RESEARCH CULTURE

Framework for advancing rigorous research

Abstract There is a pressing need to increase the rigor of research in the life and biomedical sciences. To address this issue, we propose that communities of 'rigor champions' be established to campaign for reforms of the research culture that has led to shortcomings in rigor. These communities of rigor champions would also assist in the development and adoption of a comprehensive educational platform that would teach the principles of rigorous science to researchers at all career stages.

WALTER J KOROSHETZ, SHANNON BEHRMAN, CYNTHIA J BRAME, JANET L BRANCHAW, EMERY N BROWN, ERIN A CLARK, DAVID DOCKTERMAN, JORDAN J ELM, PAMELA L GAY, KATELYN M GREEN, SHERRY HSI, MICHAEL G KAPLITT, BENEDICT J KOLBER, ALEX L KOLODKIN, DIANE LIPSCOMBE, MALCOLM R MACLEOD, CALEB C MCKINNEY, MARCUS R MUNAFÒ, BARBARA OAKLEY, JEFFREY T OLIMPO, NATHALIE PERCIE DU SERT, INDIRA M RAMAN, CERI RILEY, AMY L SHELTON, STEPHEN MILES UZZO, DEVON C CRAWFORD[†]* AND SHAI D SILBERBERG[†]*

***For correspondence:** devon.crawford@nih.gov (DCC); silberbs@ninds.nih.gov (SDS)

[†]These authors contributed equally to this work

The scientific enterprise relies on mentors teaching their students and trainees how to design and conduct studies that produce reliable scientific knowledge. A crucial part of this is teaching students and trainees how to minimize the risks that chance observations, subconscious biases, or other factors might lead to incorrect or inflated claims. However, as the demands on mentors increase, some of them unintentionally overlook this crucial aspect of scientific investigation, meaning that students and trainees are not taught how to distinguish between high- and low-quality evidence when working on their own studies and when reading about other studies (***Ioannidis et al., 2014***; ***Bosch and Casadevall, 2017***; ***Landis et al., 2012***).

Additional complications stem from the welcome rise in team-based science and a greater sophistication and range of experimental techniques (***National Research Council, 2015***), which may, in part, be driven by a feeling that only exciting and complete stories will appeal to journals and funders (***Nosek et al., 2012***; ***Casadevall et al., 2016***). Increasingly, an individual scientist cannot be an expert in all the techniques used in a research project.

Taken together, these developments suggest that enhanced training in the fundamental principles of rigorous research common to most, if not all, experimental practices is needed to ensure that the outputs of scientific research remain reliable and robust. Such principles include strong reasoning and inference based on valid assertions, which requires the proper interpretation of uncertainty and a motivation to identify inconsistencies (***Bosch and Casadevall, 2017***; ***Casadevall and Fang, 2016***; ***Munafò and Davey Smith, 2018***; ***Wasserstein et al., 2019***). For studies that test hypotheses, researchers should: clearly define interventions; identify and disclose possible confounding factors; transparently report project workflows, experimental plans, methods, data analyses, and any divergence from pre-planned procedures; and fully report their competing interests (see https://www.equator-network.org/ for reporting guidelines). The requirements for studies intended to generate hypotheses will be different but should be equally described (***Dirnagl, 2019***).

