies. There is evidence that regular use of LC by this large group of students may diminish the quality of their learning. We offer research-informed, evidence-based recommendations to mitigate the unplanned and counterproductive impact of LC implementation.

Keywords Lecture capture · Lecture recording · Mathematics education · Attendance · Attainment · Tertiary education

✉ Tanya Evans
t.evans@auckland.ac.nz

[1] Department of Mathematics, University of Auckland, Auckland, New Zealand

Introduction

This review aims to provide a snapshot of the current literature on lecture capture (LC) usage in tertiary mathematics education, specifically its effects on student attendance and attainment.

Lecture capture (also referred to as online lectures, video podcasts, Web-based lecture technology (WBLT), or lecture recordings) is a term in the education literature that refers to a range of technologies. While most commonly audiovisual recordings of face-to-face lectures, it can also be short videos intended to be watched before lectures, additional content, or complete video substitutes for lectures (Williams et al., 2012). This review will only focus on lecture capture (LC), which is defined following Yoon et al. (2014) as "synchronized audio and visual recordings of live lectures, which students can download to view at their own leisure" (p. 228) but also includes what Meehan and McCallig (2019) referred to as online lectures—recordings of the lecture content done by the lecturer (not necessarily during the live lecture) which have a one-to-one correspondence with a live lecture from the course. Sometimes those online lectures can be split into many shorter videos—on average, 7 min long (Meehan & McCallig, 2019).

In recent years, the usage of LC has experienced mass adoption in Western universities (Wood et al., 2018). Data from a 2017 survey showed that 86% of UK universities had at least partial adoption of lecture capture (Newland, 2017), up from 71% in 2016 (Walker et al., 2016). In Australia, almost all universities have some form of LC, although it may only be present in select faculties (Dona et al., 2017). Alongside the perceived educational benefits, institutional factors have been a key driver of this uptake (Njenga & Fourie, 2010). As the technology is seen to be catering to most students in some capacity (e.g., students who work part-time or are too unwell to attend in person; Nordmann et al., 2019), it can be used as another promotional tool for universities in the competitive tertiary education market.

Despite the rapid, widespread implementation, research regarding the impact LC has on pedagogy and student attainment is limited and not conclusive in its findings. It is still unclear if there is a causal or a correlated relationship between attainment and usage of LC, but regardless, the wave of "techno-positivism" towards the technology from university administrations and students continues (Njenga & Fourie, 2010). Lecturers, however, often express apprehension, fearing decreases in lecture attendance, leading to decreases in student performance (Hall et al., 2020; Loch et al., 2016).

In the wake of the Covid-19 pandemic, the urgency of obtaining clear answers about the impact of LC is paramount. The recent worldwide shift to online teaching as an emergency response to the COVID-19 pandemic has resulted in an unprecedented use of LC at scale. It appears that a large majority of tertiary teachers have had to develop video resources to replace face-to-face lectures and deliver them online, putting their hesitation and trepidation aside. With the abundance of newly developed video resources, the post-COVID-19 educational landscape is foreshadowed to be vastly different, skipping a natural gradual stage of continuous developmental changes to the sector. This development could be a welcome breakthrough, but, as never before, it amplifies the big issue: research is lagging the implementation. With a stark sense of urgency, the adoption of LC needs to be thoroughly investigated.

It appears that any proper investigation of LC adaptation necessitates a nuanced, discipline-specific approach. A 2017 survey of Australian lecturers found that 91% of mathematics and science lecturers predominantly taught face-to-face, compared to just 44% in arts (Dona et al., 2017). In terms of different LC usage patterns, it is known that students in STEM subjects who use LC view more of recorded content than students in any other subject, and arts and social sciences students are the lowest users (Morris et al., 2019). More specifically, STEM students have significantly longer view durations and more presentations watched per user than students in other subject areas. This may suggest that generalizing across disciplines is unwise, thus accentuating the need for this review to be conducted with a specific focus on mathematics.

The most recent mathematics-specific review was conducted in 2012 by Trenholm et al. who examined available literature published prior to 2011. The main goal of their review was to document available research on tertiary mathematics lecturing and to discuss issues raised by the emergence of LC. Their comprehensive synthesis provided the following finding: while noting student and lecturer satisfaction with the utility of LC reported in the literature, they emphasized that very little empirical evidence exists on the impact on student learning and lecturer practice. Moreover, the available evidence indicates a negative correlation between LC use and student achievement, thus raising serious questions about the impact of LC on the learner community and on learning outcomes.

A decade later, the question still remains, is the cart before the horse? To better understand the implications of LC on mathematics teaching and learning at university, this systematic review of the research literature published over the last decade is structured around the following research questions:

1. What are students' perceptions of lecture capture and its uptake?
2. Does lecture capture have an effect on attendance?
3. What is the relationship between lecture capture usage and student attainment?

Methodology

Article collection

Since this literature review aimed to highlight relevant literature on lecture capture technology in mathematics education at the tertiary level, the sources collected were primarily studies investigating mathematics and statistics courses. The databases Scopus, ProQuest, ERIC, Web of Science, and PsycInfo were searched in January–July 2020 with the key terms of *mathematics* (math* OR calculus* OR statistics*), *post-secondary* (undergraduate* OR post-secondary* OR tertiary*) and *lecture capture* ("lecture capture" OR "recording" OR "online viewing" OR "watch online"). In addressing our research questions, we restricted the findings to studies pertaining to student attendance and attainment by using additional key terms (attainment* OR attendance*), allowing for synonyms. Only peer-reviewed journal articles, conference proceedings, and doctoral dissertations that had been published since 2010 in English were chosen by applying refinement criteria on certain databases (ProQuest and Scopus). On the Scopus database, the subject area was limited to STEM and social sciences, including economics, econometrics, and finance, resulting in 282 returned articles. On the general ProQuest database, only relevant subject databases were selected, such as the Psychology Database, Education Database, Research Library: Social Sciences, Social Science Database, Science Database, Computer Science Database, and Social Services Abstracts with the Higher Education filter, resulting in 541 articles returned. Fewer articles were returned from the search queries of the ERIC and Web of Science databases, with a total of 14 results each.

We also manually screened Google Scholar with the search parameter ((math* OR calculus* OR statistics*) AND (undergraduate* OR post-secondary* OR tertiary* OR universit*) AND (recording OR lecture capture OR online viewing OR watch online) AND (attainment* OR attendance*), with the first author screening through 385 articles and the second author checking abstracts for 250 articles.

