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CURRICULUM AND EDUCATION

Teaching with Avida-ED: instructor experiences following an in-person professional development program aimed at increasing active learning and experimentation in evolution education

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Abstract

Avida-ED is a model system that lets students explore evolution and the nature of science by observing and manipulating the evolutionary dynamics of digital organisms. Over 5 years, we ran eight 2.5-day in-person professional development workshops for 105 primarily college biology instructors to introduce them to Avida-ED and digital evolution and to help them to plan implementations. In this paper, based upon 60-min interviews with 46 of the attendees, we describe what they found to be of value in the workshop itself and the implementations of Avida-ED that they subsequently carried out. The Active LENS workshops were universally valued by the interviewees as a professional development experience; they valued the overall experience of the workshops, their organization and content, and the instructor support materials. Of the 46 teachers that we interviewed, 41 implemented Avida-ED in their classrooms, in 66 separate implementations. We characterized these with respect to the nature of the implementation and its duration, and examined the data in relation to course type, course level, and stated learning goals of the instructors. The most common use was to have students learn evolutionary concepts by observing them in action. A smaller fraction used it to provide a complete research experience.

Keywords Science education, Evolution, Avida-ED, Training-of-Trainers, STEM professional development

Introduction

Despite its central place as the foundational concept in biology (Dobzhansky 1973), as well as being integral to reform biology teaching recommendations (AAAS 2011; NRC 2012b; Brownell et al. 2014), the effective teaching of evolution remains one of the major challenges in undergraduate biology education. The reasons for this are many and varied. Understanding of evolution requires overcoming the naive intuitive reasoning about biological phenomena common in many students (Gregory 2009) and the synthesis of abstract biological concepts across temporal and spatial scales (White et al. 2013), which sometimes involves mastering "threshold

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concepts" (Tibell and Harms 2017) and avoiding misunderstandings about emergent phenomena (Cooper 2017). In addition, there are well-characterized societal pressures to reject fundamental evolution concepts (Scott 2005). Nelson (2008) argued that many instructors teach evolution concepts ineffectively; he suggested that using interactive engagement, critical comparisons of evidence, and directly addressing common misconceptions is essential for promoting student learning. Active and inquiry-based pedagogies are some of the best-known evidence-based reformed teaching practices, and many published biology education research studies have shown not only the efficacy of active learning (compared to traditional) approaches, but also have shown that reformed pedagogies tend to promote the success and retention of people in traditionally underrepresented groups (Nelson 2008; Armbruster et al. 2009; Freeman et al. 2007, 2014; Dirks 2011; Dewsbury et al. 2022). The research literature also makes clear the value of inquiry-based learning in helping students practice solving problems to increase their abilities to think critically and improve their quantitative literacy (NRC 2012a; Goldey et al. 2012; Wilkins 2016; Mentkowski et al. 2016). However, such active and inquiry-based learning is difficult to implement in evolution education because evolutionary processes involve slow changes in populations of organisms over hundreds and thousands of generations, which precludes the kind of hands-on experimentation one can conduct in lab classes in other sciences. The Active LENS project worked to address these challenges using the Avida-ED digital evolution platform.

Based on the Avida research platform used by researchers, Avida-ED is an artificial life model system that allows students to explore evolutionary concepts and carry out evolution experiments using digital organisms (Pennock 2007; Speth et al. 2009; Smith et al. 2016; Kohn et al. 2018). Free and readily available online (avida-ed.msu.edu), the program is supplemented by teacher support materials, including model exercises and published activities and instructional sequences (Johnson et al. 2011a, 2011b; Lark et al. 2014; Smith et al. 2016; Kohn et al. 2018). Avida-ED allows students to engage evolution as an experimental science, rather than as a body of historical facts, providing them with opportunities to confront their misconceptions about evolutionary processes directly via active engagement and experimentation. It lets them wrestle with threshold concepts, such as randomness (Tibbell and Harms 2017) so they can overcome misconceptions through direct encounters with experimental evidence. These aspects of Avida-ED make it ideally suited for both inquiry-based lab experiences (Sundberg and Moncada 1994) and course-based undergraduate research experiences (CUREs; Auchincloss et al. 2014), both of which allow students to engage in the complete set of scientific practices identified in the National Research Council's Next Generation Science Standards (NRC/NGSS; NRC 2012a).

To encourage and assist biology teachers who were interested in incorporating Avida-ED in their courses and equip them to train others themselves, we designed and produced a series of Active LENS professional development Training of Trainers (ToT) workshops. Faculty professional development programs are a common and effective way to introduce faculty to new pedagogical tools, such as Avida-ED, whose adoption and adaptation may require new technological knowledge and skills on the part of instructors (Gerard et al. 2011; Lark et al. 2020). In general, professional development programs that focus on subject matter, are of long duration, and incorporate social engagement among participants have been observed to be most effective (Garet et al. 2001; Wilson and Berme 1999). Further, Gerrish et al. (2015) noted that because biology faculty have different levels of understanding of evolution concepts, they have additional needs for professional development and curriculum support materials to gain the pedagogical content knowledge (PCK) necessary to implement new tools in the classroom related to evolution. In addition, computer programs such as Avida-ED require instructors to gain additional technological pedagogical content knowledge (Lark et al. 2020; Mishra and Koehler 2006) associated with the incorporation of a new technology in their classroom.

The 2.5-day Active LENS workshops were held at Michigan State University (MSU) in 2015 and 2016, MSU and the University of Washington in Seattle in 2017, MSU and North Carolina Agricultural and Technical University in 2018, and MSU and the University of Texas in Austin in 2019, which 105 individuals from across the United States attended over the course of the five-year period (Table 1).[1] Each of these consisted of prepared talks and working sessions: the talks, given by the project PIs, introduced Avida-ED and provided background on its history, theoretical foundation, and programming as well as to experimental evolution in general and to pedagogical design for active learning for evolution; in the working sessions, attendees were introduced to Avida-ED as students on Day 1, and coached while preparing Avida-ED curriculum and lessons as instructors on Day 2. Attendees presented the results of their working sessions

[1] Additionally, another 50 individuals attended a 1-day virtual workshop held in 2020 during the COVID-19 pandemic and over 200 attended half-day demonstration workshops we put on at various conferences. Because these workshops differed substantially from the full version, we omitted them from this study.