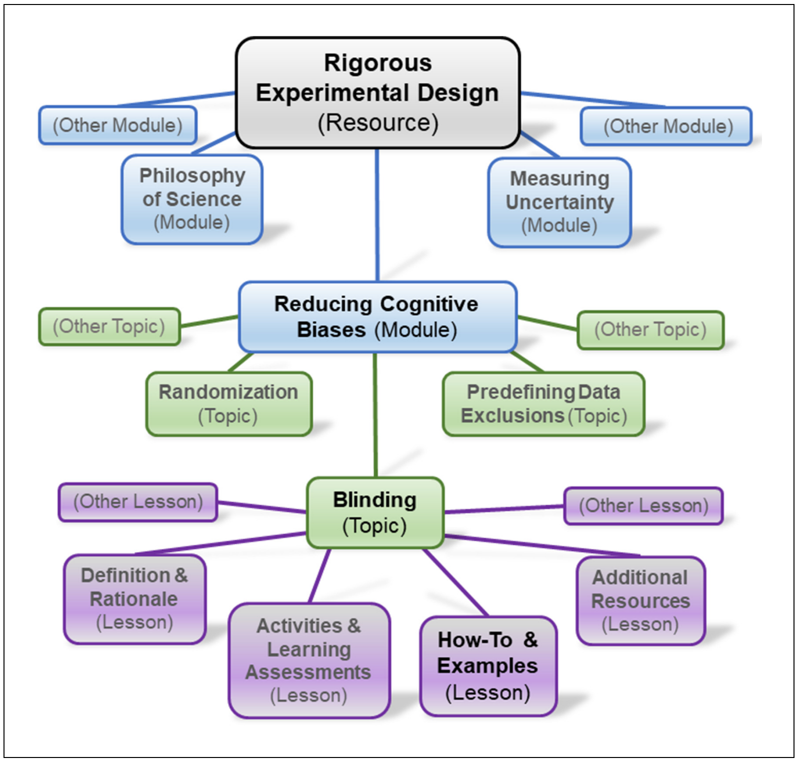

Figure 1. Outline of an educational resource on the principles of rigorous research suitable for a variety of audiences. We envision a comprehensive resource that can be used by scientists at all stages of their career to explore the principles of rigorous research at various levels of detail. We envision modules on a range of topics (such as reducing cognitive biases), each of which contains a number of topics (such as blinding), each of which contains a number of lessons (such as practical examples).

Before formulating solutions to these issues, we assessed current training practices at the graduate and postdoctoral levels by surveying all 41 institutions in the United States that held at least one training grant from the National Institute of Neurological Disorders and Stroke (NINDS) in May 2018. Only 5 of the 37 institutions that responded to the survey reported providing a course predominantly dedicated to principles of rigorous research, with others using a range of approaches – such as seminars, lectures within other coursework, workshops, and informal mentoring – to teach good research practices. However, few if any of the institutions covered the full range of principles that need to be learned and understood. Although the sample in our survey was small, the responses reinforced the common belief that formal training in rigorous research needs to be enhanced (***Ioannidis et al., 2014***; ***Munafò et al., 2017***).

While numerous training materials related to rigorous research are available online, finding suitable materials and assembling them into a cohesive course is challenging. Having access to a free, organized suite of educational resources could greatly reduce the energy barrier for institutions and scientists to implement enhanced training at all levels, from undergraduate education to faculty professional development.

Towards this end NINDS convened a workshop attended by a range of stakeholders: basic, translational, and clinical neuroscientists; scholars of education and science communication; educational platform developers; and trainees. Although neuroscience served as a focal point, the four outcomes of the discussions apply widely across the biomedical sciences: i) there is a clear need for a platform that teaches the principles of rigorous research and covers the needs of scientists at all career stages; ii) effective educational interventions should lead to measurable behavioral change; iii) academic institutions need to play a proactive role in promoting rigorous research practices; iv) progress in this area will require cultural change at academic institutions, funders, and publishers (***Casadevall et al., 2016***; ***Munafò et al., 2017***; ***Collins and Tabak, 2014***; ***Begley et al., 2015***; ***Casadevall and Fang, 2012***).

Building communities of rigor champions

To unleash the motivation for a cultural change evident in discussions between the authors and early-career researchers and others, and to provide momentum for change across different sectors, we propose the establishment of inter- and intra-institutional communities of 'rigor champions' who are committed to promoting rigor and transparency in research. We know there are many such individuals working at different levels of seniority in different types of organizations (such as universities, funders, publishers, and scientific societies), but they often feel isolated and under-resourced. To seed this effort and to help like-minded individuals in different organizations to find each other and join forces, NINDS has created a website for researchers, educators, trainees, organizational leaders and others who are passionate about the issues discussed here. This website includes currently available resources for making science more rigorous and transparently reporting results, as well as instructions for identifying yourself as a rigor champion.

More information about the different activities that these communities could undertake are

Table 1. Activities for communities of rigor champions to promote the principles of rigorous research.