Inclusion and exclusion criteria

The screening process followed the PRISMA protocol (Fig. 1) and was conducted independently by the two authors. Only higher education studies investigating a mathematics or statistics course were chosen. By a course, we mean a single unit of tertiary study, which is usually completed by students over a semester (also known as a module, paper, or subject in different higher education institutions). Conforming

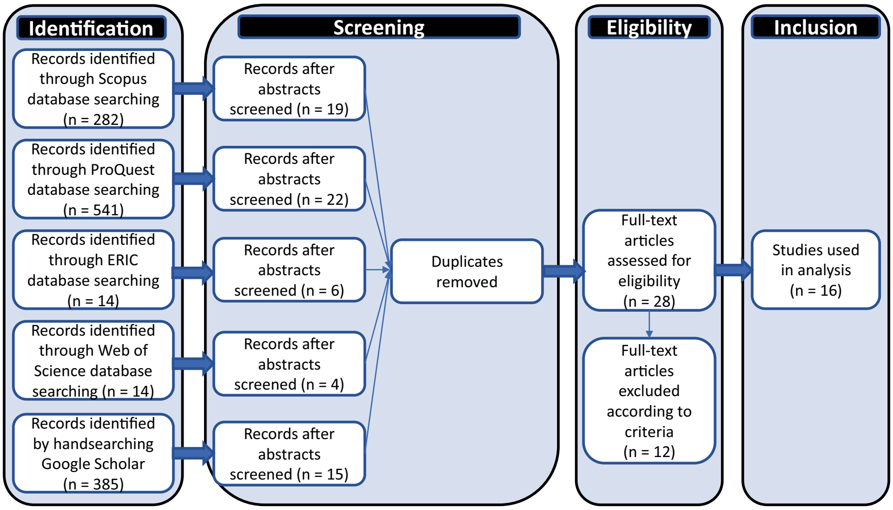

Fig. 1 PRISMA flow diagram of the literature search and processing of records

to the present time "mainstream," these courses were chosen only if they followed a non-compulsory lecture format to best mirror traditional mathematics courses and may have had additional practical problem-solving sessions (tutorials) once a week.

Because of the rapid nature of technological change, this review did not consider literature older than 10 years. It is well documented that broadband capabilities, access to 1–1 devices, and students' relationships with technology are ever evolving on university campuses (Seilhamer et al., 2018). This review assumes the more recent sources will better reflect the current university environment and culture.

As this review focuses on capture of face-to-face lectures, research on online universities and distance learning was omitted, as was all research with mandatory lecture attendance.

Results

After screening using the inclusion criteria, a final 16 studies were selected for systematic analysis. These sources are listed in Table 1, which contains a concise description of the studies' characteristics: location, learning context, type of data, sample size, research approach, and attainment measures.

The included studies were systematically analyzed by making use of two coding schemes: one on the study level and one on the results of those studies (Lipsey & Wilson, 2001). In the first coding scheme, general study information (such as publication year, study design, and methods), sample characteristics (gender and age), educational context specifics (such as the tertiary institution, its region, and the student cohort), and methodological characteristics (such as the type of comparison groups, type of data collected, analysis used, and methodological concerns) were coded for each study. In the second coding scheme capturing the results of the studies, we gathered information about the conclusions reached regarding the impact of LC on attainment, attendance, and students' perceptions about the LC. The double-coding of the 17 articles was conducted separately by the two authors and then compared. There were no disagreements to be resolved.

In the following sections, we explore the themes reported in the identified studies to answer the research questions.

What are students' perceptions of lecture capture and its uptake?

Students see immense value in LC because of the flexibility it provides, this being the most obvious and widely accepted perception of LC (e.g., Hall et al., 2020; Meehan & McCallig, 2019; Trenholm et al., 2019; Yoon & Sneddon, 2011; Yoon et al., 2014). Because the lecture information can be accessed at any time, LC availability is perceived to facilitate a better study/work/life balance and provide equitable access to content for students who have other commitments (Hall et al., 2020). Frequently, it is seen as a safety net (Loch et al., 2016).

Table 1 Studies selected for the systematic review

Article	Location	Mathematical learning context	Type of data	Sample size	Research approach	Measures of attainment
Docherty et al. (2019)	University of Edinburgh	Introduction to Linear Algebra, Mathematics for Physics	Video 'clicks', viewing time, attendance data, student interviews (for 10 individuals)	1000	Regression and qualitative interview analysis	-
Gouia-Zarrad and Gunn (2018)	American University of Sharjah	Mathematics for Engineers	Video 'clicks', attendance data, survey of students LC perceptions	70	Presenting data	-
Howard et al. (2018)	University College Dublin	Mathematics for Business	Video 'clicks', attendance data, survey data (open-ended)	522	Cluster analysis of usage patterns and qualitative interview analysis	Course mark
Inglis et al. (2011)	Loughborough University	Multivariate Calculus	Viewing time, attendance data, academic results	534	Cluster analysis of usage patterns	Diagnostic test, final exam
Jones et al. (2018)	University College London	Linear Models and the Analysis of Variance	Viewing time, academic results	190	Multiple linear regression	Exam mark
Khan (2013)	University of Western Australia	Statistics for Business	Academic results	400	Longitudinal analysis of teaching change over 4 semesters	Course mark
Le et al. (2010)	University of Toronto	Calculus I, Calculus for Management, Calculus II for Physical Sciences	Viewing time, self-report attendance survey, academic results	500	Multiple linear regression	Course mark
Loch et al. (2016)	Swinburne University of Technology	Engineering Mathematics 3	Survey of students' perception of LC	23	Comparisons across years	-
Meehan and McCallig (2019)	University College Dublin	Mathematics for Business	Video 'clicks', academic results	123	Multiple linear regression	School score, course mark

Table 1 (continued)