Table 1 Avida-ED Active LENS Workshop Cohorts

Cohort	# Attendees[a]	# Study Participants	% Participated	# Known Implementers[b]	% Implemented[b]
2015 MSU	19	6	31.6%	13	68.4%
2016 MSU	16	9	56.2%	13	81.2%
2017 UW (Seattle, WA)	13	6	46.2%	6	46.2%
2017 MSU	11	8	72.7%	10	90.9%
2018 NCAT (Greensboro, NC)	12	2	16.7%	3	25.0%
2018 MSU	15	6	42.8%	7	46.7%
2019 UT (Austin, TX)	7	3	37.5%	5	71.4%
2019 MSU	12	6	46.2%	5	41.7%
Total	105	46	43.8%	62	59.0%

[a] #Attendees includes all who met the requirements outlined in "Study Participant Recruitment"

[b] #Known Implementers includes individuals who implemented but did not participate in the study. We were made aware of these additional implementations by communications with the Attendees themselves and/or with Study Participants

on Day 3. A representative schedule for an Active LENS workshop is included as Supplementary File 1.

In this paper, we report and discuss the experiences of college teaching faculty (instructors) and high school teachers who attended these workshops. Forty-six workshop attendees (out of 105 attendees total) made themselves available to be interviewed in the latter half of 2020. Each 60-min interview was held via video conference. We queried each instructor about the impact the Active LENS workshops had on their own teaching and professional development, the extent to which they had incorporated Avida-ED into their classrooms, and the learning outcomes workshop attendees hoped to achieve in their students when using Avida-ED. Although some instructors also discussed their perceptions of learning improvements among their students, this study did not collect data about student learning as a result of workshop attendance and Avida-ED classroom implementations; an independent study about student learning is forthcoming (Cavender et al. in preparation). Finally, we also asked our interviewees to comment on how Avida-ED affected teaching during Spring 2020 (the coronavirus pandemic, or COVID-19 pandemic) and their views of Avida-ED's utility in a remote teaching environment.

Overall, the Active LENS workshop series appears to have provided a successful platform for preparing instructors to implement Avida-ED. The study participants valued the overall experience of the workshop, were very pleased with the organization and content of the workshop, and praised the ready availability of support materials that simplified Avida-ED implementation in their classrooms. The interviews revealed that most of the instructors felt prepared to implement Avida-ED after the workshop; most of the study participants incorporated Avida-ED into their courses, as did the majority of the workshop attendees overall. We also found a correlation between the stated learning outcomes of instructors using Avida-ED and the course types in which it was used. Study participants had mixed attitudes regarding the use of Avida-ED in remote learning environments, with instructor self-confidence having a large influence on its success in their own virtual teaching. Finally, the interviews illuminated for us areas where Avida-ED is an effective teaching tool, pointing the way towards its appropriate use, and showing us where further Avida-ED curriculum development might occur.

Methods

Ethical approval statement

All participants interviewed in this study provided voluntary consent and no financial or gift incentives were provided to elicit participation. Following a determination that its procedures and outcomes were all of minimal risk to participants, this study was determined to be exempt from additional review by MSU's Institutional Review Board.

Workshop attendee recruitment

We recruited attendees by advertising the workshop opportunity in online biology education forums and listservs. We also sent notices to the chairs of university biology departments located near the non-MSU hosting institutions, when workshops were held in those areas. Attendees applied online for specific workshops, answering questions about their learning goals and potential future use of Avida-ED. We encouraged applicants to apply in teams of two, to facilitate faculty interaction during the workshop itself and after returning to campus. The Active LENS project covered all invited attendees' workshop expenses.

Study participant recruitment

Two authors (BSG and JJS) recruited study participants from the complete register of Active LENS workshop attendees; this pool of individuals included anyone who attended an Active LENS workshop from 2015 to 2019, who indicated they were course instructors, and who were not members of the Active LENS research team. Of the 110 total individuals who attended a workshop during this five-year period, 105 met these criteria (Table 1).

We divided all attendees into three subsets and then invited each attendee by email to participate in a remote interview. The subset first contacted (n = 14) were instructors who had previously contributed data from their course implementations to a separate study related to using Avida-ED to address evolutionary misconceptions (Cavender et al. in preparation). The next-contacted group (n = 14) were those who had remained in regular communication with Active LENS personnel, though who had not necessarily collaborated or participated in other ways. Finally, we contacted the remaining attendees (n = 77). Those who did not initially respond to the first invitation email received one follow-up email again requesting their participation. Every invitation included the study's consent script as an attached file.

Of the 105 attendees, three could not be located and contacted by email. For the remaining 102, we received responses from 57. Our study participants are the 46 individuals who ultimately participated in a remote interview. All participants were instructors at institutions in the United States. Though we did not ask for participants' gender identities during interviews, we observationally identified 28 of the participants as women and 18 as men. Twenty participants later provided their gender identity when registering for the 2022 Active LENS Academic Congress; none of these responses contradicted our observations.

Interview protocol

To develop our interview protocol, we relied on an iterative process; interviews conducted with study participants drawn from the first subset of the recruitment pool served as the primary sources for protocol adjustments (Ayres 2008). These adjustments were minor—reordering topics of discussion and providing some additional specificity for clarity. Interviews from the second subset served as a test of the revisions and opportunity for potential further changes, should they have been needed (but were not). Our final interview protocol is included as Supplementary File 2. The protocol was designed for interviews of 40 to 60 min, beginning with background questions regarding participants' current place of work and position, their place of work and position at the time of their attendance of an Active LENS workshop, and a list of courses in which they used or considered using Avida-ED. Following these were open-ended questions about: their experiences at the Active LENS workshop they attended; their course-planning process regarding the aforementioned courses; and later, their institution's response to the COVID-19 pandemic and its effect on their teaching responsibilities. Because the protocol's adjustments were minor, the small differences between the first and final iterations are not likely to have led to significant interview experiences between participants from the first subset of invitees and everyone else.

