*Research in Learning Technology*
Vol. 26, 2018

## ORIGINAL RESEARCH ARTICLE

# Teaching movement science with full-body motion capture in an undergraduate liberal arts psychology class

Shengwei Yao[a], Elizabeth Queathem[b], David Neville[c] and Damian Kelty-Stephen[d]*

[a]*Psychology Department, Grinnell College, Grinnell, IA, United States of America;* [b]*Biology Department, Grinnell College, Grinnell, IA, United States of America;* [c]*Center for Teaching, Learning & Assessment, Grinnell College, Grinnell, IA, United States of America;* [d]*Psychology Department, Grinnell College, Grinnell, IA, United States of America*

*(Received: 23 July 2018; final version received: 30 August 2018)*

Movement science is a field that is quickly growing in its scope, leaning heavily on psychological expertise for research design with human participants but requiring computational and engineering ability. Undergraduate psychology curricula are in a unique position to train some of its future scholars. This report reviews an attempt to pilot a class on motion capture for undergraduate psychology students. Recent developments in motion-capture technology have opened up the opportunity for giving hands-on experience with high-quality motion capture for students at liberal-arts colleges with leaner research budgets. Post-course responses to the Research on Integrated Science Curriculum (RISC) survey demonstrated that our students made significantly large gains in their ability to organise an empirical approach to study a complex problem with no clear solution, and to collect and analyse data to produce a coherent insight about that problem. Students may benefit from incorporating motion capture into their undergraduate psychology curriculum.

**Keywords:** motion capture, psychology, movement science, integrated science curriculum, inertial measurement units

To access the supplementary material, please visit the article landing page

Often neglected in the shadowy academic space between biomechanics, physiology and psychology (Rosenbaum 2005), the science and technology of coordinated bodily movement is currently coming into its own. Movement science is becoming essential for an ageing population, for a health care industry keen to advocate physical fitness as a preventative measure that is cheaper and more effective than treating the symptoms of sedentary lifestyles and for a technological industry eager to make machines more responsive and better adapted to our motor capacities. Movement science will require a multidisciplinary perspective as capable to do the mathematics of biomechanical modelling as to troubleshoot the software and hardware. Whatever movement science learns, the translation of those insights will come in the form of instructions or wearable technologies that need to fit the human users and support the many constraints, preferences and quirks texturing individual people's goal-directed movement, that is, to support a truly complex system with a personal, idiosyncratic touch (Cavanaugh, Kelty-Stephen, & Stergiou 2017). Therefore, movement science

*Corresponding author. Email: keltysda@grinnell.edu





Citation: Research in Learning Technology 2018, **26**: 2119 - http://dx.doi.org/10.25304/rlt.v26.2119
**(page number not for citation purpose)**

will remain a solidly psychological science, and we may better serve our psychology students by giving them exposure to this field of research with hands-on experience and skills. Conversely, exposure to movement science will provide students with skills beyond what standard psychology classes might train.

## Aims for the report

The goal of this article is to provide evidence that newly accessible technology for human motion capture offers a rich opportunity for inquiry-driven science training, allowing not only domain-specific training in movement science but also supporting a variety of domain-general skills for an integrated science curriculum for liberal arts students. This article documents the piloting of a class format built around content and technology often completely absent from the curriculum and resources of a small liberal arts class. We aim to bridge the gap between liberal arts and technical trainings, emphasising critical thinking across disciplines and domain-specific skills, respectively. It may seem that 'critical thinking' is too diffuse to be valuable, and it may equally seem that technical skills are too narrowly focused to support the growth of a fully functioning citizen or professional employee. Newly available technology at prices within the budget of a small liberal arts college's research funds might allow new expressions of the close-knit, collaborative energies of liberal arts students. The potential here is for learning new skills in navigating complex empirical/theoretical challenges when technology becomes sufficiently accessible to fall into the hands of a group of students typically more dedicated to training of critical-thinking skills.

Our intent is not to make an air-tight experiment demonstrating the superiority of this format to any other comparable class format. We have used a survey standard to a consortium of small liberal arts colleges, and we used this class format in one semester amidst the service requirements for more standard class offerings. The survey provides a pre-semester assessment and a post-semester assessment, but the sample is small because we work at a small liberal arts college, and there is no control group suitable to this intent because we are not full-time educational psychologists. These limitations have drawn understandably harsh peer review, but we persist in thinking that these results are worth sharing if only as an existence proof.