Article	Location	Mathematical learning context	Type of data	Sample size	Research approach	Measures of attainment
Mullamphy (2011)	James Cook University	Engineering Mathematics I	Survey of students' perception of LC	34	Students perceptions of LC	-
Sorensen (2015)	University of South Dakota	Applied Calculus	Viewing time, academic results, survey	200	Multiple linear regression	Course mark
Trenholm et al. (2019)	Loughborough University, University of South Australia	Engineering Mathematics 3, Mathematical Methods for Engineers 2	Pre/post semester surveys: self-report data on LC usage, R-SPQ-2F questionnaire, numeracy test	97	Two-phase multi-site quasi-experimental pre- and post-test design study; descriptive stats, group differences (paired t-tests)	Pre/post numeracy test (NAPLAN)
Wood et al. (2018)	University of Edinburgh	Introduction to Linear Algebra, Mathematics for Physics	Individual student interviews	10	Students perceptions of LC	-
Yoon et al. (2014)	University of Auckland	Calculus I and Linear Algebra I	Survey of student views on LC (open-ended)	337	Qualitative analysis of student views	-
Yoon and Sneddon (2011)	University of Auckland	Calculus I and Linear Algebra I	Survey of learning behaviour	172	Descriptive stats, association analysis	Course mark
Zimmermann et al. (2013)	University of Ludwigsburg (Germany)	Introduction to Elementary Geometry, Didactics of Geometry, Application-oriented Mathematics	Viewing time, self-report attendance survey, academic results	119	Multiple linear regression	Exam mark

From an academic perspective, students see LC as a positive influence because of its utility as a study tool to re-watch content (e.g., Hall et al., 2020; Yoon & Sneddon, 2011). Gouia-Zarrad and Gunn (2018) survey of engineering mathematics students found that 93% of students perceived LC as a necessary support. Clearly, the majority of students find use in technology. Moreover, it is argued that LC is especially useful in mathematics, as discussed by Loch et al. (2016), who reasoned that as mathematics is a hierarchical subject (knowledge building on previous knowledge), students can use LC as a tool to avoid falling behind.

Unsurprisingly, high utility value perceptions translate into high uptake. In Jones et al. (2018) study of an undergraduate statistics class, 88% of students accessed LC at least once. The proportion reported in Yoon and Sneddon (2011) is even higher, with 95.5% of students watching at least one recorded mathematics lecture. The purpose of LC is that students who would be discouraged after falling behind now have the tools to catch up. On the other hand, LC makes students more likely to fall behind because of this sense of security, which may lead to increased cramming near key assessments.

However, even after attending the lecture, some students still often find value in watching the recording (Hall et al., 2020; Yoon & Sneddon, 2011; Yoon et al., 2014). For example, in a study of two first-year mathematics courses at the University of Auckland, Yoon and Sneddon (2011) analyzed student viewing patterns through a self-report questionnaire. They found that a large proportion of students reported pausing their LC viewing “for examples and ideas, toggling back and forth within the lecture or only watching relevant parts” (p. 439). This behavior was especially prominent for non-native speakers, who are potentially more susceptible to falling behind because of language comprehension difficulties. In a recent study of first- and final-year mathematics students’ experiences at two Australian universities, participants reported that “they were rarely able to fully understand content by attending lectures in person and found that the ability to pause and rewind the recordings mitigated these issues. These capabilities were particularly valued by participants who described themselves as “slow learners” or “not that good at maths”” (Hall et al., 2020, p. TBA).

However, this positivity towards LC should not be confused with a desire to replace lectures. Wood et al. (2018) reported that physics/mathematics students still saw value in attending the lecture over watching the recording because of the social contact and ability to ask questions. Similarly, Loch et al. (2016) found that nearly all students surveyed did not want a reduction in contact hours (e.g., lectures, tutorials). Perhaps it is the safety net LC provides that gives it universal praise from students, yet the evidence asserting its value when directly compared to traditional teaching is missing.

A minority of students do see LC as a substitute for attendance. Based on an analysis of student self-reports in a large first-year mathematics course at the University of Auckland, Yoon and Sneddon (2011) revealed that 30% of students viewed LC as a replacement for live lecture attendance. Similar perceptions were reported by Khan (2013): in a large statistics course at the University of Western

Australia, 23–25% of students identified LC as a primary reason for missing lectures. Of note, Docherty et al. (2019) investigation on first-year mathematics students at the University of Edinburgh found that only 9% of students who missed class went on to watch the lecture. The performance aspect of this relationship is discussed more in the attainment section below.

Does lecture capture have an effect on attendance?

A concern for staff is the perceived impact that LC has on attendance, with the fear that students will use LC as a substitute for rather than a supplement to face-to-face lectures (Loch et al., 2016; Wood et al., 2018), yet the current research on the relationship between LC and attendance is mixed.

Of the 16 relevant studies this review identified, 10 did not consider attendance, none reported a positive impact, three sources reported insignificant/no change, and four reported a negative impact on attendance (Table 2). Attendance was often not considered, perhaps because (1) it is difficult to record non-compulsory attendance, (2) there is little desire to investigate it because of the prevailing staff opinion that LC decreases attendance, and (3) attainment was the main focus of the studies.

In all studies that explicitly reported a drop in attendance, the total attendance reductions were in the range of 23–30%. However, none of these studies were specifically designed to establish a causal relationship. All four studies used student self-report data and/or lecturer observations to reach a conclusion (from the University of Western Australian by Khan (2013), from the University of Auckland by Yoon and Sneddon (2011), from Germany by Zimmermann et al. (2013), and from a multi-site study of two mathematics for engineering courses at the University of South Australia and Loughborough University, UK, by Trenholm et al. (2019)). For example, as seen in both Zimmermann et al. (2013) and Yoon and Sneddon (2011), 30% of students stated that using LC was a substitute for attending class. Statistically analyzing group differences in students' questionnaire responses at the start and the end of the semester, Trenholm et al. (2019) observed that individuals who watched lecture recordings attended significantly fewer lectures than their peers who rarely watched videos.

This tendency for a large group of students to see LC usage as an "either-or" instead of a "both-and" appears common, as explicated in studies like Yoon et al. (2014) and Trenholm et al. (2019). Students in a multivariate calculus course at Loughborough University exhibited this behavior, as reported in a study by

Table 2 Summary of conclusions about the effect of LC on attendance

Study conclusion on attendance	Number of studies
Not considered	9
Positive change to attendance	0
No change to attendance	3
Negative change to attendance	4

Inglis et al. (2011). The researchers investigated ways in which students used learning resources in a typical blended learning environment with an option to use LC instead of attending lectures. In their analysis, which included tracking the lecture attendance of 534 students (via swiping their library cards on entry) and recording of LC access, the data were entered into a hierarchical cluster analysis in order to classify the typical behavior of students. To their surprise, the result revealed that none of the identified behavioral clusters involved students making heavy use of more than one resource, meaning that students who relied on watching videos for content rarely came to live lectures and vice versa. The finding led to the authors' suggestion that what they observed was "blended teaching" (p. 500) as opposed to blended learning. Le et al. (2010) concluded similar findings: less than 10% of students both attended and watched more than half of the lectures online. In the same vein is a finding from another large-scale study of student usage patterns of LC and live lectures by Howard et al. (2018) at University College Dublin. In a Maths for Business course, students were given the choice of going over the course contents via LC (presented as short online mini-lectures), live lectures, or a combination of both. Researchers collected quantitative data on each student's resource usage (attendance at live lectures and usage of online videos) for the entire class of 522 students and employed model-based clustering to identify four distinct resource usage patterns with lectures and/or videos. Remarkably, the largest cluster ($N = 313$, 60%) consisted of students who chose to cover the course material through videos and did not make much use of live lectures as a resource.