The most time-intensive portion of the protocol concerned details about a participant's recollections of specific implementations of Avida-ED. In this study we consider as an "implementation" any Avida-ED use by a participant that occurred within a listed course at an established educational institution. Whenever possible, we collected the course's title, a short description, the number of students per section, the number of sections taught, and the general course schedule. We also included open-ended questions about the course's plan of Avida-ED implementation, the targeted learning goals meant to be addressed by Avida-ED (specifically asking about evolutionary concepts), the completion expectations for students' Avida-ED related tasks, any challenges that arose when implementing Avida-ED, how participants have adapted their implementation plans for repeated iterations of a given course or for other courses, and how participants assessed student learning outcomes.

Interviews

Of the 46 study participants, two pairs of participants taught their courses jointly and so were interviewed together; the remaining 42 participants were interviewed individually. Each interview was approximately 45 to 60 min in duration. Two authors (BSG and JJS) utilized the semi-structured protocol to guide the conversation. We conducted these interviews remotely over a popular video conferencing platform. Each interview began with greetings and introductions, a reading of the consent script, and verbal confirmation of the participant's consent, before working through the protocol. Most participants agreed to additionally share digital copies of their course syllabi, their Avida-ED instruction and evaluation materials, and other documents relevant to their pedagogical use of Avida-ED.

Data coding

BSG relied upon both his and JJS's contemporaneous interview notes to compile a confidential, standardized record for each participant to note portions of the interview responses and digital file contents that correlate to specific subjects from the protocol. (See Supplementary

File 3 for an example record, shared with specific consent of the participant.) The record also lists all existing digital files associated with the interview, such as the researchers' interview notes, and any course syllabi or lesson handouts provided by the instructor.

This record primarily collates each participant's course load and implementations. For implementations, the record captures the first academic term of implementation, their course type, course level, number of course sections and enrollment, curricular details–such as number and duration of sessions, the lesson plan, and mode of instruction–implementation challenges, and student learning goals, among other subjects. The diversity of learning goals, discussed below, was of great interest, so we spent significant effort on learning-goal-specific coding.

Learning-goal coding

Because learning goals were shared conversationally by participants, they were not standardized, so we developed a standardized code schema and defined five broad categories of codes (Fig. 3, in Discussion below): Evolutionary Concepts, Nature of Science Concepts, Scientific Skills, General Skills, and Pedagogy.[2] For example, the code *natural selection concepts*, categorized within Evolutionary Concepts, was associated with participant-provided goals that referenced: understanding natural selection; random vs. directed mutations; natural selection is not random, but also not artificially directed; differences between mutation appearance and mutation persistence in a population; mutations are not directed; mutations are neither universally beneficial nor detrimental, but rather dependent upon environment-specific circumstances; and an intention for students to overcome existing misconceptions related to the other *natural selection concepts* goals.

To illustrate this learning goal coding process, the Avida-ED Lab Book (hereafter, lab book)[3] serves as a useful example. The lab book includes four model exercises that instructors could use or adapt when implementing Avida-ED as well as a final section about how to use Avida-ED for independent research projects. Though each exercise describes multiple learning goals for students who work through it, each can be coded according to our schema. Since Exercise 1 is designed to convey the random nature of mutations, this is simply coded as such (*random nature of mutations*). Exercise 2 primarily intends to convey that mutations do not arise due to population need nor due to some directional force. We code this as *natural selection concepts*. Exercise 3 is about how evolutionary fitness is environmentally specific: a group of organisms that evolve to be fit in one environment may not be fit when transferred to another. We code this as *fitness concepts*. Exercise 4 covers the concept of genetic drift and other non-adaptive mechanisms of evolution. We code this as *genetic drift*. We categorize all four of these exercise-associated codes as Evolutionary Concepts. Finally, the Independent Research section of the lab book shows how instructors can broaden their implementation to other learning goals, including all those we categorize as either General Skills or Scientific Skills.

Results

Workshop cohorts

Over the course of 5 years (2015–2019), the Active LENS team recruited eight cohorts for summer workshops. The 105 total attendees, 14 of whom identified as under-represented minorities, included 63 women and 42 men and hailed from 24 states. Their 56 diverse public (41) and private (15) institutions included all major Carnegie Basic Classification (Indiana University Center for Postsecondary Research n.d. 2021). Ten attendees came from high school institutions and three came from institutions that conduct college preparation activities. Figure 1 includes a more detailed breakdown institution type together with the numbers of participants and their implementations.

Active *LENS* experiences described by study participants

Our protocol included prompts for any positive and/or negative feedback about participant experiences at the Active LENS workshop they attended. Overall, these responses were quite positive. Many spoke about enjoying the thoroughness of the workshop content with respect to the design, function, and usability of the Avida-ED program. Participants also positively noted the time devoted to personal lesson design and presentation. In contrast, participants' attitudes towards the housing accommodations for the workshop period were more mixed. However, many did also mention the usefulness of the workshop for professional networking, including the fact that all were housed in the same location.

One ubiquitous response from participants regarded the usefulness of the lab book. Nearly every participant either directly noted the benefit of receiving the book during the workshop and using it when learning about the software or spoke about using its exercises when

[2] It was beyond the scope of the current study to categorize learning goals with respect to specific misconceptions and their associated cognitive construals (e.g., teleological reasoning, essentialist thinking, and anthropocentric thinking) as defined by Coley and Tanner (2015). Instead, BSG relied on our schema to code each stated learning goal, for analysis.

[3] The Avida-ED Lab Book was developed and updated over time by the Active LENS Project curriculum development team. Because each workshop received a slightly different lab book version and past attendees were informed of lab book updates that they could freely access for ongoing instruction, we refer to all these versions collectively as the "lab book".

Carnegie Classifications:

Institution Type	# Attendees	# Participants	# Implementations
Doctoral Universities: Very High Research Activity (R1)	30	12	14
Doctoral Universities: High Research Activity (R2)	8	3	5
Doctoral/Professional Universities (D/PU)	2	0	0
Master's Colleges & Universities: Larger Programs (M1)	17	8	13
Master's Colleges & Universities: Medium Programs(M2)	5	2	3
Baccalaureate Colleges, Multiple Foci	15	7	11
Mixed Baccalaureate/Associate's Colleges	2	1	2
Associate's Colleges, Traditional & Non-Traditional, Transfer & Career	15	7	10
Special Focus 4-Year Institution	*1	*1	*1

Other Institutions:

College Preparation	3	1	1
High School	*10	*5	*6

***One participant taught at two institutions**

Fig. 1 Number of Avida-ED implementations by Institution Type. Post-secondary institutions are classified by the Carnegie Classification, using the "Basic" descriptions. Additionally, implementations occurred both at the high school level, as well as in a college preparatory institution not classified by Carnegie

designing or carrying out their implementation. About half (n = 32) of the implementations used at least one unaltered lab book exercise and nine others used one or more altered exercises to meet the participants' curricular needs. No participants indicated any specific problems with the lab book exercises, though one high school instructor reasonably pointed out the need to rewrite the exercises using level-appropriate language for their classroom, given that the book was produced for introductory-level college biology courses.