## The motion-capture class

The recent release of lower cost but high-precision motion-capture technology has opened up greater opportunities to situate motion capture in alternate class formats (e.g. Geroch 2004; Thewlis *et al*. 2013), including those available to students at liberal arts colleges with leaner research budgets. Through internal funding focused specifically on developing innovative pedagogies, we were able to purchase six of Noitom's Perception Neuron full-body suit (less than $2000 each), and in Spring 2017, we offered a 300-level course in the Psychology Department called 'Motion Capture of Human Movement' to pilot the proposal that liberal arts psychology students would benefit from the integrated science framework prompted – or sooner demanded – by working with motion-capture technology. We therefore anticipated that giving psychology students the suits to work with in the classroom would be a productive, educational experience unlike what they might have expected to find in a psychology classroom.

The format of the classroom was superficially flexible in day-to-day delivery but firmly rooted around workshop-style pedagogical principles. The superficial


Citation: Research in Learning Technology 2018, **26**: 2119 - http://dx.doi.org/10.25304/rlt.v26.2119

flexibilities were permitted by the class size allowing for catch-up time, for remedial redeliveries of lecture material or for class discussion. However, at the root of the course planning was the ethos of investing student effort in repeated iterations of inquiry-driven work. The iterations repeated a similar form, sending students from communal to individual work and back to communal work each week: brief lecture-like instruction with a brief reading sample would open a topic or challenge, students would break into small groups or solo efforts to observe and discover, documenting their observations and experiences in formal American Psychological Association (APA) format would bring their independent or smaller group ruminations and observations into a more communal/communicative mindset, and lastly, the students and class would come back together to share lessons learnt and reflect on how the next installment of lecture might bring new questions and discoveries into focus. This iterative fanning-out to smaller groups and returning to the larger class group repeated around progressively more elaborate, more abstract principles important to the science. This iterative, inquiry-driven process has been a proven way to scaffold undergraduate science students' feelings of understanding and belonging amidst the scientific culture (Di Bartolo *et al*. 2016; Gregg-Jolly *et al*. 2011, 2016; Schneider 2001; Walker and Kelemen 2010; Walker and Schneider 1996).

The first week began with lecture on history of motion capture, brief details on how inertial measurement units (IMUs) work and some hands-on orientation to donning and calibrating the suit. The class also included time searching peer-reviewed literature on movement research because the constraints of course offerings at a small liberal arts college left most students unaware that movement itself was a topic of peer-reviewed basic research. Roughly each week afterwards, there were weekly assignments: students had the task of delving briefly into a small research project, making their own variant of a general concept/task, collecting a rudimentary data set, performing rudimentary statistical and time-series analysis in the computer language R (R Core Team 2013), and interpreting their findings and reflecting on use of the motion-capture suits as well as the software. Their weekly assignments culminated in short narratives about the topic of research and their experience using the motion-capture technology and the software, noting difficulties, discoveries and successes along the way.

Topics included fine-motor synchronisation to a metronome, dancing to music, playing Dance Dance Revolution, playing Rock Band, free-throw basketball shooting, playing table tennis and target practice with bean bags or Nerf guns. The first three topics allowed them to practice analysing the measured time-series data to empirically determine the frequency of regularly oscillating movements. The fourth topic appeared only after the students had a week of lecture to work through basic concepts of motor coordination, conceived as a set of phase relationships amongst joint angles (Latash and Turvey 1996). Students then had to estimate not only frequency at one limb but also task-relevant phase relationships. For instance, the game aspects of Rock Band allowed students to generate pilot data, examining possible relationships between phase patterns and total points scored.

