

## The Need to Be Sure About CUREs: Discovery and Relevance as Critical Elements of CUREs for Nonmajors

To the Editor,

We read with interest the recently published paper from Ballen and colleagues (1), who indicated that *discovery* and *relevance* may be insignificant components of course-based undergraduate research experiences (CUREs) for nonbiology majors. We appreciate the authors for addressing this important topic because there is a need for empirical evidence to shed light on design features that are hypothesized to make CUREs distinctive as learning experiences (2). We write this letter in this spirit of collegial exchange and with the aim of promoting further investigation on how CURE instruction influences the learning and development of diverse students. In doing so, we also respectfully submit our opinion that the claims made by Ballen and colleagues overstate the evidence they present and potentially mislead readers in judging the importance of *discovery* and *relevance* to CUREs.

Of most concern is what we consider to be a basic validity flaw in the design of Ballen *et al.*'s comparison groups. The study is described as a "backward elimination experimental design," which utilizes what are assumed to be critical differences in three educational experiences, termed: 1. CURE treatment group, 2. Discovery-based inquiry group, and 3. Inquiry-based treatment group. According to the authors, the difference between these groups is the presence of components hypothesized by Auchincloss *et al.* (2), specifically, the inclusion or exclusion of the "experience of *discovery*" and the inclusion or exclusion of "dissemination of data broadly relevant to the scientific community" (i.e., *relevance*). According to Ballen *et al.*, the CURE group had all the components specified by Auchincloss *et al.* and the Discovery group had all the components except *relevance*. The third group was a form of control and did not have either the experience of *discovery* or *relevance*. As such, the validity of the design and all subsequent results and conclusions is based on the *discovery* and *relevance* variables.

The basic validity problem is in the definition of *discovery* and *relevance* and thus the definition of a CURE. Ballen and colleagues specified that the experience of *discovery* consisted of students constructing and addressing their own research questions "not asked before in the literature" during five lab sessions, based on the data they received

from the Program in Human Sexuality on campus. We are skeptical that five sessions worth of work with limited understanding of or access to the scientific field actually constitutes scientific *discovery*. Ballen and colleagues further specified that *relevance* consisted of students e-mailing their final "presentations to a researcher at the Program in Human Sexuality." We are similarly skeptical that e-mailing a presentation to a professor at one's own institution constitutes *relevance* to a larger community. Other CUREs have engaged students in making discoveries that are documented in products relevant to stakeholders in the research, such as journal articles, conference presentations, database entries, and community reports (3–9). Furthermore, Shaffer and colleagues have demonstrated that sustained engagement in research (>36 hours) is necessary for students to fully realize certain benefits of these experiences (10).

The question as to whether or not the three groups varied in their levels of *discovery* or *relevance* and whether or not the CURE group included both *discovery* and *relevance* could have been addressed empirically. There are existing measures that Ballen and colleagues could have used to demonstrate that the experiences of the three groups are indeed distinct. For example, we (LAC, ELD) have developed and validated a survey measure of *relevance* and *discovery* in undergraduate lab courses (11), and responses to this instrument have been shown to distinguish between different types of lab courses in multiple studies (11, 12). Ballen and colleagues could have measured these variables in other ways, but such measures would need to be accompanied by evidence of their validity and reliability in order to draw meaningful conclusions (13–15). Regardless of the measures used, Ballen and colleagues should also have measured the *relevance* and *discovery* variables in each laboratory section to demonstrate that their interventions were implemented with fidelity and differed as intended (16). Without these data, and in light of the limitations inherent in the study design, we have no idea what the manipulations of the groups actually mean. Further evidence of this validity problem is apparent in Figure 2 of their article, in which students in all three treatments rate the level of *discovery* and *relevance* similarly. This result suggests the treatments may not have been meaningfully different, which is what we would predict from the descriptions of the groups.