Avida-ED implementations described by study participants

These next sections describe the implementations carried out by the study participants, including their institution types, course types and levels, and the learning goals that were addressed using Avida-ED. Implementations happened at a wide diversity of institutions, at all levels of high school and undergraduate biology instruction, and in courses with a wide range of course topics. Supplementary Table S1 lists all 66 implementations shared by participants. Table 2 presents a representative set of 10 implementations.

Institution types

Of the 66 total implementations, 10 took place in Associate's Colleges, two in Mixed Baccalaureate/Associates Colleges, 11 in Baccalaureate Colleges, 16 in Master's Colleges and Universities, 19 in Doctoral Universities, one at a Special Focus Graduate Institution, and six in High Schools. One implementation occurred at a college preparation organization. The number of participants of each classification is reported in Fig. 1.

Course levels and types

The courses for participant implementations varied widely, from introductory and upper division biology courses to a 400-level computer science course about Artificial Intelligence (discussed below). Table 3a reports the numbers of implementations for each instructional level, from Grade 9 in high school to the highest undergraduate course level in US universities, as well as in Training of Trainers (ToT) educational settings.

Course types were more difficult to quantify, as most implementations fell into a minimum of two categories. For instance, one implementation occurred in a course categorized both as an Evolution course and as a Capstone course; two other Evolution courses were also labeled by participants as Population Genetics courses. One participant reported an implementation in an introductory course, with an emphasis on Allied Health concepts, which included both biology majors and non-majors. Figure 2 lists all course types, as well as the most common secondary types for introductory courses.

Almost all (60) of the implementations occurred in college biology departments or by high school biology instructors, with Introductory Biology courses comprising almost half of all implementations (n = 32; Table S1). At least 10 of the 13 Evolution courses were at the upper-division level or as degree program capstone courses; one other was a ToT K-12 pedagogy course

Table 2 Representative Avida-ED Implementations in Courses Taught by Active LENS Workshop Attendees

Participant	Course type	Institution type	Duration	Content
E	Intro Bio—Organismal	Associate's Colleges: Mixed Transfer/Career & Technical-High Traditional	Two lab class sessions	Exercises 3 & 4
F	Intro Bio—Cell and Molecular	Doctoral Universities: Very High Research Activity	One lecture class session	Exercise 3—modified
M	Intro Bio—Non-majors	Associate's Colleges: Mixed Transfer/Career & Technical-Mixed Traditional/Nontraditional	One Lecture Session	Exercise 1 (in support of Nature of Science)
OO	General Bio—9th grade	High School	3–4 Class sessions	Exercise 1
DD	Evolution	Other	Parts of 3–4 90 min class sessions	Exercises 1–3, then some competitions
FF	Evolution—3xx	Doctoral Universities: High Research Activity	Three studio lecture sessions (2 h each)	Self-produced lessons on Selection, Mutation, and Drift (Hardy–Weinberg Equilibrium)
KK	Genetics—2xx	Master's Colleges & Universities: Larger Programs	One Lab Session (3 h) plus required "Homework Lab"	Exercises 3 & 4 (for Pop Gen week)
"Rich" and "Daniel"	Microbiology Lab—3xx	Doctoral Universities: High Research Activity	Extensive throughout semester	Intro, Exercises 1–4, three add'l Avida-ED exercises from website, plus self-produced phylogenetics exercise and bracketed head-to-head tournament
Z	Environmental Physiology—3xx	Baccalaureate Colleges: Arts & Sciences Focus	One class session, one lab session	Introduction; Self-produced exercise on evolution of adaptations in animals
BB	Artificial Intelligence—4xx	Master's Colleges & Universities: Medium Programs	One Lab Week	Exercises 1 & 2

For the full list of implementations, see Supplementary Table S1

Table 3 Aspects of the 66 Avida-ED implementations

Course level	# Implementations
(a) Number of implementations at various course education levels	
High School	6
College 1xx	32
College 2xx	3
College 3xx	10
College 4xx	10
ToT	2
Unspecified	3

	Total known	Intro bio	High school	Other	Not specified
(b) Instruction duration					
≥ 3 Instruction Sessions	24	8	6	10	6
Research Projects	14	4	5	5	3

Numbers of implementations with three or more instruction sessions and research projects, broken down into the total number across all 66 implementations, the number of intro biology implementations, high school implementations, other (non-intro biology college courses, college preparatory courses, and Training of Trainer courses), and finally the number of implementations for which this information went unspecified

focused on teaching evolution. (We did not capture the course level for the other three.) Six implementations occurred in courses with a Microbiology focus, with one of these taught in a nursing program. Other notable types included Genetics (with two being the aforementioned Evolution and Population Genetics courses),

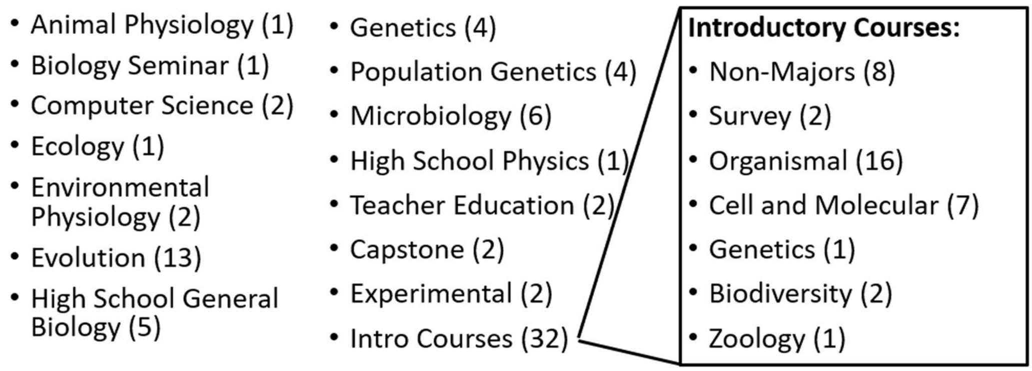

Fig. 2 Avida-ED implementations by course type. Some implementations are counted under multiple topics (the total does not add to 66). Introductory course implementations are further broken down by their subtopics, where some once again fall under multiple topics

Environmental Physiology, Microbiology, and Capstone courses. Five implementations were reported in high school level General Biology courses. One was at the 9th grade level, two as joint 9th and 10th grade courses, one at the 11th grade, and one Advanced Placement Biology course for the 12th grade.