Gradually, the class moved closer to more standard focuses of movement science. A brief set of lectures introduced the notion of motor learning in terms that Bernstein (1967) made popular, that is, an initial freezing of motor components and then, with greater expertise, a relaxing of those limbs to open them up to reactive forces available from the context (e.g. Latash 2008). Students were all relatively inexpert in table tennis, and so the repeated exposure to it allowed them to test hypotheses about how practice across a week led to observable differences in phase relationships. The newly developed Immersive Experiences Laboratory on campus – dedicated to exploring new ways to approach liberal arts pedagogies through three-dimensional (3D), virtual- and augmented-reality technologies – offered students an opportunity to investigate motor adaptation to using virtual reality equipment, posing the intriguing logistical challenge of exploring the mechanical compatibility of two separate pieces of to-be-worn technology. Virtual reality also poses an altogether new question about how movement might change as users learn to move in two spaces at once: the virtual space of the immersive visual stimulus and the lab space whose limits (e.g. walls and furniture) run at odds with what the virtual space invites.

The last third of the class focused on gait. Bipedal gait analysis required students to estimate the time-averaged gait cycle (with 95% confidence interval) for ankle, knee, and hip and to estimate phase relationships under the different manipulations of walking with eyes open or with eyes closed. Next, we borrowed from a research paradigm that investigated intralimb coordination between dyads linked mechanically together while walking, for example, with the hands of the rear walker on the shoulders of the front walkers (Harrison and Richardson 2009). Lastly, we encouraged students to take the motion-capture suits across the campus to find accessibility problems and to examine how different constraints (e.g. walking with a crutch or with a heavy backpack) changed the movement coordination situated in its context.

## The RISC survey

To evaluate what the students drew from this experience, in addition to consulting end-of-course evaluations, we administered the RISC survey (Lopatto 2010) (see the 'Methods' section for full details). Many of the items on the survey focused on learning specific subject matter, and we did not expect students to have learnt many facts; rather we expected that gains would be apparent in specifically those items addressing working in groups, working on problems without clear solutions, on data collection/organisation and interpretation, and on using this technology and related data to describe the complexity of human movement. The capacity of the RISC survey or its components to measure students' increasing dexterity with these research skills has been demonstrated repeatedly in inquiry-driven science classrooms (Burnette and Wessler 2013; Call *et al*. 2007; Clark *et al*. 2009; Jordan *et al*. 2014; Kowalski, Hoops and Johnson 2016; Lopatto *et al*. 2008; Mader *et al*. 2017; Makarevitch, Frechette and Wiatros 2015; Miller *et al*. 2013; Reed and Richardson 2013; Sarmah *et al*. 2016; Staub *et al*. 2016). We aimed to identify whether there were post-course gains that might exceed the average of all students responding to the RISC of that semester.

## Method

### *Participants*

The enrolment for the spring 2017 offering of the course 'Motion Capture of Human Movement' at a small liberal arts college included 11 third- and fourth-year students. The RISC survey included questions about demographics, major field of undergraduate study, amount of science background and plans for future science training. The total number of students completing the RISC survey in the same semester was 3301.

### Materials

#### RISC survey

The RISC survey has been developed by member schools within the Interdisciplinary Learning Consortium (ILC), whose founding members are Carleton College, Grinnell College, Hope College, St. Olaf College and Whitman College. RISC surveys have been exempted from IRB review. Participation in the survey is voluntary and not a requirement for receiving course credit, and students may discontinue the survey or leave any questions unanswered.

A pre-course RISC survey prompts students, 'For each [of 48] Course Element[s], [to] give an estimate of [their] current level of ability before the course begins' (RISC Survey, n.d.; see selection of total 48 in Table 2). These course elements appear in list form as verb phrases (e.g. 'collecting data' or 'analysing data') and address understanding the cultural values of science at large, blending concepts from more than one field together and engaging in science creatively with hands-on problems without clear solutions. The pre-course RISC survey prompts students to rate their own ability in each item on a scale from 1 ('no experience or feel inexperienced') to 5 ('extensive experience or mastered this element'). The post-course RISC survey prompts students to 'please rate how much learning [they] gained from each element [they] experienced in this course' (RISC Survey n.d.) for precisely the same list of 48 verb phrases as in the pre-course survey and asks for ratings from 1 ('no gain or very small gain') to 5 ('very large gain'). The post-course RISC survey also asks students to evaluate their learning gains on 21 skills normally developed in summer research experiences (Table 1). Specifically, the RISC survey asks students to 'consider a variety of possible benefits you may have gained from your course experience' and to rate each of a list of skills (e.g. 'ability to integrate theory and practice') on a scale from 1 ('no gain or very small gain') to 5 ('very large gain').