The contextual factors, such as institutional characteristics and location, could play a significant role. Reasonably, the more commuter-oriented a university is, the more likely a student is to choose LC over attendance because of the opportunity cost in time. The same logic would hold for any negative perception of attending campus (e.g., cost of campus food, weather); thus, different institutions may face more extreme attendance decreases than what is listed above because of their individual circumstances. But rationally, in all cases, attendance would likely decrease (at least marginally). However, great care should be taken in extrapolating these attendance reduction figures to other institutions. Attendance being a multi-variable function, it would be unwise to expect identical results. The figures above are only presented as an illustration of what appears to be the norm.

The method of recording attendance that each study used may influence these data. This review supposed that self-reporting bias would be a factor, projecting that surveys may show a more positive image of attendance than the reality (Chester et al., 2011), but taking attendance slips may also artificially improve attendance; this is discussed in more detail in the "Methodological concerns" section. In a similar vein, perhaps studies that investigated the initial implementation of LC and others that investigated already-established LC may show differences in attendance conclusions (students may form non-attendance habits over time). But there are not enough attendance data to investigate this question in this review.

Assuming attendance is affected, should it matter if LC is a perfect substitute for attendance? Attainment, not attendance, is the main measure of learning outcomes of higher education. This question is discussed in the next section.

What is the relationship between lecture capture usage and student attainment?

The most contentious aspect of LC is the impact its implementation has on student attainment (Nordmann et al., 2019). Reasonably, LC can provide repeat learning opportunities for students to engage in revision and better understand the content. As explained by Zimmermann et al. (2013), mathematics proofs are often not understood the first time around, and hence, LC could be a worthwhile tool for mathematics in particular. However, it may also provide a shortcut for less motivated students.

While recognizing the limitations regarding the use of students' grades to reflect the changes in their mathematical cognition, we use the term "attainment" in the most commonly understood way, as educational achievement in the course of study, which is usually measured by student performance on assessment components (e.g., Pournara et al., 2015).

Of the 16 studies investigated in this review, six did not report on attainment, one concluded the neutral impact of LC (with the exception of students who were not following up on their intentions to watch LC after missing a lecture—this practice was strongly associated with poor grades; Yoon & Sneddon, 2011), one concluded a positive relationship, and nine concluded a negative relationship between LC and attainment (Table 3). This lends some rudimentary evidence that the blanket LC policies that are being rolled out at many tertiary institutions across all faculties may be premature.

Of the eight studies that reported a negative impact on attainment, all found that regular substitution of live lecture attendance with LC was associated with lower achievement (Howard et al., 2018; Inglis et al., 2011; Le et al., 2010; Meehan & McCallig, 2019; Mullamphy, 2011; Sorensen, 2015; Trenholm et al., 2019; Zimmermann et al., 2013). Consistent with the literature review of the previous decade, Trenholm et al. (2019) concluded that there is a significant negative correlation between final course grade and LC views ($\rho = -0.443$, $p = 0.014$).

However, these studies did see benefits to groups of students who used LC supplementarily (Meehan & McCallig, 2019), but once a student used LC as their primary learning tool, they underperformed compared to their peers attending

Table 3 Summary of findings: relationship between LC and attainment

Study conclusion on attainment	Number of studies
Not considered	6
Positive relationship	1
Neutral relationship	1
Negative relationship	8

lectures. Sorensen (2015), examining data from 12 semesters at the University of South Dakota, found that the failure rates in the second year calculus courses were significantly higher in the semesters when the LC was provided; however, Zimmermann et al. (2013), reporting on the incorporation of the LC into two courses (Introduction to Elementary Geometry and Application-oriented Mathematics) for pre-service teachers in Germany, pointed out that "[t]he failure rate in the exams of both investigated courses is about 23%, which is relatively low for mathematics courses at German universities." (p. 154). Arguably, in Zimmermann et al.'s case, such a comparison cannot be taken as objective evidence in the absence of data from the same courses for pre-service teachers without the LC's provision. This is because the educational context and demographic characteristics cannot be ruled out as primary factors in the observed relationships and, therefore, should be adequately controlled for in all reported associations.

Only one study reported a potential positive impact of LC on attainment. Based on qualitative analysis of in-depth interviews of students, Wood et al. (2018) reasoned that LC increased attainment because of its usefulness when circumstances stopped a student attending class, preventing a student from falling behind. LC's utility in re-watching content is a reason why student attainment may improve. Additionally, the authors posited that the use of LC could compensate for disadvantages of attending information-heavy live lectures, as all students reported that having to multitask in taking notes while listening to the lecturer effectively was cognitively demanding. In spite of this plausible reasoning based on students' opinions, it is worth noting that the study was not designed to empirically ascertain the impact of LC on attainment.

Some studies found that students who were already performing poorly were the most affected by the introduction of LC (Trenholm et al., 2019). Interestingly, this negative relationship between attainment and LC often appears in disconnect with the perception some students have of the utility they gain from LC (Trenholm et al., 2019). Gouia-Zarrad and Gunn (2018) found that students perceived increased performance and satisfaction with a course when LC was implemented despite a weak negative relationship between LC usage and performance, with low-achieving students using LC the most. Similarly, Howard et al. (2018) found not only that the group of students who relied on watching LC and not attending lectures (the largest cluster, $N=313$, 60%) achieved the lowest grades in the course, but also that a "portion of students in this cluster strongly believed videos are superior to lectures in maximising their learning for the time available owing to a more concise format with less repetition, flexible use, efficient and faster pace" (p. 542). At James Cook University (Australia), in a survey of a mathematics for engineering class, 85% of students felt that LC did not have a negative effect on their academic performance (Mullamphy, 2011).