Interestingly, an additional high school implementation–in a 9th grade physics course–was one of six implementations in courses taught outside of biology departments. The others were: a computer science course, which the participant described as "Biology-Inspired Computation"; another upper-division computer science course, on "Artificial Intelligence"; the aforementioned microbiology for nurses course; the aforementioned ToT evolution instruction course; and a ToT pedagogy certification course focused on high school Science Methods.

Of the 32 "Introductory Biology" course implementations, the most common course type, 23 occurred in a biology "Majors" sequence (which is typified by a two-semester series), an "Organismal" course (with content ranging from ecology and evolution to surveys of organismal diversity), or a "Cell and Molecular" course (with content focused on events at the cell and molecular level). In one case, a participant reported genetics as the topic for their introductory biology course. Another implementation occurred in an introductory course focused on "Allied Health" and designed for both majors and non-majors. Seven instructors implemented in introductory courses for non-majors.

The second-most common course type for implementation was "Evolution," including both a senior capstone course and a ToT pedagogy course for K-12 instructors. Of the evolution courses for which instructors reported their course level, all occurred at the upper-divisional level, save for this ToT course.

Cessation of implementations

All but four participants reported implementing Avida-ED initially and continuing to use it in subsequent terms of their instruction. Two participants explained their discontinuation of using Avida-ED. For May,[4] this was straightforward: she was a graduate student who, at the time of her attendance in Active LENS and up until the 2020 Spring term, had assigned teaching duties in her department. Her first implementation was a limited introduction to the Avida-ED software and a voluntary exercise which few students completed; given the lack of interest, May chose not to repeat this. Her second implementation–in a separate evolution course and repeated over multiple terms–was much more robust, with a self-produced introductory exercise and a second self-produced exercise to teach students about fitness landscapes. But when May received a doctoral fellowship that did not include a teaching assignment, she ceased implementing as she was no longer an instructor. However, we note that, after May moved on from teaching this course, another instructor–who was an Active LENS attendee but did not participate in this study–continued to incorporate Avida-ED into this second course.

The other participant to cease using Avida-ED explained a different scenario. After attending Active LENS with their department chair, Kali implemented in the organismal-oriented introductory biology sequence course in her department. However, after a few years (the exact number went unspecified) she stopped using Avida-ED because she found that student evaluations criticized the Avida-ED project. She also spoke about how, in her observation, students did not seem to learn the desired concepts as well through this participatory project, compared to lecture-based instruction.

[4] We use pseudonyms for every named participant in this article.

Non-implementation

Two participants reported not implementing Avida-ED in their classrooms. (There are several reasons why workshop attendees who did not implement Avida-ED might not want to join this study as a participant, which we expand upon below.) One of these, Rachel, attended a workshop that concluded 2 weeks prior to the start of the fall term at her institution, which she determined was not enough time to write an implementation into the course she would be teaching. She also noted several barriers that contributed to her not having implemented. These included: her impression of a steep learning curve for students, which would require significant instruction time for learning the software and thus larger project to justify the initial instruction; a dissatisfaction with the current curricula of her institution's two-course intro biology sequence and desire to fully redesign them, rather than merely a minor adjustment just to include Avida-ED; her institution's investment in other tools for instruction and lack of interest in Avida-ED; institutional budgetary concerns regarding computing equipment for student instruction; and her lack of course assignments over the next several terms due to an awarded research grant.

For Sofia, non-implementation was a consequence of her professional position in the years following her Active LENS workshop attendance. While still a PhD candidate, she was not in a position to add Avida-ED to the curricula of any courses with which she was associated. When interviewed, Sofia had since defended her dissertation and started a postdoctoral fellowship at another institution, but this fellowship did not include any teaching responsibilities. However, given her then-upcoming transition to a tenure-track position at a third institution, she spoke at length about her planned course curriculum for an introductory biology lab course there, which would include an Avida-ED based research project.

Avida-ED curriculum types

We observed a wide range of Avida-ED implementations among study participants. The most frequently observed implementations were in Introductory Biology courses (n = 32), which as a subset reflect the diversity observed among all reported implementations. Within this set, implementations mostly utilized one (n = 10) or two (n = 11) instructional sessions, while fewer (n = 8) used three or more. (In three cases we were only made aware of the implementation's existence but did not capture their details.) With respect to instructional content, more than half (n = 17) involved an introduction to Avida-ED followed by one or two exercises for exploring some aspect of evolutionary processes. Twelve intro biology implementations included three, four, or more exercises, including independent research projects or student evolutionary competitions (described below) in four introductory biology implementations. In contrast, five of the six high school implementations included a research component and all six used three or more instructional sessions. The counts of implementations with three or more instruction sessions, and those that included research projects, can be found in Table 3b.

One notable difference between the Introductory Biology subset and other implementations is that only four of the former included a large research or competition component outside of the instructional sessions, whereas ten non-Introductory Biology implementations included such a component, for a total of 14. This is mainly attributable to the fact that five of the six high school implementations included research components. Another difference is that there were more implementations of three or more instructional sessions in the full set (n = 24) than either one or two-session implementations. Once again, this difference is driven by the high school level, where all six implementations used three or more instructional sessions. The college-level implementations for which we captured numbers of instructional sessions (n = 52) were nearly evenly split between one-session (n = 16), two-session (n = 18), and three-or-more-session (n = 18) implementations.

Of all implementations for which participants described their curriculum (n = 60), the majority (n = 42) relied on at least one exercise from the lab book, either as written or with course-specific modifications; 19 used three or all four exercises from that text.