Community	Intra-organizational activities	Inter-organizational activities
Trainees	• Promote transparency and other rigorous practices among colleagues and mentors • Advocate for resources to facilitate rigorous research practices	• Share institutional resources and practices in education and training • Call for changes in institutional culture and policies
Researchers	• Transparently report all experiments, including neutral outcomes • Promote rigorous practices among colleagues and trainees • Call for changes to institutional culture, policies, and infrastructure	• Share effective training practices and useful laboratory resources • Coordinate with the broader scientific community to promote better incentive structures
Educators	• Suggest improvements to available resources that address rigor • Integrate rigorous research principles into all coursework	• Share resources and educational best practices • Share effective learning evaluation methods
Institutional Leaders	• Enact policies and support infrastructure to incentivize transparency and other rigorous research practices • Explicitly incorporate mentoring, collaboration, and rigorous research practices into promotion procedures • Initiate and share outcomes from piloted educational resources	• Support and promote communities of rigor champions • Disseminate policy changes, new initiatives, educational successes, and implementation strategies • Develop tangible outcome measures to evaluate impact
Journal Editors and Reviewers	• Promote thorough review of research practices in publications • Explicitly support research transparency and neutral outcomes • Educate reviewers on which scientific practices are valued by the journal	• Collaborate to implement best practices consistently across different publishers
Scientific Societies and Organizations	• Support the founding of communities of rigor champions • Compile and encourage best practices used by the scientific community • Host workshops and educational materials for members	• Promote and maintain communities of rigor champions • Encourage institutional policies that promote research quality and effective education
Funding Organizations	• Emphasize attention to rigor in peer review • Reward rigorous research practices and outstanding mentorship • Support infrastructure for transparent and rigorous science • Support educational resources and initiatives	• Support and promote communities of rigor champions • Share best practices for incentivizing rigorous research and educating scientists • Develop partnerships to support better training and facilitate cultural changes

given in ***Table 1***. Researchers, educators and trainees are best placed to collaborate on new tools, share best practices, and promote rigorous research in their local scientific communities. Societies are in a position to advocate for widespread policy changes, while funders and journals have important gatekeeping roles (***Collins and Tabak, 2014***; ***McNutt, 2014***; ***Cressey, 2015***; ***PLOS Biology, 2018***). The recently established UK Reproducibility Network (***Munafò et al., 2020***) and the PREMIER project (***Dirnagl et al., 2018***), both of which aim to improve scientific practices, may serve as models for these communities.

NINDS, for example, has proactively sought effective approaches to support greater transparency in reporting. An NINDS meeting with publishers led to changes in journal policies regarding transparency of reporting at various journals (***Nature, 2013***; ***Kelner, 2013***). Recommendations for greater transparency at scientific meetings stemmed from an NINDS roundtable with conference organizing bodies (***Silberberg et al., 2017***) and are being piloted by the Federation of American Societies for Experimental Biology (FASEB). To recognize outstanding mentors, NINDS established the Landis Mentoring Award, and by providing greater stability to meritorious scientists though the NINDS R35 Program, it is anticipated that the pressures to rush studies to publication will be mitigated.

In particular we hope that leaders at academic institutions – such as department chairs, deans, and vice-presidents of research – will become involved because they are uniquely placed to shape the culture and social norms of institutions (***Begley et al., 2015***). For example, faculty evaluation criteria should be modified to place greater emphasis on data sharing, methods transparency, demonstrated rigor, collaboration, and mentoring, with less emphasis on the number of publications and journal impact factors (***Casadevall and Fang, 2012***; ***Moher et al., 2018***; ***Bertuzzi and Jamaleddine, 2016***; ***Lundwall, 2019***; ***Strech et al., 2020***; ***Casci and Adams, 2020***; see also https://sfdora.org/read). When publications are being evaluated, rigorously obtained null results should be valued as highly as positive findings. Institutional leaders are also uniquely placed to ensure that scientific rigor is properly taught to trainees and incorporated into day-to-day lab work (***Casadevall et al., 2016***; ***Begley et al., 2015***; ***Bosch, 2018***; ***Button et al., 2020***). Moreover, evaluations of trainees should emphasize experimental and analytic skills rather than where papers are published.

Building an educational resource for rigorous research

The establishment of communities of rigor champions will set the stage for the creation of an educational platform designed by the scientific community to communicate the principles of rigorous research. Given the rapid evolution of technologies and learning practices, it is difficult to predict what resource formats will be most effective in the future, so the platform will need to be open and freely available, easily discoverable, engaging, modular, adaptable, and upgradable. It will also need to be available during coursework and beyond so that scientists can use it to answer questions when they are doing research or as part of life-long learning (***Figure 1***). This means that the platform will have to embody a number of principles of effective teaching and mentoring (see ***Table 2***).