Another substantive validity concern is that the study relies only on single items to make inferences about the extent to which students develop a sense of *ownership* over their coursework. This is problematic from a measurement

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perspective (13, 14), similar to measuring the quality of “fun” at an amusement park based on a single ride. In order to measure a latent variable such as students’ level of ownership, there is widespread agreement in the education measurement literature that multiple items—worded slightly differently yet each getting at “ownership”—should be used in order to best assess the construct of interest (6). Furthermore, while the survey items were adapted from an established measure, the Project Ownership Survey (POS) (17), some of the items used by Ballen and colleagues are unrelated to the items in the POS, which raises questions about what the responses on those items actually mean. In general, any selective or modified uses of items from existing measures should be accompanied by validity evidence (13), which Ballen and colleagues did not provide. Because of these validity issues, it seems impossible to examine how student engagement in discovery and dissemination relates to their project ownership, as the study purports to do. We (LAC, ELD) have examined these relationships in our work and find that, at least for science majors, students who have opportunities to make relevant discoveries in their lab courses are more likely to develop a sense of project ownership, but that opportunities to engage in iterative work, such as repeating experiments, troubleshooting, and problem-solving, may be more influential than opportunities to make discoveries (12).

Our final concern is more theoretical in nature and relates to the overall study design. CURE instruction has grown rapidly in response to national calls for transforming undergraduate STEM education (18, 19). This growth has the potential to outpace careful, local-level thinking about whether, why, and how to teach CUREs. For instance, CUREs could be integrated into introductory biology courses to introduce students to research and help them decide whether to pursue additional research experiences or a career involving research; existing theories related to career development are useful for examining this (e.g., 20). Alternatively, CUREs could be integrated into general education courses with the aim of familiarizing students with the practice and nature of science, and for this examining this situation, existing theories related to student understanding of the nature and practice of science are useful (e.g., 21, 22). Similarly, we and others have offered guidance on how to align CURE instruction with educational goals and explained different theories that may help to elucidate how CUREs function (23, 24). The paper by Ballen and colleagues did not present their rationale (i.e., a theory) for the design of the courses in the study. It was unclear to us why they expected the outcomes they studied (e.g., course grades) to differ between the different treatments, or why a lack of effect on course grades would lead to the conclusion that *relevance* and *discovery* are “insignificant” elements of course design for the population in question. The study from Ballen *et al.* was also limited to one course at one institution with one particular population of students (i.e., nonbiology majors).

Therefore, we respectfully disagree with the authors’ conclusion that the “results have broad implications for the development of scalable CUREs in university curricula.” Nevertheless, the authors are asking an important and timely question: whether and how the course design features hypothesized to make CUREs distinctive as learning environments relate to desirable student outcomes. We encourage the community to test, refine, and even refute the framework we have proposed (2). To be informative, however, such studies must address both related and contradictory research, and they must attend to the theory behind CUREs as an intervention, measure the implementation of any interventions, and demonstrate the validity and reliability of the measures.

Sincerely,

Lisa A. Corwin  
Ecology & Evolutionary Biology  
University of Colorado Boulder  
Boulder, CO  
lisa.corwin@colorado.edu

Erin L. Dolan  
Biochemistry & Molecular Biology  
University of Georgia  
Athens, GA  
eldolan@uga.edu

Mark J. Graham  
STEM Program Evaluation and Research Lab  
(STEM-PERL)  
Ecology & Evolutionary Biology  
Yale University  
New Haven, CT  
mark.graham@yale.edu

David I. Hanauer  
Professor of Applied Linguistics/English  
Indiana University of Pennsylvania  
Indiana, PA  
hanauer@iup.edu

Nancy Pelaez  
Department of Biological Sciences  
Purdue University  
West Lafayette, IN  
npelaez@purdue.edu

## REFERENCES

1. Ballen CJ, Thompson SK, Blum JE, Newstrom NP, Cotner S. 2018. Discovery and broad relevance may be insignificant components of course-based undergraduate research experiences (CUREs) for non-biology majors. *J Microbiol Biol Educ* 19.