#### End of course evaluations

Students filled out evaluations, indicating their agreement with each of six statements on a scale from 1 (strongly disagree) to 6 (strongly agree). The first five statements dealt specifically with how well the class meetings, instructor, group activities, oral/written exercises and readings each supported student learning, and the sixth statement queried the students' estimation of whether they had 'learnt a lot' in the class.

Table 1. End-of-course evaluations.

| Statement to agree or disagree with | Average | SE |
|---|---|---|
| The course sessions were conducted in a manner that helped me to understand the subject matter of the course. | 5.22 | 0.28 |
| The instructor helped me to understand the subject matter of the course. | 5.56 | 0.18 |
| Worked completed with and/or discussion with other students in this course helped me to understand the subject matter of the course. | 5.56 | 0.29 |
| The oral and written work, tests and/or other assignments helped me to understand the subject matter of the course. | 5.33 | 0.24 |
| Required readings or other course materials helped me to understand the subject matter of the course. | 4.86 | 0.36 |
| I learned a lot in this course. | 5.56 | 0.24 |

## Results and discussion

Table 1 shows the average response as well as standard error (SE) on a scale from 1 (strongly disagree) to 6 (strongly agree) in response to the six statements about the class from student's end-of-course evaluations. Students rated the class favourably across all items, with the lowest average rating for readings (Question 4) but with all other responses between 5 and 6. This low point is understandable given that there was no single text, and the students' readings came from literature searches of peer-reviewed literature.

Response to the RISC survey includes both Course Element Gains and Learning Gains. Students rate their gains on the post-course survey on a scale from 1 (least gain) to 5 (most gain). Table 2 lists the post-course Course Element Gains for which the present course exceeded the average for all students completing the RISC survey.

This course led students to feel they had gained most in the skills of approaching a new problem with unknown solution, learning to plan an empirical approach in a group and to have direct input into that plan that included collecting, analysing and interpreting data under uncertainty using computer models to understand a complex system.

The other Course Elements not listed here (but available through online supplemental materials) had more to do with mastery of subject-specific content. The students did not rate other gains higher than average for the other Course Elements, perhaps because they saw motion capture as homogeneous no matter the subject material. While the course posed a diverse set of subject materials for applying motion-capture technology, the instruction kept needed data organisational and data analytical tools to a minimum so as to give students a set of tools to practice and hone without overwhelming the students with options. Perhaps a repeat offering of the course might include more about different approaches to analysing the motion-capture data. However, keeping the programming needs to a minimum allowed students unfamiliar with programming to master this small number of approaches and gain more confidence in their new skills. Course Elements focused on reading primary materials, listening to lecture and providing poster/oral presentation did not show stronger gains because this class directed student effort mostly towards hands-on experimentation in groups, and only written documentation. Oral presentations might make a nice addition to a potential future iteration of the course, particularly if the students had the challenge of developing a semester-long project around a theme of their choice.

Table 2. Gains on Course Elements reported on the post-course RISC survey.

| Course element | My students | All students |
|---|---|---|
| Problems where no one knows the answer | 4.50 | 3.31 |
| At least one problem assigned and structured by the instructor | 4.13 | 3.74 |
| A problem where students have input into process or topic | 4.38 | 3.84 |
| Work in small groups or teams | 4.00 | 3.86 |
| Collect data | 4.38 | 3.68 |
| Analyse data | 4.63 | 3.89 |
| Approach problems in different and conflicting ways | 4.00 | 3.81 |
| Present intellectual work in written papers or posters | 4.00 | 3.54 |
| Attempt complete understanding of a complex problem | 4.00 | 3.72 |
| Computer modelling of complex systems | 4.00 | 3.26 |

As for Learning Gains, students in the motion-capture class reported significantly higher ratings than the entire sample of RISC respondents in all but four goals (Table 3). These ratings suggest that this course was a successful attempt to train students in applying theory and technology to build their own empirical projects and to collect data that can talk about theoretical issues. Specific learning gains included interpretation of results, integrating theory into practice, understanding how scientists work on real problems and surmounting obstacles in a communal process, ability to analyse data and synthesise disparate sources of information. The experience gave students better command of scientific communication and of their ability to teach the science that they had learnt. It was also a helpful experience in helping students understand science in general, as a social process in which multiple voices work to construct knowledge in a social process that leaves room for independence while also affording group work in the search for new evidence and/or better solutions to pressing problems.