We envision the platform being developed via a hub-and-spoke approach as discussed at a recent National Advisory Neurological Disorders and Stroke Council meeting. A centralized mechanism (the 'hub') will provide financial and infrastructural support and guidance (possibly via a steering committee) and facilitate sharing and coordination between groups, while rigor champions will come together to design specific modules (spokes) for the platform by using existing resources or designing new ones from scratch as needed. We envision worldwide teams of experts collaborating on building and testing the resource. Rigor champions with experience in defining clear learning objectives, building curricula, and evaluating success, for example, will collaborate with content experts to design topics needed in the resource. Importantly, potential users will be involved from the beginning of the development stage, and onwards through the design and implementation stages, to provide feedback about effectiveness and usability.

Given the importance of being able to measure the effectiveness (or otherwise) of the platform (***Table 2***), individual components should be released publicly as they are completed to allow

Table 2. Key elements of teaching and learning to include in an educational resource on the principles of rigorous research.

Key element	Teaching and learning principle
Clear learning objectives	Define the learning objectives upfront, identify ways to measure achievement of these objectives, and then design activities to support learning (***Bradforth et al., 2015***).
Inquiry-based learning	Encourage students to pose their own questions, apply commonly used tools and methods to actively explore their questions, and provide evidence when explaining phenomena (***Bradforth et al., 2015***; ***Corwin et al., 2015***; ***Minner et al., 2010***; ***Handelsman et al., 2004***).
Relevance	Provide feedback on real-world experiments, whether in the classroom or the laboratory, as a way to demonstrate relevance and stimulate interest. Opportunities for personalized application and discussion in the local setting with the help of a facilitator's guide are particularly critical, as adults typically learn most effectively when given the opportunity for immediate personal utility and value (***Walkington and Bernacki, 2018***). Emphasize the ability to contribute to a larger purpose or gain social standing (***Yeager et al., 2014***).
Individuality	Include a range of approaches to teaching and learning to accommodate different levels of knowledge and skills, motivations, and senses of self-efficacy (***Walkington and Bernacki, 2018***; ***Raman, 2014***).
Self-efficacy	Allow individuals to gain self-efficacy by experiencing a feeling of progress, being challenged in low-stakes environments, and working through confusing concepts successfully (***D'Mello et al., 2014***). This is more effective when the person feels psychologically safe to take risks and fail in front of their local scientific community.
Belonging	Facilitate learning, foster collaboration, and recognize diverse perspectives in order to encourage learners to gain agency and forge a connection with the intellectual community (***Bjork et al., 2013***; ***Brown and Adler, 2008***).
Recognition of complexity	Include complexity and inconsistencies in training examples rather than simplification for the sake of a persuasive story (***Howitt and Wilson, 2014***; ***Coleman, 1987***). This counteracts the drive to smooth over inconvenient but potentially important details and highlights the importance of confounding variables, potential artefactual influences, reproducibility, and robustness of the findings.
Cultivation of growth	Nurture positive behaviors, like acknowledging and learning from mistakes, rather than penalize imperfect practices (***Alberts et al., 2015***). Mentors at all career stages are encouraged to model these positive behaviors and to share their own failures, the drudgery and frustrations of science, and their approaches to coping emotionally and growing intellectually while maintaining rigorous research practices.
Assessment of behavioral change	Measure success via gains in learner competency and changes to their real-world approaches to research. Changes in laboratory practice could be assessed by user self-reports, by analysis of research presented at meetings (***Silberberg et al., 2017***) and in publications (***MacLeod et al., 2015***), or by querying scientists on whether discussions with their mentors and colleagues led to changes in laboratory and institutional culture. Collaborate from the beginning with individuals who specialize in assessment design in higher education settings (***Bradforth et al., 2015***).

educators and users to iteratively test and improve the resource as it unfolds. As with science itself, the developers will need to experiment with content and delivery. If the resource does not improve the comprehension and research practice of individuals, or add value to the research community, rigorous approaches should be applied to improve it.

Once a functioning and effective resource has been built, it will be essential to promote its use and adoption. One approach would be to host 'train-the-trainer' programs (***Spencer et al., 2018***; ***Pfund et al., 2006***): those involved in building the resource share it with small groups of mentors, who are then better equipped to use the resource with their own mentees and to encourage their colleagues to use it. This form of dissemination also creates buy-in from mentors who need to model the behaviors they are teaching. Rigor champions, meanwhile, can encourage their institutions and colleagues to adopt and use the resource.