2. Auchincloss LC, Laursen SL, Branchaw JL, Eagan K, Graham M, Hanauer DI, Lawrie G, McLinn CM, Pelaez N, Rowland S, Towns M, Trautmann NM, Varma-Nelson P, Weston TJ, Dolan EL. 2014. Assessment of course-based undergraduate research experiences: a meeting report. *CBE Life Sci Educ* 13:29–40.
3. National Academies of Sciences, Engineering, and Medicine. 2015. Integrating discovery-based research into the undergraduate curriculum: report of a convocation. The National Academies Press, Washington, DC.
4. Leung W, Shaffer CD, Cordonnier T, Wong J, Itano MS, Tempel EES, Kellmann E, Desruisseau DM, Cain C, Carrasquillo R, Chusak TM, Falkowska K, Grim KD, Guan R, Honeybourne J, Khan S, Lo L, McGaha R, Plunkett J, Richner JM, Richt R, Sabin L, Shah A, Sharma A, Singhal S, Song F, Swope C, Wilen CB, Buhler J, Mardis ER, Elgin SCR. 2010. Evolution of a distinct genomic domain in *Drosophila*: comparative analysis of the dot chromosome in *Drosophila melanogaster* and *Drosophila virilis*. *Genetics* 185:1519–1534.
5. Leung W, Shaffer CD, Reed LK, Smith ST, Barshop W, Dirkes W, Dothager M, Lee P, Wong J, Xiong D, Yuan H, Bedard JEJ, Machone JF, Patterson SD, Price AL, Turner BA, Robic S, Luippold EK, McCartha SR, Walji TA, Walker CA, Saville K, Abrams MK, Armstrong AR, Armstrong W, Bailey RJ, Barberi CR, Beck LR, Blaker AL, Blunden CE, Brand JP, Brock EJ, Brooks DW, Brown M, Butzler SC, Clark EM, Clark NB, Collins AA, Cotteleer RJ, Cullimore PR, Dawson SG, Docking CT, Dorsett SL, Dougherty GA, Downey KA, Drake AP, Earl EK, Floyd TG, Forsyth JD, Foust JD, Franchi SL, Geary JF, Hanson CK, Harding TS, Harris CB, Heckman JM, Holderness HL, Howey NA, Jacobs DA, Jewell ES, Kaisler M, Karaska EA, Kehoe JL, Koaches HC, Koehler J, Koenig D, Kujawski AJ, Kus JE, Lammers JA, Leads RR, Leatherman EC, Lippert RN, Messenger GS, Morrow AT, Newcomb V, Plasman HJ, Potocny SJ, Powers MK, Reem RM, Rennhack JP, Reynolds KR, Reynolds LA, Rhee DK, Rivard AB, Ronk AJ, Rooney MB, Rubin LS, Salbert LR, Saluja RK, Schauder T, Schreiber AR, Schulz RW, Smith KE, Spencer S, Swanson BR, Tache MA, Tewilliger AA, Tilot AK, VanEck E, Villerot MM, Vylonis MB, Watson DT, Wurzler JA, Wysocki LM, Yalamanchili M, Zaborowicz MA, Emerson JA, Ortiz C, Deuschle FJ, DiLorenzo LA, Goeller KL, Macchi CR, Muller SE, Pasiere BD, Sable JE, Tucci JM, Tynon M, Dunbar DA, Beken LH, Conturso AC, Danner BL, DeMichele GA, Gonzales JA, Hammond MS, Kelley CV, Kelly EA, Kulich D, Mageeney CM, McCabe NL, Newman AM, Spaeder LA, Tumminello RA, Revie D, Benson JM, Cristostomo MC, DaSilva PA, Harker KS, Jarrell JN, Jimenez LA, Katz BM, Kennedy WR, Kolibas KS, LeBlanc MT, Nguyen TT, Nicolas DS, Patao MD, Patao SM, Rupley BJ, Sessions BJ, Weaver JA, Goodman AL, Alvendia EL, Baldassari SM, Brown AS, Chase IO, Chen M, Chiang S, Cromwell AB, Custer AF, DiTommaso TM, El-Adaimi J, Goscinski NC, Grove RA, Gutierrez N, Harnoto RS, Hedeon H, Hong EL, Hopkins BL, Huerta VF, Khoshabian C, LaForge KM, Lee CT, Lewis BM, Lydon AM, Maniaci BJ, Mitchell RD, Morlock EV, Morris WM, Naik P, Olson NC, Osterloh JM, Perez MA, Presley JD, Randazzo