Not all learning gains were better in this class than in other classes. Ethical issues may not have fit organically with the rest of the class business, but future offerings of this class could attempt it. The other items with lower ratings were not part of original goals for the class; therefore, they highlight room for development of the course rather than shortcomings.

## Detailed reflections and example of student experiences

The course necessarily involved a fluid, context-sensitive format in which students regularly discovered previously unknown constraints as well as unknown capacities. We see

Table 3. Learning Gains, ranked from highest to lowest in my class and compared to all SURE-item respondents.

| Learning gains | My students | All students |
|---|---|---|
| Skill in the interpretation of results | 4.25 | 3.46 |
| Ability to integrate theory and practice | 4.25 | 3.45 |
| Understanding of how scientists work on real problems | 4.25 | 3.58 |
| Ability to analyse data and other information | 4.13 | 3.62 |
| Tolerance for obstacles faced in the research process | 4.00 | 3.47 |
| Understanding the research process in your field | 4.00 | 3.44 |
| Understanding science | 4.00 | 3.50 |
| Becoming part of a learning community | 4.00 | 3.49 |
| Understanding that scientific assertions require supporting evidence | 3.88 | 3.55 |
| Learning laboratory techniques | 3.88 | 3.39 |
| Understanding how knowledge is constructed | 3.75 | 3.40 |
| Skill in science writing | 3.75 | 3.24 |
| Self-confidence | 3.75 | 3.74 |
| Learning to work independently | 3.75 | 3.25 |
| Readiness for more demanding research | 3.63 | 3.40 |
| Understanding of how scientists think | 3.63 | 3.34 |
| Confidence in my potential as a teacher of science | 3.25 | 2.89 |
| Learning ethical conduct in your field | 3.25 | 3.32 |
| Ability to read and understand primary literature | 2.83 | 3.29 |
| Skill in how to give an effective oral presentation | 2.50 | 3.12 |
| Clarification of a career path | 2.38 | 3.01 |

some of this in the strong learning gains in the understanding of the scientific process and learning to apply theory, while also learning to tolerate obstacles. As an illustrative example, one pair of students struggled with the motion-capture suit failing to function as usual 1 day. These two students took the occasion to debug the problem – indeed, they might not have recognised their efforts as debugging, but they were discovering their very own principled manner of testing the functioning of subparts. These two students – relatively untrained in programming or engineering – were able to isolate the specific part of the suit that had broken, and furthermore, they discovered a flexibility in the motion-capture system that allowed alternative connections around the broken portion, that is, patching a work-around that allowed typical motion capture through most of the suit. Motion-capture research can be peppered with unanticipated and unclear technology failures that can and do frustrate professional researchers and require letting participants go without any successful data collection. This debugging served as only one among many exercises in problem solving that the students experienced.

Practiced scholars in movement science fields have taken that patient diligence on as a second nature. Behind this illustrative case of experience with debugging is a crucial point. Liberal arts students may often feel insecure and unable to wield technology as anything more than an end-user swiping a touch screen, and there has been much clamour and controversy about the value of a liberal arts education as contrasted with more vocational training in technical skills (e.g. Breneman 1994). But the dichotomy between liberal-arts values of learning how to learn in any context and vocational values of honing technical skills with digital technology may just be a false dichotomy (Grubb and Lazerson 2005; Selingo 2016). There is an opportunity not only for greater skill with digital technologies but also for metacognition about how critical thinking really will transfer to tasks that do not look like traditional liberal arts. In other words, digital technologies such as motion capture may be a ready vehicle for liberal arts lessons.

Overall, this project was a productive and instructive early effort. The initial results suggest that a motion-capture laboratory fits well with the aims and constraints of a small liberal arts college setting.