Setting up and supporting communities of rigor champions and developing educational resources on rigorous research will be complex and likely require multiple sources of support. However, with the participation of all sectors of the scientific enterprise, the actions proposed herein should, within a decade, lead to improvements in the culture of science as well as improvements in the design, conduct, analysis, and reporting of biomedical research. The result will be a healthier and more effective scientific community.

Disclaimer

The content of this publication does not necessarily reflect the views or policies of the Department of Health and Human Services, nor does mention of trade names, commercial products, or organizations imply endorsement by the US Government.

Walter J Koroshetz is at the National Institute of Neurological Disorders and Stroke, Rockville, MD, United States
https://orcid.org/0000-0001-7292-7831

Shannon Behrman is at iBiology, San Francisco, CA, United States
https://orcid.org/0000-0001-5236-0559

Cynthia J Brame is at the Center for Teaching and Department of Biological Sciences, Vanderbilt University, Nashville, TN, United States

Janet L Branchaw is in the Department of Kinesiology and Wisconsin Institute for Science Education and Community Engagement, University of Wisconsin - Madison, Madison, WI, United States

Emery N Brown is in the Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Harvard Medical School, Boston, MA, and the Department of Brain and Cognitive Science, Institute of Medical Engineering and Sciences, the Picower Institute for Learning and Memory, and the Institute for Data Systems and Society, Massachusetts Institute of Technology, Cambridge, MA, United States

Erin A Clark is in the Department of Biology and Program in Neuroscience, Brandeis University, Waltham, MA, United States
https://orcid.org/0000-0002-4013-325X

David Dockterman is at the Harvard Graduate School of Education, Harvard University, Cambridge, MA, United States
https://orcid.org/0000-0003-3701-1427

Jordan J Elm is in the Department of Public Health Sciences, Medical University of South Carolina, Charleston, SC, United States

Pamela L Gay is at the Planetary Science Institute, Tucson, AZ, United States

Katelyn M Green is in the Cellular and Molecular Biology Graduate Program, University of Michigan, Ann Arbor, MI, United States
https://orcid.org/0000-0001-5562-9920

Sherry Hsi is with The Concord Consortium, Emeryville, CA, United States
https://orcid.org/0000-0001-8356-3279

Michael G Kaplitt is in the Department of Neurological Surgery, Weill Cornell Medical College, New York, NY, United States

Benedict J Kolber is in the Department of Biological Sciences, Duquesne University, Pittsburgh, PA, United States
https://orcid.org/0000-0001-8665-1805

Alex L Kolodkin is in the Solomon H. Snyder Department of Neuroscience, Johns Hopkins School of Medicine, Baltimore, MD, United States
https://orcid.org/0000-0001-7562-5513

Diane Lipscombe is in the Carney Institute for Brain Science, Department of Neuroscience, Brown University, Providence, RI, United States
https://orcid.org/0000-0002-7146-9119

Malcolm R MacLeod is in the Centre for Clinical Brain Sciences, University of Edinburgh, Edinburgh, United Kingdom
https://orcid.org/0000-0001-9187-9839

Caleb C McKinney is in Biomedical Graduate Education, Georgetown University Medical Center, Washington, DC, United States

Marcus R Munafò is in the MRC Integrative Epidemiology Unit, School of Psychological Science, University of Bristol, Bristol, United Kingdom

Barbara Oakley is at Oakland University, Rochester, MI, United States
https://orcid.org/0000-0003-2706-0751

Jeffrey T Olimpo is in the Department of Biological Sciences, The University of Texas at El Paso, El Paso, TX, United States

https://orcid.org/0000-0002-9322-1050

Nathalie Percie du Sert is in the National Centre for the Replacement, Refinement and Reduction of Animals in Research (NC3Rs), London, United Kingdom

https://orcid.org/0000-0002-9478-0540

Indira M Raman is in the Department of Neurobiology, Northwestern University, Evanston, IL, United States

https://orcid.org/0000-0001-5245-8177

Ceri Riley is with Complexly, Missoula, MT, United States

Amy L Shelton is at the Center for Talented Youth and School of Education, Johns Hopkins University, Baltimore, MD, United States