Learning goals

Participants used Avida-ED to address a broad range of learning goals in their courses. We identified and coded 188 discrete learning goals, with each goal classified into one of the five broad categories described in Methods. While most of the goals mentioned by participants in their interviews were in the Evolutionary Concepts category (115/188 total, or 61.2%), Scientific Skills received 33 mentions (17.6%), Nature of Science Concepts received 31 (16.5%), General Skills received 7 (3.7%), and Pedagogy were mentioned twice (1.1%). Briefly, the most common codes were *natural selection concepts* (n = 32), *random nature of mutations* (n = 20), and *data management, curation, and presentation* (n = 18). For the complete list of learning goal codes and their respective counts, see Fig. 3 in Discussion below.

Dissemination

One key component of the Active LENS workshops was the direction to attendees to disseminate Avida-ED to other instructors, as these were ToT workshops.

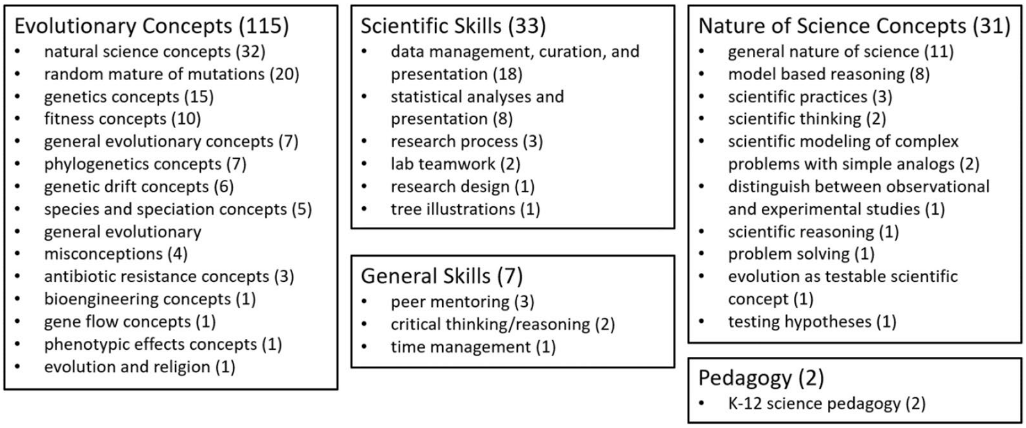

Fig. 3 Categorization of learning goals. Reported learning goals were coded and placed into one of five categories as described in Methods. Figure shows the reported number of Avida-ED implementations that addressed each learning goal

However, evidence from our interviews suggests this activity was not as widely pursued by attendees as was implementation. First, as a part of Active LENS workshops from 2016 to 2020 (with 2020 held virtually due to the COVID-19 pandemic), one or two members from a previous year's cohort of attendees were invited back to present their implementation to the new cohort. This qualified as dissemination in this study. Nine attendees were invited back over this time period; all nine also participated in this study.

In response to a direct question about dissemination, 32 participants spoke about sharing knowledge of Avida-ED with other instructors or scholars. Eighteen of these indicated that their introduction of Avida-ED to other instructors was through some form of formal presentation to scholars or instructors, in many cases at academic conferences. Eleven described introductions of Avida-ED to their colleagues or other instructors via casual or informal conversations. Six participants described either helping their colleagues with implementing Avida-ED—whether a one-off circumstance, or by adopting Avida-ED as a part of the department's curriculum for a particular course regardless of instructor—or using Avida-ED in ToT course. Two participants additionally published journal articles about using Avida-ED.

In total, 35 participants either shared with us dissemination activities or did not share activities but returned to Active LENS the following year to present about their implementation.

Discussion

Below, we discuss what we learned by capturing descriptions of and characterizing the implementations of Avida-ED carried out by our study participants with respect to the different course types in which Avida-ED was used, the types of implementations produced, and the learning goals that instructors addressed via its implementation.

Participant experience at active *LENS*

Overall, study participants communicated that the Active LENS workshops were of high quality and value to them. Among the themes that emerged from our conversations was that the workshop attendees appreciated that we provided them with ready-to-use curricular materials via the lab book (described in Learning Goal Coding above), which we explored and unpacked together during the workshop sessions. For the most part, these required little modification in order to allow attendees to adapt them to their own teaching situation. They also appreciated that the provided materials were tried and true; the materials had been used by workshop facilitators in their own courses so that many of the potential pitfalls had already been discovered and addressed.

These ready-to-use materials mostly came from the lab book, which was mentioned by most participants as particularly valuable. Some participants adapted the materials for their particular courses. Commonly-shared changes involved modifying the language of a given exercise to make it more understandable for a particular instruction level, changing the text of the reflective questions at the end of each exercise to tailor these to their own students, and modifying the activities to align more closely with the participant's intended topic of instruction. No participants spoke about a need to adjust the Independent Research portion of the lab book in their research project implementations, owing to this section's wide adaptability to possible research topics.

Avida-ED implementations

Participation in Active LENS workshops led to a broad and diverse set of Avida-ED implementations in classrooms across the US. Of the 46 Active LENS attendees who participated in our study, 44 (95.6%) implemented Avida-ED in their classrooms.

While we observed Avida-ED implementations at all levels of instruction (high school to advanced undergraduate) and in a wide variety of biology and other course types in our interviews, nearly half of them occurred in Introductory Biology courses (32/66 implementations, or 48.4%). In general, these implementations had short durations (one or two class sessions), and addressed a narrower set of well-defined learning objectives, often guided by the lab book. The introductory biology implementations of Avida-ED often occurred in the lecture classroom instead of the laboratory, involved a small number of class sessions, and gave students the opportunity to interact with Avida-ED for a limited amount of time. Because of this, we consider that these implementations were of lower impact than those which implemented Avida-ED via more substantial periods of time, or as research projects in following with the lab book's final section. The former of these still represent meaningful implementations of Avida-ED in situations where longer-term or larger implementations would not be desired or even feasible; implementations as a research project align with what Lark et al. describes as "engaging students in authentic science practices" (Lark et al. 2018), (2018:82).