MJ, Regan MK, Rossi FG, Smith MA, Soliterman EA, Sparks CJ, Tran DL, Wan T, Welker AA, Wong JN, Sreenivasan A, Youngblom J, Adams A, Alldredge J, Bryant A, Carranza D, Cifelli A, Coulson K, Debow C, Delacruz N, Emerson C, Farrar C, Foret D, Garibay E, Gooch J, Heslop M, Kaur S, Khan A, Kim V, Lamb T, Lindbeck P, Lucas G, Macias E, Martiniuc D, Mayorga L, Medina J, Membreno N, Messiah S, Neufeld L, Nguyen SF, Nichols Z, Odisho G, Peterson D, Rodela L, Rodriguez P, Rodriguez V, Ruiz J, Sherrill W, Silva V, Sparks J, Statton G, Townsend A, Valdez I, Waters M, Westphal K, Winkler S, Zumkehr J, DeJong RJ, Hoogewerf AJ, Ackerman CM, Armistead IO, Baatenburg L, Borr MJ, Brouwer LK, Burkhart BJ, Bushhouse KT, Cesko L, Choi TYY, Cohen H, Damsteegt AM, Darusz JM, Dauphin CM, Davis YP, Diekema EJ, Drewry M, Eisen MEM, Faber HM, Faber KJ, Feenstra E, Felzer-Kim IT, Hammond BL, Hendriksma J, Herrold MR, Hilbrands JA, Howell EJ, Jelgerhuis SA, Jelsema TR, Johnson BK, Jones KK, Kim A, Kooienga RD, Menyes EE, Nollet EA, Plescher BE, Rios L, Rose JL, Schepers AJ, Scott G, Smith JR, Sterling AM, Tenney JC, Uitvlugt C, Dyken REV, VanderVennen M, Vue S, Kokan NP, Agbley K, Boham SK, Broomfield D, Chapman K, Dobbe A, Dobbe I, Harrington W, Ibrahim MN, Kennedy A, Koplinsky CA, Kubricky C, Ladzekpo D, Pattison C, Ramirez RE, Wande L, Woehlke S, Wawersik M, Kiernan E, Thompson JS, Banker R, Bartling JR, Bhatiya CI, Boudoures AL, Christiansen L, Fosselman DS, French KM, Gill IS, Havill JT, Johnson JL, Keny LJ, Kerber JM, Klett BM, Kufel CN, May FJ, Mecoli JP, Merry CR, Meyer LR, Miller EG, Mullen GJ, Palozola KC, Pfeil JJ, Thomas JG, Verbofsky EM, Spana EP, Agarwalla A, Chapman J, Chlebina B, Chong I, Falk IN, Fitzgibbons JD, Friedman H, Ighile O, Kim AJ, Knouse KA, Kung F, Mammo D, Ng CL, Nikam VS, Norton D, Pham P, Polk JW, Prasad S, Rankin H, Ratliff CD, Scala V, Schwartz NU, Shuen JA, Xu A, Xu TQ, Zhang Y, Rosenwald AG, Burg MG, Adams SJ, Baker M, Botsford B, Brinkley B, Brown C, Emiah S, Enoch E, Gier C, Greenwell A, Hoogenboom L, Matthews JE, McDonald M, Mercer A, Monsma N, Ostby K, Ramic A, Shallman D, Simon M, Spencer E, Tomkins T, Wendland P, Wylie A, Wolyniak MJ, Robertson GM, Smith SI, DiAngelo JR, Sassu ED, Bhalla SC, Sharif KA, Choeying T, Macias JS, Sanusi F, Torchon K, Bednarski AE, Alvarez CJ, Davis KC, Dunham CA, Grantham AJ, Hare AN, Schottler J, Scott ZW, Kuleck GA, Yu NS, Kaehler MM, Jipp J, Overvoorde PJ, Shoop E, Cyrankowski O, Hoover B, Kusner M, Lin D, Martinov T, Misch J, Salzman G, Schiedermaier H, Snavelly M, Zarrasola S, Parrish S, Baker A, Beckett A, Belella C, Bryant J, Conrad T, Fearnow A, Gomez C, Herbstsomer RA, Hirsch S, Johnson C, Jones M, Kabaso R, Lemmon E, Vieira CM, McFarland D, McLaughlin C, Morgan A, Musokotwane S, Neutzling W, Nietmann J, Paluskievicz C, Penn J, Peoples E, Pozmanter C, Reed E, Rigby N, Schmidt L, Shelton M, Shuford R, Tirasawasdichai T, Udem B, Urlick D, Vondy K, Yarrington B, Eckdahl TT, Poet JL, Allen AB, Anderson JE, Barnett JM, Baumgardner JS, Brown AD, Carney JE, Chavez RA, Christgen SL, Christie JS, Clary AN, Conn