https://orcid.org/0000-0002-2299-7214

Stephen Miles Uzzo is at the New York Hall of Science, Flushing Meadows Corona Park, NY, United States

https://orcid.org/0000-0002-6508-3535

Devon C Crawford is at the National Institute of Neurological Disorders and Stroke, Rockville, MD, United States

devon.crawford@nih.gov

https://orcid.org/0000-0002-9354-4976

Shai D Silberberg is at the National Institute of Neurological Disorders and Stroke, Rockville, MD, United States

silberbs@ninds.nih.gov

https://orcid.org/0000-0002-5306-664X

Author contributions: Walter J Koroshetz, Shannon Behrman, Cynthia J Brame, Janet L Branchaw, Emery N Brown, Erin A Clark, David Dockterman, Jordan J Elm, Pamela L Gay, Katelyn M Green, Sherry Hsi, Michael G Kaplitt, Benedict J Kolber, Alex L Kolodkin, Diane Lipscombe, Malcolm R MacLeod, Caleb C McKinney, Marcus R Munafò, Barbara Oakley, Jeffrey T Olimpo, Nathalie Percie du Sert, Indira M Raman, Ceri Riley, Amy L Shelton, Stephen Miles Uzzo, Conceptualization, Writing - review and editing; Devon C Crawford, Shai D Silberberg, Conceptualization, Writing - original draft, Writing - review and editing. DCC and SDS wrote the manuscript; all authors provided intellectual input and contributed to the editing of the manuscript

Competing interests: The authors declare that no competing interests exist.

Published 04 March 2020

Funding

Funded by the National Institute of Neurological Disorders and Stroke (NINDS).

References

Alberts B, Cicerone RJ, Fienberg SE, Kamb A, McNutt M, Nerem RM, Schekman R, Shiffrin R, Stodden V, Suresh S, Zuber MT, Pope BK, Jamieson KH. 2015. Self-correction in science at work. *Science* **348**:1420–1422. DOI: https://doi.org/10.1126/science.aab3847

Begley CG, Buchan AM, Dirnagl U. 2015. Robust Research: Institutions must do their part for reproducibility. *Nature* **525**:25–27. DOI: https://doi.org/10.1038/525025a, PMID: 26333454

Bertuzzi S, Jamaleddine Z. 2016. Capturing the value of biomedical research. *Cell* **165**:9–12. DOI: https://doi.org/10.1016/j.cell.2016.03.004, PMID: 27015300

Bjork RA, Dunlosky J, Kornell N. 2013. Self-regulated learning: beliefs, techniques, and illusions. *Annual Review of Psychology* **64**:417–444. DOI: https://doi.org/10.1146/annurev-psych-113011-143823, PMID: 23020639

Bosch G. 2018. Train PhD students to be thinkers not just specialists. *Nature* **554**:277. DOI: https://doi.org/10.1038/d41586-018-01853-1, PMID: 29446388

Bosch G, Casadevall A. 2017. Graduate biomedical science education needs a new philosophy. *mBio* **8**:17. DOI: https://doi.org/10.1128/mBio.01539-17

Bradforth SE, Miller ER, Dichtel WR, Leibovich AK, Feig AL, Martin JD, Bjorkman KS, Schultz ZD, Smith TL. 2015. University Learning: Improve undergraduate science education. *Nature* **523**:282–284. DOI: https://doi.org/10.1038/523282a, PMID: 26178951

Brown JS, Adler RP. 2008. Minds on fire: open education, the long tail, and learning 2.0. *EDUCAUSE Review* **43**:16–32.

Button KS, Chambers CD, Lawrence N, Munafò MR. 2020. Grassroots training for reproducible science: a consortium-based approach to the empirical dissertation. *Psychology Learning & Teaching* **19**:77–90. DOI: https://doi.org/10.1177/1475725719857659

Casadevall A, Ellis LM, Davies EW, McFall-Ngai M, Fang FC. 2016. A framework for improving the quality of research in the biological sciences. *mBio* **7**:e01256. DOI: https://doi.org/10.1128/mBio.01256-16, PMID: 27578756

Casadevall A, Fang FC. 2012. Reforming science: methodological and cultural reforms. *Infection and Immunity* **80**:891–896. DOI: https://doi.org/10.1128/IAI.06183-11, PMID: 22184414

Casadevall A, Fang FC. 2016. Rigorous Science: A how-to guide. *mBio* **7**:e01902. DOI: https://doi.org/10.1128/mBio.01902-16, PMID: 27834205

Casci T, Adams E. 2020. Setting the right tone. *eLife* **9**:e55543. DOI: https://doi.org/10.7554/eLife.55543, PMID: 32036857

Coleman B. 1987. Science writing: Too good to be true? *New York Times*. https://www.nytimes.com/1987/09/27/books/sceince-writing-too-good-to-be-true.html [Accessed February 29, 2020].