Lark et al. identifies uses of Avida-ED in authentic research as one of its highest impact uses (2018:84). Research using Avida-ED engages students in the complete set of science and engineering practices identified by NRC/NGSS from hypothesis generation and protocol development to experiment, data collection, analysis and presentation. (Kohn et al. 2018). Only 14 participants had their students conduct a full research project using Avida-ED. Somewhat surprisingly, high school was the instruction level with the highest concentration of participants who had students engage in Avida-ED based research: four of five high school instructor participants, and five of their six implementations. This may be due to the fact that the high school teachers that attended the Active LENS workshops tended to be extremely well informed and experienced practitioner, but it is more likely due to their having greater flexibility in the time they could allocate to it in their class compared to college instructors, such as those who incorporated Avida-ED into lecture courses without lab sections. The need to save time may also account for the fact that some instructors had their students generate their own research questions, while others provided more guidance and even mandated choice of projects from a predefined list. Another likely reason is that many instructors simply had different learning goals for their courses. Avida-ED was designed to give users maximum flexibility for a wide range of learning goals related to evolution. Some instructors chose to use Avida-ED as a platform for a full independent student research project, but others used it for a more focused purpose, such as to illustrate a particular evolutionary concept in action or to provide hands-on experience of some scientific practice. This is borne out by analysis of our subjects' reported learning goals.

Learning goals

The learning goals that we discuss here were self-reported by study participants and were coded by one of us (BSG), with the codes themselves being assigned to one of five categories (Fig. 3; also see Methods). Study participants reported learning goals related not only to evolution core concepts and misconceptions, but also pertaining to the nature and practices of science (Fig. 3). It was beyond the scope of the current study to categorize learning goals with respect to specific misconceptions and their associated cognitive construals (e.g., teleological reasoning, essentialist thinking, and anthropocentric thinking) as defined by Coley and Tanner (2015), but instructors no doubt had these in mind and they figured in the learning goals that are associated with the lab book exercises that many used.

Given that Avida-ED is a program designed primarily for teaching evolution, it is of no surprise that by far the most commonly-associated codes fell into the Evolutionary Concepts category, including the two most common codes: *natural selection concepts* (n = 32) and *random nature of mutations* (n = 20), which correspond to the second and first lab book exercises, respectively. Importantly, our code of *natural selection concepts* includes instances where instructors wanted students to understand the key differences between random and directed mutations, which is what distinguishes these from other cases where the instructor only expected students to learn about mutation randomness.

Somewhat surprisingly, the third-most commonly associated code was of goals related to *data management, curation, and presentation* (n = 18), the most common of the goals categorized as Scientific Skills (n = 33, or 17.6%). Another 31 goals (16.5%) were categorized as Nature of Science Concepts. This highlights that our participants relied on Avida-ED to incorporate not only evolutionary concepts but also general science concepts and practices, including skills important for scientific pursuits. Another surprisingly common learning goal code in our data is *genetics concepts* (n = 15, 8.0%), particularly given that *genetic drift concepts*, the goal associated with the lab book's fourth exercise, was counted separately in our analysis (see Fig. 3) and that genetics was not a common course type in which participants implemented Avida-ED. These unexpected learning goals highlight the adaptability of Avida-ED to a wide range of classroom circumstances.

Study participants incorporated about the same number of Nature of Science learning goals (n = 31, or 16.4%) as Scientific Skills. The NRC Framework (2012) lists eight science practices that are core components of the Next Generation Science Standards (NGSS). These are: (1) Asking questions; (2) Developing and using models; (3) Planning and carrying out investigations; (4) Analyzing and interpreting data; (5) Using mathematics and computational thinking; (6) Constructing explanations; (7) Engaging in argument from evidence; and, (8) Obtaining, evaluating, and communicating information. Though participants may have been focused on evolutionary concepts as learning goals for their implementations, in using Avida-ED to achieve these goals, they also achieved several, if not most, of the eight NGSS science practices. Using Avida-ED as a research tool thus allows students to engage in all eight practices to an extent only limited by the design of the research experience. As Kohn et al. (2018) shows, using the first four lab book exercises will end up meeting seven of the eight NGSS core components, with only the first core component– "Asking questions"–de-emphasized or excluded. Having students engage in independent research projects after working through the four lab book exercises would incorporate "Asking questions" into the outcomes.

Example research implementation in an upper division microbiology lab course

Perhaps the most extensive implementation of Avida-ED shared by participants took place in a Microbiology lab course at an R2-classified institution. In this course, instructors Rich and Daniel had students work with Avida-ED throughout the semester, with explicit tie-ins to concepts in biological systems. In the first of three instructional units, Rich and Daniel introduced students to Avida-ED via a three-pronged approach. They introduced students to what Avidians are and how they work, relying on two videos about Avida-ED and digital evolution (Wiser 2016; Adami 2012), and then had students build a phylogenetic tree and read Carl Zimmer's article in *Discover* magazine (2005). In Unit 2, they had students explore the random nature of mutation using Exercises 1 and 2 in the lab book and tied these to their lab activities carrying out the Fluctuation Test of Luria and Delbruck (1943). In Unit 3, students completed Exercise 3 and did Amy Lark's Fukushima Butterflies exercise (Lark et al. 2014), and Wendy Johnson's Evolution of TCE Biodegraders Exercise (Johnson et al. 2011b). Finally, Daniel and Rich worked out a genotype-to-phenotype exercise using in silico mutagenesis via systematic deletion mutations (genome engineering), which they paired with a CRISPR/Cas9 exercise in the wet lab. Their implementation culminated in a "March Madness"-style series of competitions, in which students evolved their own competitors for a tournament, which led to the crowning of a "champion" Avidian.

Non-implementations and cessations of implementation

Participants who discussed either their discontinuation of implementation or their lack of implementation entirely, reported several direct barriers leading to these outcomes, reported above. These indicate a number of broader issues which may hamper an instructor's successful and sustained implementation of Avida-ED. There were several parallels between Kali's and Rachel's contexts that speak to these barriers. For one, Kali's department chair settled on a different computer program for teaching similar concepts in similar courses at their institution. Similarly, Rachel informed us that her department was already invested in other teaching tools and showed little interest in switching to Avida-ED. For another, Kali could not implement Avida-ED in the lab portion of the introductory biology sequence because the lab is standardized for the whole department and the other instructor responsible for teaching this course did not agree to use it. Rachel also could not persuade fellow instructors of standardized courses to change them by incorporating Avida-ED. Finally, at the time of Kali's first implementation, Avida-ED was not yet a browser-based program. This technical limitation meant it had to be installed on each machine used for the implementation, which limited its use to university-owned laptops since the process of installation on student-owned laptops, if students had one at all, was too varied and complex to guarantee. Rachel similarly found too much complexity with the program, with its steep learning curve, as a similar technological barrier to its use.