MA, Cooper KM, Crowley MJ, Crowley ST, Doty JS, Dow BA, Edwards CR, Elder DD, Fanning JP, Janssen BM, Lambright AK, Lane CE, Limle AB, Mazur T, McCracken MR, McDonough AM, Melton AD, Minnick PJ, Musick AE, Newhart WH, Noynaert JW, Ogden BJ, Sandusky MW, Schmuecker SM, Shipman AL, Smith AL, Thomsen KM, Unzicker MR, Vernon WB, Winn WW, Woyski DS, Zhu X, Du C, Ament C, Aso S, Bisogno LS, Caronna J, Fefelova N, Lopez L, Malkowitz L, Marra J, Menillo D, Obiorah I, Onsarigo EN, Primus S, Soos M, Tare A, Zidan A, Jones CJ, Aronhalt T, Bellush JM, Burke C, DeFazio S, Does BR, Johnson TD, Keysock N, Knudsen NH, Messler J, Myrski K, Rekaï JL, Rempe RM, Salgado MS, Stagaard E, Starcher JR, Waggoner AW, Yemelyanova AK, Hark AT, Bertolet A, Kuschner CE, Parry K, Quach M, Shantzler L, Shaw ME, Smith MA, Glenn O, Mason P, Williams C, Key CS, Henry TCP, Johnson AG, White JX, Haberman A, Asinof S, Drumm K, Freeburg T, Safa N, Schultz D, Shevin Y, Svoronos P, Vuong T, Wellinghoff J, Hoopes LLM, Chau KM, Ward A, Regisford EGC, Augustine L, Davis-Reyes B, Echendu V, Hales J, Ibarra S, Johnson L, Ovu S, Braverman JM, Bahr TJ, Caesar NM, Campana C, Cassidy DW, Cognetti PA, English JD, Fadus MC, Fick CN, Freda PJ, Hennessy BM, Hockenberger K, Jones JK, King JE, Knob CR, Kraftmann KJ, Li L, Lupey LN, Minniti CJ, Minton TF, Moran JV, Mudumbi K, Nordman EC, Puetz WJ, Robinson LM, Rose TJ, Sweeney EP, Timko AS, Paetkau DW, Eisler HL, Aldrup ME, Bodenbergh JM, Cole MG, Deranek KM, DeShetler M, Dowd RM, Eckardt AK, Ehret SC, Fese J, Garrett AD, Kammrath A, Kappes ML, Light MR, Meier AC, O'Rouke A, Perella M, Ramsey K, Ramthun JR, Reilly MT, Robinett D, Rossi NL, Schueler M, Shoemaker E, Starkey KM, Vctor A, Vrable A, Chandrasekaran V, Beck C, Hatfield KR, Herrick DA, Khoury CB, Lea C, Louie CA, Lowell SM, Reynolds TJ, Schibler J, Scoma AH, Smith-Gee MT, Tuberty S, Smith CD, Lopilato JE, Hauke J, Roecklein-Canfield JA, Corriellus M, Gilman H, Intriago S, Maffa A, Rauf SA, Thistle K, Trieu M, Winters J, Yang B, Hauser CR, Abusheikh T, Ashrawi Y, Benitez P, Boudreaux LR, Bourland M, Chavez M, Cruz S, Elliott G, Farek JR, Flohr S, Flores AH, Friedrichs C, Fusco Z, Goodwin Z, Helmreich E, Kiley J, Knepper JM, Langner C, Martinez M, Mendoza C, Naik M, Ochoa A, Ragland N, Raimey E, Rathore S, Reza E, Sadovsky G, Seydoux M-IB, Smith JE, Unruh AK, Velasquez V, Wolski MW, Gosser Y, Govind S, Clarke-Medley N, Guadron L, Lau D, Lu A, Mazzeo C, Meghdari M, Ng S, Pamnani B, Plante O, Shum YKW, Song R, Johnson DE, Abdelnabi M, Archambault A, Chamma N, Gaur S, Hammett D, Kandahari A, Khayrullina G, Kumar S, Lawrence S, Madden N, Mandelbaum M, Milnthorp H, Mohini S, Patel R, Peacock SJ, Perling E, Quintana A, Rahimi M, Ramirez K, Singhal R, Weeks C, Wong T, Gillis AT, Moore ZD, Savell CD, Watson R, Mel SF, Anilkumar AA, Bilinski P, Castillo R, Closser M, Cruz NM, Dai T, Garbagnati GF, Horton LS, Kim D, Lau JH, Liu JZ, Mach SD, Phan TA, Ren Y, Stapleton KE, Strelitz JM, Sunjed R, Stamm J, Anderson MC, Bonifield BG, Coomes D, Dillman A, Durchholz EJ, Fafara-Thompson AE, Gross MJ, Gygi AM, Jackson LE,