Collins FS, Tabak LA. 2014. NIH plans to enhance reproducibility. *Nature* **505**:612–613. DOI: https://doi.org/10.1038/505612a, PMID: 24482835

Corwin LA, Graham MJ, Dolan EL. 2015. Modeling course-based undergraduate research experiences: an agenda for future research and evaluation. *CBE—Life Sciences Education* **14**:es1. DOI: https://doi.org/10.1187/cbe.14-10-0167, PMID: 25687826

Cressey D. 2015. UK funders demand strong statistics for animal studies. *Nature* **520**:271–272. DOI: https://doi.org/10.1038/520271a, PMID: 25877180
Dirnagl U, Kurreck C, Castaños-Vélez E, Bernard R. 2018. Quality management for academic laboratories: burden or boon?. *EMBO Reports* **19**:e47143. DOI: https://doi.org/10.15252/embr.201847143, PMID: 30341068
Dirnagl U. 2019. Resolving the ttension between exploration and confirmation in preclinical biomedical research. In: *Handbook of Experimental Pharmacology*. Berlin, Heidelberg: Springer. DOI: https://doi.org/10.1007/164_2019_278
D'Mello S, Lehman B, Pekrun R, Graesser A. 2014. Confusion can be beneficial for learning. *Learning and Instruction* **29**:153–170. DOI: https://doi.org/10.1016/j.learninstruc.2012.05.003
Handelsman J, Ebert-May D, Beichner R, Bruns P, Chang A, DeHaan R, Gentile J, Lauffer S, Stewart J, Tilghman SM, Wood WB. 2004. Scientific teaching. *Science* **304**:521–522. DOI: https://doi.org/10.1126/science.1096022, PMID: 15105480
Howitt SM, Wilson AN. 2014. Revisiting "Is the scientific paper a fraud?". *EMBO Reports* **15**:481–484. DOI: https://doi.org/10.1002/embr.201338302
Ioannidis JPA, Greenland S, Hlatky MA, Khoury MJ, Macleod MR, Moher D, Schulz KF, Tibshirani R. 2014. Increasing value and reducing waste in research design, conduct, and analysis. *The Lancet* **383**:166–175. DOI: https://doi.org/10.1016/S0140-6736(13)62227-8
Kelner KL. 2013. Playing our part. *Science Translational Medicine* **5**:190ed7. DOI: https://doi.org/10.1126/scitranslmed.3006661
Landis SC, Amara SG, Asadullah K, Austin CP, Blumenstein R, Bradley EW, Crystal RG, Darnell RB, Ferrante RJ, Fillit H, Finkelstein R, Fisher M, Gendelman HE, Golub RM, Goudreau JL, Gross RA, Gubitz AK, Hesterlee SE, Howells DW, Huguenard J, et al. 2012. A call for transparent reporting to optimize the predictive value of preclinical research. *Nature* **490**:187–191. DOI: https://doi.org/10.1038/nature11556, PMID: 23060188
Lundwall RA. 2019. Changing institutional incentives to foster sound scientific practices: one department. *Infant Behavior and Development* **55**:69–76. DOI: https://doi.org/10.1016/j.infbeh.2019.03.006, PMID: 30933839
MacLeod MR, Lawson McLean A, Kyriakopoulou A, Serghiou S, de Wilde A, Sherratt N, Hirst T, Hemblade R, Bahor Z, Nunes-Fonseca C, Potluru A, Thomson A, Baginskaite J, Baginskitae J, Egan K, Vesterinen H, Currie GL, Churilov L, Howells DW, Sena ES. 2015. Risk of bias in reports of in vivo research: a focus for improvement. *PLOS Biology* **13**:e1002273. DOI: https://doi.org/10.1371/journal.pbio.1002273, PMID: 26460723
McNutt M. 2014. Journals unite for reproducibility. *Science* **346**:679. DOI: https://doi.org/10.1126/science.aaa1724, PMID: 25383411
Minner DD, Levy AJ, Century J. 2010. Inquiry-based science instruction-what is it and does it matter? results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching* **47**:474–496. DOI: https://doi.org/10.1002/tea.20347