A previously mentioned study by Inglis et al. (2011) examined students' patterns of usage with lectures, online videos, and the university mathematics support centre in three similar mathematics courses at Loughborough University ($n=534$). For each student, the following was recorded: attendance at live lectures (via swiping the students' library cards), the number of times they viewed online lectures (via logfiles on their Virtual Learning Environment server), and their number of visits to the mathematics support centre. However, it could not be confirmed that the visits to the mathematics support center were in relation to the courses in the study (as students could be seeking support for other problems). On performing a hierarchical cluster analysis, the authors identified four clusters of students: those who primarily attended live lectures ($N=214$), those who primarily accessed the online lectures ($N=70$), those who primarily used the mathematics support center ($N=60$), and those who made little use of any resources ($N=185$). It was shown that the students in the different clusters adopted significantly different strategies for their academic study and that, across all participants, the most important predictors of examination success were incoming diagnostic test achievement and attendance of live lectures during the course.

In a later study at University College Dublin, Meehan and McCallig (2019), on performing a cluster analysis, found that the students in the predominantly LC cluster ($N=30$) achieved worse when compared to the students in the predominantly live lectures cluster ($N=22$) (55.26% versus 57.69% on the final exam). Importantly, this was despite the inverse difference for the two clusters on the measure of prior achievement recorded in the Irish school system: 47.50 points (out of 100) for the predominantly LC cluster versus 43.21 points for the predominantly live lectures cluster.

As investigated by Le et al. (2010), a potential explanation for the association between poor performance and LC is not only that less motivated students use LC but that the technology facilitates more of a surface learning approach. Le et al. (2010) study of two calculus courses found that the highest usage of the ‘pause feature’ in LC was associated with the lowest attainment. Interestingly this contradicts a result from a previous identical study of a psychology course (Bassili, 2006). Le et al. (2010) reasoned that mathematics requires less rote memorisation and more understanding of concepts; usage of the pause feature may indicate memorisation. These findings were not controlled for prior achievement, so they may instead highlight students who could not keep up with the speed of the lecture and thus were more likely to perform poorly. However, Trenholm et al. (2019), who controlled for prior attainment, also found evidence to support Le et al. (2010) claim through the usage of the learning approaches questionnaire R-SPQ-2F. Regular LC users scored significantly higher in the “surface approach” category of the questionnaire relative to less frequent LC users. This lends support to the hypothesis that the relationship between LC usage and low attainment is not only because low-achieving/less motivated students tend to use LC more but because of some intrinsic quality of LC itself. As summarized by Trenholm et al. (2019), “regular RLV [recorded lecture videos] use, overall, maybe depressing the quality of student learning” (p. 13).

For some, there is no apparent reason why LC is not a functional substitute for a classroom in terms of the audiovisual content, but perhaps the lack of an academic environment leads students to be more easily distracted when using LC, thus lowering the quality of their cognitive engagement. This report hypothesizes that this is one of the principal reasons a negative correlation is often found between LC and attainment. LC may be a functional substitute for a highly motivated student, but removing a strict academic environment (i.e., social pressure from the classroom environment) allows a less motivated student to get the impression of learning even when they are not cognitively engaged. Trenholm et al. (2019) also reasoned in support of this hypothesis, suggesting an explanation for why LC may be an inferior learning method: because there is a lack of two-way interactivity (even in courses with little student input), as there is a "tacit acknowledgement of the 'other' in the room" (p. 14).

A perceived reason why LC may increase attainment—that LC encourages students to spend less time note-taking and more time focusing/engaging in lectures (Wood et al. 2018)—appears to be questionable. As mentioned in the previous section, only a minority of students attend lectures and watch LC; thus, this benefit of LC appears weak. In this review, no current studies that investigated this phenomenon in a mathematics course were found. Another behavioral change this review could not find research on was the social interactions students have before/after lectures. The introduction of LC may reduce incentives for students to form academic relationships with each other (e.g., talking about and checking someone else's notes for a missed class), and because of this fewer student-to-student discussions may take place, reducing learning opportunities.

Methodological concerns

There are notable inconsistencies in the results and conclusions within the literature on LC and its impact on student attendance and attainment. This is expected, as they are multivariate factors, but it may partially stem from varying methodological issues in said literature.

Timeframes are one such concern. Studies such as Trenholm et al. (2019), Wood et al. (2018), and Yoon and Sneddon (2011) investigated the initial impact of the introduction of LC but did not investigate the impact past a year, thus not capturing potential changes in usage over a longer period as student culture became accustomed to the technology. This needs to be taken into account, since some studies from non-mathematical contexts have shown that viewership after the introduction of LC increased significantly in the second year of implementation (e.g., Aldamen et al., 2015), though this is far from conclusive. It is noteworthy that this review could not identify any current literature on long-term systematic research pertaining to changes in student perceptions of LC, which may be a factor influencing the disconnect between the widespread perceived decreases in attendance (Secker et al., 2010) and literature claiming no correlations between LC and attendance. Following the findings from Nordmann et al. (2019) and Trenholm et al. (2019), it would also be unwise to generalize LC usage or effectiveness across year levels. Students of different levels appear to use the technology in different ways, which makes comparisons between studies difficult.

Self-reporting is also a major concern. Studies using surveys (Le et al., 2010; Mullamphy, 2011; Yoon & Sneddon, 2011; Yoon et al., 2014; Zimmermann et al., 2013) relied on students to accurately estimate their own attendance, which may have led to overreported results, as shown in Chester et al. (2011). Others instead used physical sign-in sheets or required swiping cards on entry, which also could skew results. The disconnect between the prevailing negative opinion about the effect on lecture attendance and the neutral position that the literature often reports may be affected by these factors.

Moreover, a greater concern regarding the use of self-report data is in relation to students' judgments about the impact of lecture capture on their attainment. A body of research on learning, memory, and metacognitive processes has provided evidence that learners often have an inaccurate mental model of how they learn and remember, making them prone to misjudge how successful they have been in achieving a learning goal (see, for example, Bjork et al., 2013). Hence, the reliance on self-report data concerning attainment is problematic, as it can lead to inaccurate conclusions about the impact of LC.

Publication bias is another source of contention that may skew the literature positive, as Njenga and Fourie (2010) show there is often "techno-positivism" that overestimates the impact of technology in education, with LC often being extolled without regard to its potential negatives.