## Acknowledgements

We acknowledge the support of Grinnell College Psychology, Grinnell College Immersive Experience Laboratory and the Grinnell College Innovation Fund.

## Ethics, consent and permissions

This article documents data from the Research on Integrated Science Curriculum (RISC) survey, for which participation is voluntary and exempted from Institutional Review Board (IRB) review. The RISC survey is administered by the Center for Teaching, Learning and Assessment (CTLA) at Grinnell College, and the CTLA regularly consults with Grinnell College's federally compliant IRB to ensure ethicality of continued data collection.

## Permission to publish

All participants consent before completing the RISC survey to contributing their responses to the Grinnell College CTLA for research and publication purposes.

The CTLA aggregates individual student responses into whole-class data summaries, and instructors whose students complete the RISC survey (e.g. the authors) receive this information only in terms of whole-class data summaries but receive no individual student responses. Hence, this article only reports on class-data summaries and does not document any individual student responses. Indeed, while the authors possess no information on individual student responses, all individual student responses remain secure in the records of the CTLA.

## Competing interests

The authors have no competing interests with regard to the publication of this article. Grinnell College is a non-profit institution.

## References

Cavanaugh, J. T., Kelty-Stephen, D. G. & Stergiou, N. (2017). 'Multifractality, interactivity, and the adaptive capacity of the human movement system: Perspective for advancing the conceptual basis of neurologic physical therapy', *Journal of Neurologic Physical Therapy*, vol. 41, no. 4, pp. 245–251. http://doi.org/10.1097/NPT.0000000000000199

Bernstein, N. A. (1967) *The Coordination and Regulation of Movements*, Pergamon Press, Oxford.

Breneman, D. W. (1994) *Liberal-arts College: thriving, Surviving, or Endangered?* Brookings Institution Press, Washington, DC.

Burnette, J. M. & Wessler, S. R. (2013) 'Transposing from the laboratory to the classroom to generate authentic research experiences for undergraduates', *Genetics*, vol. 193, no. 2, pp. 367–375. https://doi.org/10.1534/genetics.112.147355

Call, G. B., *et al*., (2007) 'Genomewide clonal analysis of lethal mutations in the Drosophila melanogaster eye: comparison of the x chromosome and autosomes', *Genetics*, vol. 177, no. 2, pp. 689–697. https://doi.org/10.1534/genetics.107.077735

Clark, I. E., *et al*., (2009) '"Deconstructing" scientific research: a practical and scalable pedagogical tool to provide evidence-based science instruction', *PLoS Biology*, vol. 7, no. 12, pp. e1000264. https://doi.org/10.1371/journal.pbio.1000264

Di Bartolo, P. M., *et al*., (2016) 'Principles and practices fostering inclusive excellence: lessons from the Howard Hughes Medical Institute's Capstone institutions', *CBE Life Sciences Education*, vol. 15, no. 3, pp. ar44. https://doi.org10.1187/cbe.16-01-0028

Geroch, M. S. (2004) 'Motion capture for the rest of us', *Journal of Computing Sciences in Colleges*, vol. 19, no. 3, pp. 157–164.

Gregg-Jolly, L. A., *et al*., (2011) 'Benefits of intertwining teaching and research', *Science*, vol. 331, no. 6017, pp. 532. https://doi.org/10.1126/science.331.6017.532-a

Gregg-Jolly, L., *et al*., (2016) 'Situating second-year success: understanding second-year STEM experiences at a liberal-arts college', *CBE Life Sciences Education*, vol. 15, no. 3, ar43. https://doi.org/10.1187/cbe.16-01-0044

Grubb, W. N. & Lazerson, M. (2005) 'Vocationalism in higher education: the triumph of the education gospel', *Journal of Higher Education*, vol. 76, no. 1, pp. 1–25. https://doi.org/10.1080/00221546.2005.11772273

Harrison, S. J. & Richardson, M. J. (2009) 'Horsing around: spontaneous four-legged coordination', *Journal of Motor Behavior*, vol. 41, no. 6, pp. 519–524. https://doi.org/10.3200/35-08-014

Jordan, T. C., *et al*., (2014) 'A broadly implementable research course in phase discovery and genomics for first-year undergraduate students', *mBio*, vol. 5, no. 1, pp. e01051–13. https://doi.org/10.1128/mBio.01051-13

Kowalski, J. R., Hoops, G. C. & Johnson, R. J. (2016) 'Implementation of a collaborative series of classroom-based undergraduate research experiences spanning chemical biology, biochemistry, and neurobiology', *CBE Life Sciences Education*, vol. 15, no. 4, pp. ar55. https://doi.org/10.1187/cbe.16-02-0089

Latash, M. L. (2008) *Synergy*, Oxford University Press, Oxford.