Johnson A, Kocsisova Z, Manghelli JL, McNeil K, Murillo M, Naylor KL, Neely J, Ogawa EE, Rich A, Rogers A, Spencer JD, Stemler KM, Throm AA, Camp MV, Weihsbrecht K, Wiles TA, Williams MA, Williams M, Zoll K, Bailey C, Zhou L, Balthaser DM, Bashiri A, Bower ME, Florian KA, Ghavam N, Greiner-Sosanko ES, Karim H, Mullen VW, Pelchen CE, Yenerall PM, Zhang J, Rubin MR, Arias-Mejias SM, Bermudez-Capo AG, Bernal-Vega GV, Colon-Vazquez M, Flores-Vazquez A, Gines-Rosario M, Llavona-Cartagena IG, Martinez-Rodriguez JO, Ortiz-Fuentes L, Perez-Colomba EO, Perez-Otero J, Rivera E, Rodriguez-Giron LJ, Santiago-Sanabria AJ, Senquiz-Gonzalez AM, Soto-delValle FR, Vargas-Franco D, Velázquez-Soto KI, Zambrana-Burgos JD, Martinez-Cruzado JC, Asencio-Zayas L, Babilonia-Figueroa K, Beauchamp-Pérez FD, Belén-Rodríguez J, Bracero-Quiñones L, Burgos-Bula AP, Collado-Méndez XA, Colón-Cruz LR, Correa-Muller AI, Crooke-Rosado JL, Cruz-García JM, Defendini-Ávila M, Delgado-Peraza FM, Feliciano-Cancela AJ, González-Pérez VM, Guiblet W, Heredia-Negrón A, Hernández-Muñiz J, Irizarry-González LN, Laboy-Corales ÁL, Llaurador-Caraballo GA, Marín-Maldonado F, Marrero-Llerena U, Martell-Martínez HA, Martínez-Traverso IM, Medina-Ortega KN, Méndez-Castellanos SG, Menéndez-Serrano KC, Morales-Caraballo CI, Ortiz-DeChoudens S, Ortiz-Ortiz P, Pagán-Torres H, Pérez-Afanador D, Quintana-Torres EM, Ramírez-Aponte EG, Riascos-Cuero C, Rivera-Llovet MS, Rivera-Pagán IT, Rivera-Vicéns RE, Robles-Juarbe F, Rodríguez-Bonilla L, Rodríguez-Echevarría BO, Rodríguez-García PM, Rodríguez-Laboy AE, Rodríguez-Santiago S, Rojas-Vargas ML, Rubio-Marrero EN, Santiago-Colón A, Santiago-Ortiz JL, Santos-Ramos CE, Serrano-González J, Tamayo-Figueroa AM, Tascón-Peñaranda EP, Torres-Castillo JL, Valentín-Feliciano NA, Valentín-Feliciano YM, Vargas-Barreto NM, Vélez-Vázquez M, Vilanova-Vélez LR, Zambrana-Echevarría C, MacKinnon C, Chung HM, Kay C, Pinto A, Kopp OR, Burkhardt J, Harward C, Allen R, Bhat P, Chang JHC, Chen Y, Chesley C, Cohn D, DuPuis D, Fasano M, Fazio N, Gavinski K, Gebreyesus H, Giarla T, Gostelow M, Greenstein R, Gunasinghe H, Hanson C, Hay A, He TJ, Homa K, Howe R, Howenstein J, Huang H, Khatri A, Kim YL, Knowles O, Kong S, Krock R, Kroll M, Kuhn J, Kwong M, Lee B, Lee R, Levine K, Li Y, Liu B, Liu L, Liu M, Lousarian A, Ma J, Mallya A, Manchee C, Marcus J, McDaniel S, Miller ML, Mollleston JM, Diez CM, Ng P, Ngai N, Nguyen H, Nylander A, Pollack J, Rastogi S, Reddy H, Regenold N, Sarezky J, Schultz M, Shim J, Skorupa T, Smith K, Spencer SJ, Srikanth P, Stancu G, Stein AP, Strother M, Sudmeier L, Sun M, Sundaram V, Tazudeen N, Tseng A, Tzeng A, Venkat R, Venkataram S, Waldman L, Wang T, Yang H, Yu JY, Zheng Y, Preuss ML, Garcia A, Juergens M, Morris RW, Nagengast AA, Azarewicz J, Carr TJ, Chichearo N, Colgan M, Donegan M, Gardner B, Kolba N, Krumm JL, Lytle S, MacMillian L, Miller M, Montgomery A, Moretti A, Offenbacher B, Polen M, Toth J, Woytanowski J, Kadlec L, Crawford J, Spratt ML, Adams AL, Barnard BK, Cheramie MN, Eime AM, Golden KL, Hawkins AP, Hill JE, Kampmeier JA, Kern CD, Magnuson EE,