Lastly, a major concern with regard to interpretation and generalization involves a lack of precision in the operationalization of student viewership. Almost all studies that quantitatively measured viewership used "hits" to investigate how often students used LC (apart from Le et al., 2010), not capturing the quality of learning different students experience with LC or how long a student watched the recording. However, in Groen et al. (2016) multi-faculty survey, only a third of students watched the entire recording. Negative correlations between LC use and attainment may exist because students are in a distracting environment, skipping through sections, multi-tasking, or watching at increased speeds, and not because of an intrinsic problem with LC. Surveys often try to capture this, but the full picture is difficult to realize. The variable "hits," because of the lack of precision, may be a cause of the resulting inconsistency in the literature.

Discussion

Given the small number of studies available, this review is limited in its ability to make broad inferences. The limitations concerning the interpretation and generalization stem from the substantial variations in the study's contexts, such as the number of participants (as low as 10 student-participants versus 1000), different geographic regions, and distinct student cohorts (pre-service teachers, studying elementary geometry; future engineers, taking advanced calculus; commerce students, learning mathematics for business). Despite the apparent difficulty in making rigorous consolidations, the literature is consistent in the opinion that students and administrators positively view LC for its utility and flexibility despite the moderately strong evidence that most institutions face attendance drops. It is clear that the literature predominantly reports a negative association between attainment and the use of LC as a substitute for live lectures. Overall, it appears that this finding is consistent with the earlier research by Trenholm et al. (2012), which synthesized the findings from the studies published in the earlier decade. This seems to reinforce concerns around the value and impact of the LC's provision in tertiary institutions and point to the following considerations.

Trend over time

Broadly, there appear to be two types of LC users: students who supplement attendance and students who substitute attendance. The latter group seems to be getting disproportionally larger, considering the trend over the decade. In studies conducted at the start of the decade, the proportion of students self-reporting using LC to substitute live lectures was not more than 30% (Zimmerman et al., 2013; Yoon & Sneddon, 2011). As seen in a large-scale study with tracked attendance (Inglis et al., 2011), the group of students relying on watching LC instead of attending lectures was rather small—13.1% (70 out of 534)—and the largest of all behavioral clusters identified in the study was the group of students attending lectures—40% (214 out of 534). Moreover, tracking attendance data, though a few years later, Meehan and McCallig (2019) researched a student cohort in first semester of 2013–2014 and reported that 37.4% of students accessed LC instead of live attendance for a large majority of lectures (combining cluster "Video preference" ($N=30$) and cluster "Low Resources with Video preference" ($N=16$) out of 123 total). However, a follow-up study (Howard et al., 2018) conducted in the same course but two years later (in 2015–2016) reported a substantially different picture, with 60% of students relying on LC only. This, indeed, is a worrying trend but hardly surprising, given the factors driving students' behavioral choices that are unpacked in this review, as our culture becomes accustomed to the technology.

As for the group of students who use LC as intended, as a supplement to live lectures, the evidence suggests that this group represents a relatively small proportion, with smaller numbers reported in more recent studies. For example, in Meehan and McCallig (2019) study conducted in 2013–2014, the cluster of students who used LC regularly as a supplement to live lectures represented 21% ($N=26$ out of 123). Meanwhile, a study conducted in the same environment but two years later (Howard et al., 2018) reported that the cluster of those dual users was only 12% ($N=61$ out of 522).

Under-researched phenomenon of 'cramming'

We want to note an important phenomenon not often addressed in the literature. Abundant anecdotal evidence points to student 'cramming' of lectures through watching hours of LC near exams as an option to pass classes despite being consistently absent during the semester. This claim is supported by evidence from research on a broader cohort of students that included mathematics students. Groen et al. (2016) survey of 1145 students from biology, chemistry, mathematics, business, and population health found that a group of students (21%) watched entire weeks of recordings in the study period leading up to exams but did not regularly watch recordings otherwise.

No research was found on this topic across mathematics/statistics studies in the last decade (except for a passing reference by Howard et al., 2018), but this review sees this behavior as a key research topic because of how clearly detrimental it would be to deep learning. This is based on research from experimental cognitive psychology accumulated over the last 100 years pertaining to the effect of distributed practice (also known as spaced practice) on long-term retention. The main finding to date demonstrates that a separation of learning episodes of the same content by time periods was found to be extremely beneficial for maximizing long-term retention (for review, see Cepeda et al., 2006).

As comments in Loch et al. (2016) report show, some students see assessment (not knowledge) as the main driver of behavior, "aiming for marks, not for understanding" (p. 379). If this is the case for a portion of students, it is clear why LC would seem to be the easiest way to achieve this. This trend may be the most worrying to educators, as if more students begin to see a university's purpose as getting a qualification rather than an education, the use of LC as a shortcut will increase.

Practical recommendations

The synthesis provided by this review points to a potential ethical dilemma that universities may face when implementing LC. The technology gives benefits to one group of students, while another may be unknowingly harmed (i.e., students who do not attend class but would attend if LC were not available). Although these types of trade-offs are common in many educational settings, we should not expect students to carry individual responsibility for their actions without informing them about the relevant research findings. This highlights the duty institutions have not only in informing students of the negatives of LC but also in proactively considering changes in the mode of lecture delivery that can rectify the problem.

As shown by Yoon et al. (2014), if a student perceives the same benefit between LC and attendance of a live lecture, then often they will choose the easier option (i.e., LC). Thus, to prevent students from seeing the two mediums as interchangeable, an aim for academic staff should be to increase the perceived value of attending lectures. The following two options outline how it can be achieved.

Option 1

Improve the value of traditional live lectures by enabling interactions. Based on the evidence reported by many studies (Howard et al., 2018; Meehan & McCallig, 2019; Wood et al., 2018; Yoon et al., 2014), it is known that the value of a live lecture is positively related to the interactions that occur during the lecture with the teacher and other students, coupled with an ability to ask clarifying questions and receive immediate feedback. Hence, to increase the value of a live lecture, an obvious recommendation is to increase class participation by devoting a small part of a lecture to in-class quizzes, group-work problem-solving, or other interactive teaching and learning approaches. This has the potential to improve the quality of student engagement during lectures and, importantly, improve attendance, thereby addressing a key concern mentioned earlier—the phenomenon of "cramming," which leads to suboptimal outcomes for long-term retention.