Latash, M. L. & Turvey, M. T. (eds) (1996) *Dexterity and its Development*, Erlbaum, Hillsdale, NJ.

Lopatto, D. (2010) 'Undergraduate research as a high-impact student experience', *Peer Review*, vol. 12, no. 2, pp. 27–30.

Lopatto, D., *et al*., (2008) 'Genomics education partnership', *Science*, vol. 322, no. 5902, pp. 684–685. https://doi.org/10.1126/science1165351

Mader, C., *et al*., (2017) 'Multi-institutional, multidisciplinary study of the impact of course-based research experiences', *Journal of Microbiology and Biology Education*, vol. 18, no. 2, pp. 44. https://doi.org/10.112/jmbe.v18i2.1317

Makarevitch, I., Frechette, C. & Wiatros, N. (2015) 'Authentic research experience and "big data" analysis in the classroom: maize response to abiotic stress', *CBE Life Sciences Education*, vol. 14, no. 3, pp. ar27. https://doi.org/10.1187/cbe.15-04-0081

Miller, C. W., *et al*., (2013) 'Extending your research team: learning benefits when a laboratory partners with a classroom', *BioScience,* vol. 63, no. 9, pp. 754–762. https://doi.org/10.1093/bioscience/63.9.754

*R* Core Team (2013) *R*: a language and environment for statistical computing. *R* Foundation for Statistical Computing, Vienna, Austria, Available at: http://www.R-project.org/

Reed, K. E. & Richardson, J. M. (2013) 'Using microbial genome annotation as a foundation for collaborative student research', *Biochemistry & Molecular Biology Education*, vol. 41, no. 1, 34–43. https://doi.org/10.1002/bmb.20663

RISC Survey (n.d.). Available at: http://www.grinnell.edu/academics/areas/psychology/assessments/risc-survey

Rosenbaum, D. A. (2005) 'The Cinderella of psychology: the neglect of motor control in the science of mental life and behavior', *American Psychologist*, vol. 60, no. 4, pp. 308–317. https://psycnet.apa.org/doi/10.1037/0003-066X.60.4.308

Sarmah, S., *et al*., (2016) 'Using zebrafish to implement a course-based undergraduate research experience to study teratogenesis in two biology laboratory classes', *Zebrafish*, vol. 13, no. 4, pp. 293–304. https://doi.org/10.1089/zeb.2015.1107

Schneider, M. B. (2001) 'Encouragement of women physics majors at Grinnell College: a case study', *The Physics Teacher*, vol. 39, no. 5, pp. 280–282. https://doi.org/10.1119/1.1375465

Selingo, J. (2016) *There is life after college*, HarperCollins Publishers, New York.

Staub, N. L., *et al*., (2016) 'Scaling up: adapting a phage-hunting course to increase participation of first-year students in research', *CBE Life Sciences Education*, vol. 15, no. 2, pp. ar13. https://doi.org/10.1187/cbe.15-10-0211

Thewlis, D., *et al*., (2013) 'Next-generation low-cost motion capture systems can provide comparable spatial accuracy to high-end systems', *Journal of Applied Biomechanics*, vol. 29, no. 1, pp. 112–117. https://doi.org/10.1123/jab.29.1.112

Walker, H. M. & Kelemen, C. (2010) 'Computer science and the liberal arts: a philosophical examination', *ACM Transactions on Computing Education*, vol. 10, no. 1, pp. 2. https://doi.acm.org/10.1145/1731041.1731043

Walker, H. M. & Schneider, G. M. (1996) 'A revised model curriculum for a liberal-arts degree in computer science', *Communications of the ACM*, vol. 49, no. 3, pp. 33–35. https://doi.org/10.1145/240483.240502