- Miller AR, Morrow CM, Peairs JC, Pickett GL, Popelka SA, Scott AJ, Teepe EJ, TerMeer KA, Watchinski CA, Watson LA, Weber RE, Woodard KA, Barnard DC, Appiah I, Giddens MM, McNeil GP, Adebayo A, Bagaeva K, Chinwong J, Dol C, George E, Haltaufderhyde K, Haye J, Kaur M, Semon M, Serjanov D, Toorie A, Wilson C, Riddle NC, Buhler J, Mardis ER, Elgin SCR. 2015. *Drosophila muller* F elements maintain a distinct set of genomic properties over 40 million years of evolution. *G3 (Bethesda)* 5(5):719–740
6. Wiley EA, Stover NA. 2014. Immediate dissemination of student discoveries to a model organism database enhances classroom-based research experiences. *CBE Life Sci Educ* 13:131–138.
  7. Pope WH, Ferreira CM, Jacobs-Sera D, Benjamin RC, Davis AJ, DeJong RJ, Elgin SCR, Guilfoile FR, Forsyth MH, Harris AD, Harvey SE, Hughes LE, Hynes PM, Jackson AS, Jalal MD, MacMurray EA, Manley CM, McDonough MJ, Mosier JL, Osterbann LJ, Rabinowitz HS, Rhyan CN, Russell DA, Saha MS, Shaffer CD, Simon SE, Sims EF, Tovar IG, Weisser EG, Wertz JT, Weston-Hafer KA, Williamson KE, Zhang B, Cresawn SG, Jain P, Piuri M, Jr WRJ, Hendrix RW, Hatfull GF. 2011. Cluster K mycobacteriophages: insights into the evolutionary origins of mycobacteriophage TM4. *PLOS One* 6:e26750.
  8. Beckham JT, Simmons S, Stovall GM, Farre J. 2015. The freshman research initiative as a model for addressing shortages and disparities in STEM engagement, p 181–212. In Peterson MA, Rubinstein YA (eds.), *Directions for mathematics research experience for undergraduates*. World Scientific, Singapore.
  9. Dolan EL. 2016. Course-based undergraduate research experiences: current knowledge and future directions. National Research Council Commissioned Paper, Washington, DC.
  10. Shaffer CD, Alvarez CJ, Bednarski AE, Dunbar D, Goodman AL, Reinke C, Rosenwald AG, Wolyniak MJ, Bailey C, Barnard D, Bazinet C, Beach DL, Bedard JEJ, Bhalla S, Braverman J, Burg M, Chandrasekaran V, Chung H-M, Clase K, DeJong RJ, DiAngelo JR, Du C, Eckdahl TT, Eisler H, Emerson JA, Frary A, Frohlich D, Gosser Y, Govind S, Haberman A, Hark AT, Hauser C, Hoogewerf A, Hoopes LLM, Howell CE, Johnson D, Jones CJ, Kadlec L, Kaehler M, Key SCS, Kleinschmit A, Kokan NP, Kopp O, Kuleck G, Leatherman J, Lopilato J, MacKinnon C, Martinez-Cruzado JC, McNeil G, Mel S, Mistry H, Nagengast A, Overvoorde P, Paetkau DW, Parrish S, Peterson CN, Preuss M, Reed LK, Revie D, Robic S, Roecklein-Canfield J, Rubin MR, Saville K, Schroeder S, Sharif K, Shaw M, Skuse G, Smith CD, Smith MA, Smith ST, Spana E, Spratt M, Sreenivasan A, Stamm J, Szauter P, Thompson JS, Wawersik M, Youngblom J, Zhou L, Mardis ER, Buhler J, Leung W, Lopatto D, Elgin SCR. 2014. A Course-based research experience: how benefits change with increased investment in instructional time. *CBE Life Sci Educ* 13:111–130.