Option 2

Flip the classroom. Given the evidence of emerging trends in student behavior, with more and more students choosing to view LC instead of attending live lectures (e.g., the largest cluster ($N=313$, 60%) reported in Howard et al., 2018), it makes perfect sense to use the class time for something other than lecturing in a traditional style. The lecture content can be viewed by students prior to class so that face-to-face time can be spent on problem-solving (individual and group), hence flipping the classroom on its head by reversing the order of activities. This mode of delivery has been extensively researched in the last 5 years with an emerging consensus. For instance, a recent meta-analytic study by Van Alten et al. (2019) quantitatively synthesized the results of 114 studies. In general, the researchers concluded that students in flipped classrooms achieve significantly higher learning outcomes (which are assessed and measured by grades) than students in traditional classrooms, and, importantly, are equally satisfied with the learning environment. The main implication is that flipped classrooms are worth implementing. However, the authors caution that attention should be paid to the design of the flipped classroom, as simply flipping the order of activities might not be successful in general. Through analysis of the heterogeneity in the effect sizes of the 114 studies, the researchers provided a few general recommendations to achieve an effective flipped classroom. The critical features for a successful implementation of a flipped classroom are sustaining face-to-face time (i.e., not reducing the number of hours) and adding quizzes as part of LC and during class time.

Conclusion

This systematic review aimed to provide a synthesis of the current literature on LC in tertiary mathematics education, focusing on its impact on student attendance and attainment. Although the literature on mathematics education is often difficult to compare because of the variation in the contexts and methods, it is clear that the literature predominantly reports a negative association between attainment and the use of LC as a substitute for live lectures. It is also clear that the proportion of students who choose to skip live lectures has steadily been on the increase over the last decade as the student campus culture becomes adjusted to the presence of LC. Within this group, this review explored the cases when LC is used imperfectly, providing false benefits, promoting surface learning strategies, and cramming. There is evidence that regular use of LC by this large group of students may be depressing the quality of their learning (Trenholm et al., 2019). We also found that the group of students who use LC as intended, as a supplement to live lectures, represents only a small proportion (e.g., 12% as reported by Howard et al., 2018). In summary, there is evidence to suggest that, specifically for mathematics education, LC that was supposed to be an asset to students has become a liability to those whose motive is to pass rather than to learn.

Accelerated by the COVID-19 pandemic, universities must embrace the new technology while striving to make research-informed decisions in order to find optimal ways to adapt. As stated by Yoon et al. (2014), LC is regarded by students as a competing or complementary resource; however, this depends on the interaction between students and staff during the live lectures. A research-informed way to move forward would be to increase the value of attending a live lecture for students by either (1) introducing more interactions that occur during the lecture with the teacher and other students, coupled with an ability to ask clarifying questions and receive immediate feedback, or (2) flipping the classroom by swapping the order of learning activities: content can be viewed by students prior to class so that face-to-face time can be spent on individual and group problem-solving and discussions (with peers and teachers).

Future research

This review synthesized the latest research literature on the implementation of LC in tertiary mathematics education and provided two recommendations for mitigation of the unplanned and counterproductive impact reported. However, future research based on the incorporation of findings from studies of non-traditional formats such as MOOCs, webinars, and contemporary distance education has the potential to inform other principally different recommendations. In light of the unprecedented global shift to online teaching and learning as a response to the COVID-19 pandemic, the body of accumulated research in the online sphere is poised to grow. Agglomerated, such findings may chart out new possibilities for replication of the characteristics that are assumed to be unique to face-to-face education, e.g., the ability to ask questions during class, opportunities for social interactions, group work, and timely feedback from a teacher.

The abundance of newly developed video resources signposts likely changes to the post-COVID-19 educational landscape. This development could be a major breakthrough leading to a revamp of higher education. If this is to occur, it is paramount that this change to the sector is well supported by research, which is leading, as opposed to lagging, the implementation.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Aldamen, H., Al-Esmail, R., & Hollindale, J. (2015). Does lecture capturing impact student performance and attendance in an introductory accounting course? *Accounting Education, 24*(4), 291–317. https://doi.org/10.1080/09639284.2015.1043563

Bjork, R. A., Dunlosky, J., & Kornell, N. (2013). Self-regulated learning: Beliefs, techniques, and illusions. *Annual Review of Psychology, 64,* 417–444. https://doi.org/10.1146/annurev-psych-113011-143823

Bassili, J. (2006). Promotion and prevention orientations in the choice to attend lectures or watch them online. *Journal of Computer Assisted Learning, 22*(6), 444–455. https://doi.org/10.1111/j.1365-2729.2006.00192.x

Cepeda, N. J., Pashler, H., Vul, E., & Wixted, J. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin, 132*(3), 354–380. https://doi.org/10.1037/0033-2909.132.3.354

Chester, A., Buntine, A., Hammond, K., & Atkinson, L. (2011). Podcasting in education: Student attitudes, behaviour and self-efficacy. *Educational Technology and Society, 14*(2), 236–247. Retrieved from https://www.jstor.org/journal/jeductechsoci

Dona, K. L., Gregory, J., & Pechenkina, E. (2017). Lecture-recording technology in higher education: Exploring lecturer and student views across the disciplines. *Australasian Journal of Educational Technology, 33*(4). https://doi.org/10.14742/ajet.3068

Docherty, P., Bailey, T., Hardy, J., Galloways, R., Sangwin, C., & Wood, A. (2019). *Lecture Recording in Mathematics and Physics: final report*. Retrieved from http://www.docs.hss.ed.ac.uk/iad/Learning_teaching/Academic_teaching/PTAS/Outputs/Lecture_Recording_in_Maths_and_Physics_full_report.pdf

Gouia-Zarrad, R., & Gunn, C. L. (2018). *Students' perceptions of lecture capture in University math classes for engineers*. Paper presented at meeting of the Advances in Science and Engineering Technology International Conferences (ASET), June, Abu Dhabi, United Arab Emirates. https://doi.org/10.1109/ICASET.2018.8376926

Groen, J. F., Quigley, B., & Herry, Y. (2016). Examining the use of lecture capture technology: Implications for teaching and learning. *The Canadian Journal for the Scholarship of Teaching and Learning, 7*(1), 1–18. https://doi.org/10.5206/cjsotl-rcacea.2016.1.8

Hall, J., Robinson, T., Flegg, J., & Wilkinson, J. (2020). First-year and final-year undergraduate students' perceptions of university mathematics departments. *Mathematics Education Research Journal,* https://doi.org/10.1007/s13394-020-00340-z

Howard, E., Meehan, M., & Parnell, A. (2018). Live lectures or online videos: Students' resource choices in a first-year university mathematics module. *International Journal of Mathematical Education in Science and Technology, 49*(4), 530–553. https://doi.org/10.1080/0020739X.2017.1387943