Both Sofia and May were graduate students at the time of their Active LENS workshop attendance, and both struggled with the limitations of that status when trying to implement. May described one of her implementations as essentially a failure, given her inability to require participation by her course section's students; Sofia did not have any courses at all in which she could have tried to implement Avida-ED. However Sofia had already reported to us her upcoming position with teaching responsibilities, and May shared her intentions to pursue a career in the academy; both of these participants might very well successfully implement Avida-ED in their future teaching positions. Sofia, May, Rachel, and Kali all had difficulty with institutional constraints; none of them were in a position to affect change within their respective departments.

Dissemination

Despite the likelihood that this study's participants would be more likely than the average attendee to disseminate Avida-ED to other instructors, the evidence of dissemination in this study was also somewhat disappointing. Our original intent in the Active LENS workshops was that we would be "training-the-trainers" who would go forth and multiply the number of Avida-ED implementers. While there were notable exceptions in this area, (for example, one study participant produced a set of YouTube videos teaching people how to use Avida-ED), we hoped that our workshop attendees would do more. While not formally studied, we suspect that we put too much of the responsibility for this endeavor in the hands of the participants, without providing appropriate structure and guidance.

Limitations

Research team members have had more regular communications with more of this study's participants than all attendees in general and those who were in more regular communication were more likely to be active users and disseminators of Avida-ED. Conversely, those attendees who did not ultimately implement Avida-ED after attending a workshop may have been discouraged from participating in this study, given that implementation and dissemination was one of the stated expectations of workshop attendance. In these senses our study sample is biased toward Avida-ED activity.

Nearly all of our study's participants (n = 44, or 95.7%) implemented Avida-ED in at least one of their courses. However, for the above reasons, we expect that this is an overestimate of the overall rate of implementation, as those who agreed to participate in the study were probably more likely to have implemented Avida-ED. If we instead incorporate reports from and about other Active LENS attendees obtained outside of this study's interviews, we estimate that 62 (59.0%) of the 105 workshop attendees implemented Avida-ED (Table 1). This figure however is a likely underestimate, as we were not able to communicate with all of the workshop attendees who did not participate in our study. Realistically, therefore, the rate of implementation among all Active LENS attendees is somewhere between these two values. Instead, this discrepancy highlights the limitation of our study, which is an outcome of our non-random participant recruitment process: our results are not representative of all Active LENS attendees because our participants are not a representative sample.

Finally, we collected our data using the semi-structured interview process, chosen for its ability to facilitate a conversational style of interview among interviewers and interviewees while still allowing for some control of the topics by interviewers (Ayres 2008). One limitation of this method is the likelihood that an interview might progress in such a way that some subjects are not captured with as much depth as others, with these discrepancies remaining undiscovered until long after the interview has concluded and often during the data analysis phase. In this study, our interviews captured only partial information about eight implementations and this affected our analysis in two instances: our quantification of Evolution courses at the upper-divisional level; and the durations of implementations in Introductory Biology courses. Additionally, it is not possible to determine how many implementations were conducted by our participants but omitted entirely from their interview responses. For these reasons we are careful to explain that our analyses are only derived from implementations for which we have all of the relevant information for the given focus and we note how many of the relevant implementations have been excluded. In cases where we included all implementations in our analysis, we had captured all the information relevant to the subject.

Conclusions and future directions

Avida-ED is an engaging and effective tool for teaching evolution and the nature of science. In the 15 years of its development, it has achieved wide usage; server logs from the last 8 months alone show that it has been accessed from 48 of the 50 US states, plus the District of Columbia and from 75 different countries. This study suggests some factors that might be addressed to further extend its use by overcoming barriers to adoption and implementation. One of our study participants commented that Avida-ED is a bit "scary" upfront for new adopters. Instructor content knowledge, pedagogical content knowledge (PCK), and technological pedagogical content knowledge (TPCK; see Lark et al. 2020) are all required to some degree to use Avida-ED effectively in the classroom. This study showed that faculty development workshops are an effective way for instructors to gain such knowledge and skills to implement this experimental platform in their own classes, but that for many instructors more is needed before they are ready to train others. A Training of Trainers model is a promising approach, as evidenced by participants who succeeded in disseminating Avida-ED beyond their own classrooms, but it sets a higher bar that requires greater preparation and support. For instance, we expect that supplemental instructional and help videos that participants could access as refresher materials would assist their ability and confidence for dissemination, so we have begun to create and make these available. Lessons learned from this experience will help improve ToT workshops in the future.

Abbreviations

BSG	Brian Samuel Geyer
COVID-19	Coronavirus 2019
JJS	James J. Smith
PCK	Pedagogical content knowledge
MSU	Michigan State University
NRC/NGSS	National Research Council's Next Generation Science Standards
ToT	Training of Trainers
TPCK	Technological pedagogical content knowledge

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12052-024-00211-2.

Supplementary material 1. Wednesday Schedule. This is the schedule of an example day for an Active LENS workshop, held in 2017 at Michigan State University.

Supplementary material 2. Interview Protocol—'Active LENS: Learning Evolution and the Nature of Science Using Evolution in Action—Instructor Implementations. This is the semi-structured protocol used for participant interviews with those who have implemented Avida-ED in their classrooms.

Supplementary material 3. This is the data coding log for one participant, which has been fully deidentified. This serves as an example of the coding log used during data analysis, to produce the final table of all AvidaED implementations.

Supplementary material 4. Supplemental Table 1–Avida-ED Implementations by Active LENS Participants. This table reports all 66 implementations by this study's participants, along with other coded information identified during data analysis.

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Author contributions
BSG and JJS conducted the remote interviews. All authors contributed to the study design, data analysis, and manuscript authorship, including the design of all figures. All authors reviewed the manuscript.

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Availability of data and materials
The coded dataset supporting the conclusions of this article is included within Supplementary Table S1, submitted along with this manuscript. This dataset has been deidentified to conserve confidentiality for study participants. The original interview audio recordings will not be made available.

Declarations

Competing interests
The authors declare no competing interests.

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