  11. Corwin LA, Runyon C, Robinson A, Dolan EL. 2015. The laboratory course assessment survey: a tool to measure three dimensions of research-course design. *CBE Life Sci Educ* 14(4):ar37.
  12. Corwin LA, Runyon CR, Ghanem E, Sandy M, Clark G, Palmer GC, Reichler S, Rodenbusch SE, Dolan EL, Hewlett J. 2018. Effects of discovery, iteration, and collaboration in laboratory courses on undergraduates' research career intentions fully mediated by student ownership. *CBE Life Sci Educ* 17:ar20.
  13. American Educational Research Association, American Psychological Association, National Council on Measurement in Education, Joint Committee on Standards for Educational, Psychological Testing (US). 2014. *Standards for educational and psychological testing*. AERA, Washington, DC.
  14. Bandalos DL. 2018. *Measurement theory and applications for the social sciences*, 1st edition. The Guilford Press, New York.
  15. Netemeyer RG, Bearden WO, Sharma S. 2003. *Scaling procedures: issues and applications*. SAGE.
  16. Stains M, Vickrey T. 2017. Fidelity of implementation: an overlooked yet critical construct to establish effectiveness of evidence-based instructional practices. *CBE Life Sci Educ* 16:rm1.
  17. Hanauer DI, Dolan EL. 2014. The project ownership survey: measuring differences in scientific inquiry experiences. *CBE Life Sci Educ* 13:149–158.
  18. American Association for the Advancement of Science. 2011. *Vision and change in undergraduate biology education: a call to action: a summary of recommendations made at a national conference organized by the American Association for the Advancement of Science, July 15–17, 2009*. Washington, DC.
  19. Olson S, Riordan DG. 2012. *Engage to excel: producing one million additional college graduates with degrees in science, technology, engineering, and mathematics*. Report to the President. Executive Office of the President, Washington, DC.
  20. Lent RW, Brown SD, Hackett G. 1994. Toward a unifying social cognitive theory of career and academic interest, choice, and performance. *J Vocat Behav* 45:79–122.
  21. Sandoval WA. 2005. Understanding students' practical epistemologies and their influence on learning through inquiry. *Sci Educ* 89:634–656.
  22. Zeineddin A, Abd-El-Khalick F. 2010. Scientific reasoning and epistemological commitments: coordination of theory and evidence among college science students. *J Res Sci Teach* 47:1064–1093.
  23. Cooper KM, Soneral PAG, Brownell SE. 2017. Define your goals before you design a CURE: a call to use backward design in planning course-based undergraduate research experiences. *J Microbiol Biol Educ* 18(2): 10.1128/jmbe.v18i2.1287.
  24. Corwin LA, Graham MJ, Dolan EL. 2015. Modeling course-based undergraduate research experiences: an agenda for future research and evaluation. *CBE Life Sci Educ* 14:es1.