Inglis, M., Palipana, A., Trenholm, S., & Ward, J. (2011). Individual differences in students' use of optional learning resources. *Journal of Computer Assisted Learning, 27*(6), 490–502. https://doi.org/10.1111/j.1365-2729.2011.00417.x

Jones, E. M., Harden, S., & Yu, J. (2018, July 9–13). *Impact of online resources in teaching statistics to undergraduates*. Paper presented at the meeting of the international association of statistics education. Japan. Retrieved from https://iase-web.org/icots/10/proceedings/pdfs/ICOTS10_9G2.pdf

Khan, N. (2013). Teaching first-year business statistics three-ways. *In D. King, B. Loch (Eds.) Shining through the fog: The 9th DELTA conference on undergraduate teaching and learning of mathematics and statistics* (pp. 81–90). Kiama, Australia, 24–29 November

Le, A., Joordens, S., Chrysostomou, S., & Grinnell, R. (2010). Online lecture accessibility and its influence on performance in skills-based courses. *Computers and Education, 55*(1), 313–319. https://doi.org/10.1016/j.compedu.2010.01.017

Lipsey, M. W., & Wilson, D. B. (2001). *Practical meta-analysis*. Thousand Oaks, CA: Sage Publications.

Loch, B., Borland, R., & Sukhorukova, N. (2016, November). *How to engage students in blended learning in a mathematics course: The students' views*. Paper presented at the meeting of ASCILITE, Adelaide, Australia. Retrieved from http://2016conference.ascilite.org/wp-content/uploads/ascilite2016_loch_concise.pdf

Meehan, M., & McCallig, J. (2019). Effects on learning of time spent by university students attending lectures and/or watching online videos. *Journal of Computer Assisted Learning, 35*(2), 283–293. https://doi.org/10.1111/jcal.12329

Morris, N., Swinnerton, B., & Coop, T. (2019). Lecture recordings to support learning: A contested space between students and teachers. *Computers and Education, 140,* 103604. https://doi.org/10.1016/j.compedu.2019.103604

Mullamphy, D. (2011). Screencasting and its effects on the traditional lecture. *Australia and New Zealand Industrial and Applied Mathematics Journal, 53*, C592-C605. https://doi.org/10.21914/anziamj.v53i0.5121

Newland, B. (2017). *Lecture Capture in UK HE 2017* (Report. 25). Brighton, United Kingdom. Retrieved from https://research.brighton.ac.uk/en/publications/lecture-capture-in-uk-he-2017-a-helf-survey-report%0A http://www.helf.ac.uk/

Njenga, J., & Fourie, L. (2010). The myths about e-learning in higher education. *British Journal of Educational Technology, 41*(2), 199–212. https://doi.org/10.1111/j.1467-8535.2008.00910.x

Nordmann, E., Calder, C., Bishop, P., Irwin, A., & Comber, D. (2019). Turn up, tune in, don't drop out: The relationship between lecture attendance, use of lecture recordings, and achievement at different levels of study. *Higher Education, 77*(6), 1065–1084. https://doi.org/10.1007/s10734-018-0320-8

Pournara, C., Hodgen, J., Adler, J., & Pillay, V. (2015). Can improving teachers' knowledge of mathematics lead to gains in learners' attainment in Mathematics? *South African Journal of Education, 35*(3), 1–10. https://doi.org/10.15700/saje.v35n3a1083

Secker, J., Bond, S., & Grussendorf, S. (2010, September). *Lecture capture: rich and strange, or a dark art?* Paper presented at the meeting of the Association for Learning Technology, Nottingham, United Kingdom.

Seilhamer, R., Chen, B., Bauer, S., Salter, A., & Bennett, L. (2018). Changing Mobile Learning Practices: A Multiyear Study 2012–2016. Retrieved from https://er.educause.edu/articles/2018/4/changing-mobile-learning-practices-a-multiyear-study-2012-2016

Sorensen, K. (2015). *Lecture capture accessibility on university student learning outcomes and student perceptions in college level mathematics courses.* (Doctorate, University of South Dakota). Available from ProQuest Central; ProQuest Dissertations & Theses Global. (1790114312).

Trenholm, S., Alcock, L., & Robinson, C. (2012). Mathematics lecturing in the digital age. *International Journal of Mathematical Education in Science and Technology, 43*(6), 703–716. https://doi.org/10.1080/0020739X.2011.646325

Trenholm, S., Hajek, B., Robinson, C. L., Chinnappan, M., Albrecht, A., & Ashman, H. (2019). Investigating undergraduate mathematics learners' cognitive engagement with recorded lecture videos. *International Journal of Mathematical Education in Science and Technology, 50*(1), 3–24. https://doi.org/10.1080/0020739X.2018.1458339

Van Alten, D. C. D., Phielix, C., Janssen, J., & Kester, L. (2019). Effects of flipping the classroom on learning outcomes and satisfaction: A meta-analysis. *Educational Research Review, 28,* 100281. https://doi.org/10.1016/j.edurev.2019.05.003

Walker, R., Voce, J., Swift, E., Ahmed, J., Jenkins, M., & Vincent, P. (2016). *UCISA REPORT 2016 Survey of Technology Enhanced Learning for Higher Education in the UK*. Oxford, United Kingdom. Retrieved from http://www.ucisa.ac.uk/

Williams, A., Birch, E., & Hancock, P. (2012). The impact of online lecture recordings on student performance. *Australasian Journal of Educational Technology, 28*(2), 199–213. https://doi.org/10.14742/ajet.869

Wood, A., Bailey, T., Galloways, R., Hardy, J., Sangwin, C., & Docherty, P. (2018). Lecture capture as an element of the digital resource landscape - a qualitative study of flipped and non-flipped classrooms. https://doi.org/10.31234/osf.io/824hv

Yoon, C., Oates, G., & Sneddon, J. (2014). Undergraduate mathematics students' reasons for attending live lectures when recordings are available. *International Journal of Mathematical Education in Science and Technology, 45*(2), 227–240. https://doi.org/10.1080/0020739X.2013.822578

Yoon, C., & Sneddon, J. (2011). Student perceptions of effective use of tablet PC recorded lectures in undergraduate mathematics courses. *International Journal of Mathematical Education in Science and Technology, 42*(6), 425–445. https://doi.org/10.1080/0020739X.2010.543165

Zimmermann, M., Jokiaho, A., & May, B. (2013). Lecture recordings in higher mathematics education: Use and impact on academic performance. *Journal of Information Technology and Application in Education, 2*(4), 150–156. https://doi.org/10.14355/jitae.2013.0204.04