Moher D, Naudet F, Cristea IA, Miedema F, Ioannidis JPA, Goodman SN. 2018. Assessing scientists for hiring, promotion, and tenure. *PLOS Biology* **16**: e2004089. DOI: https://doi.org/10.1371/journal.pbio.2004089, PMID: 29596415
Munafò MR, Nosek BA, Bishop DVM, Button KS, Chambers CD, Percie du Sert N, Simonsohn U, Wagenmakers E-J, Ware JJ, Ioannidis JPA. 2017. A manifesto for reproducible science. *Nature Human Behaviour* **1**:0021. DOI: https://doi.org/10.1038/s41562-016-0021
Munafò MR, Chambers CD, Collins AM, Fortunato L, Macleod MR. 2020. Research culture and reproducibility. *Trends in Cognitive Sciences* **24**:91–93. DOI: https://doi.org/10.1016/j.tics.2019.12.002, PMID: 31892459
Munafò MR, Davey Smith G. 2018. Robust research needs many lines of evidence. *Nature* **553**:399–401. DOI: https://doi.org/10.1038/d41586-018-01023-3, PMID: 29368721
National Research Council. 2015. *Enhancing the Effectiveness of Team Science*: The National Academies Press. DOI: https://doi.org/10.17226/19007
. **Nature** 2013 . Reducing our irreproducibility. *Nature* **496**:398. DOI: https://doi.org/10.1038/496398a
Nosek BA, Spies JR, Motyl M. 2012. Scientific Utopia: II. Restructuring incentives and practices to promote truth over publishability. *Perspectives on Psychological Science* **7**:615–631. DOI: https://doi.org/10.1177/1745691612459058, PMID: 26168121
Pfund C, Maidl Pribbenow C, Branchaw J, Miller Lauffer S, Handelsman J. 2006. The merits of training mentors. *Science* **311**:473–474. DOI: https://doi.org/10.1126/science.1123806, PMID: 16439648
PLOS Biology. 2018. Fifteen years in, what next for PLOS biology? *PLOS Biology* **16**:e3000049. DOI: https://doi.org/10.1371/journal.pbio.3000049, PMID: 30321167
Raman IM. 2014. How to be a graduate advisee. *Neuron* **81**:9–11. DOI: https://doi.org/10.1016/j.neuron.2013.12.030, PMID: 24411728
Silberberg SD, Crawford DC, Finkelstein R, Koroshetz WJ, Blank RD, Freeze HH, Garrison HH, Seger YR. 2017. Shake up conferences. *Nature* **548**:153–154. DOI: https://doi.org/10.1038/548153a, PMID: 28796229
Spencer KC, McDaniels M, Utzerath E, Rogers JG, Sorkness CA, Asquith P, Pfund C. 2018. Building a sustainable national infrastructure to expand research mentor training. *CBE—Life Sciences Education* **17**: ar48. DOI: https://doi.org/10.1187/cbe.18-03-0034
Strech D, Weissgerber T, Dirnagl U, QUEST Group. 2020. Improving the trustworthiness, usefulness, and ethics of biomedical research through an innovative and comprehensive institutional initiative. *PLOS Biology* **18**:e3000576. DOI: https://doi.org/10.1371/journal.pbio.3000576, PMID: 32045410
Walkington C, Bernacki ML. 2018. Personalization of instruction: design dimensions and implications for cognition. *The Journal of Experimental Education* **86**: 50–68. DOI: https://doi.org/10.1080/00220973.2017.1380590
Wasserstein RL, Schirm AL, Lazar NA. 2019. Moving to a world beyond "p < 0.05". *The American Statistician* **73**:1–19. DOI: https://doi.org/10.1080/00031305.2019.1583913
Yeager DS, Henderson MD, Paunesku D, Walton GM, D'Mello S, Spitzer BJ, Duckworth AL. 2014. Boring but

important: a self-transcendent purpose for learning fosters academic self-regulation. *Journal of Personality and Social Psychology* **107**:559–580. DOI: https://doi.org/10.1037/a0037637, PMID: 25222648