Open Science in Data-Intensive Psychology and Cognitive Science

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Abstract

Today, researchers can collect, analyze, and share more data than ever before. Not only does increasing technological capacity open the door to new *data-intensive perspectives* in cognitive science and psychology (that is, research that takes advantage of complex or large-scale data to understand human cognition and behavior), but increasing connectedness has sparked exponential increases in the ease and practice of scientific transparency. The growing *open science* movement encourages researchers to share data, materials, methods, and publications with other scientists and the wider public. Open science benefits data-intensive psychological science, the public, and public policy, and we present recommendations to improve the adoption of open science practices by changing the academic incentive structure and by improving the education pipeline. Despite ongoing questions about implementing open-science guidelines, policymakers have an unprecedented opportunity to shape the next frontier of scientific discovery.

Keywords: open science, transparency, data-intensive science, psychology, cognitive science, psychological science, public policy, grant funding, educational policy

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Highlights

- **Data-intensive cognitive science and psychology** leverages today's increased computational, storage, and analysis capability to understand human behavior and cognition.
- The growing **open science** movement calls for greater transparency at every stage of the scientific process—like sharing data, materials/methods (including code), and publications with other researchers and the public. Open science can dramatically improve the robustness and theoretical impact of data-intensive cognitive science and psychology.
- Grant-funding agencies and other government actors can **develop a unified open science policy framework** that would include open-access publishing, open data, and open materials and methods.
- Education policymakers can help the next generation of scientists by adapting education guidelines and structures to **embrace computational education and foster interdisciplinary collaborative education founded on open-science principles**.
- By updating educational and funding policies to embrace today's changing scientific landscape, policymakers can provide **structural support for open science practices to complement the groundswell of interest from the scientific community**.

Open Science in Data-Intensive Psychology and Cognitive Science

Innovations in computational ability and storage capacity have opened the door to new paradigms in nearly every scientific field, and increasing connectedness helps researchers share data and findings faster and with more people than ever. Coupled together, technological and connectivity advances are providing the opportunity to reimagine what psychology and cognitive science can look like in a more diverse, open, and data-rich world. While this reimagining of scientific practice and norms is still ongoing, policymakers should encourage the growth of open science principles.

Defining Open Science and Data-Intensive Perspectives

With computational and connected technology rapidly growing, innovations around data and scientific stewardship are gaining traction—including the concept of *open science*. Scholars have been concerned about public access to scientific discoveries for centuries (see David, 1998), but the spirit of that concern has expanded in recent years (Boulton et al., 2012; Guest & Rougier, 2016; Nosek & Bar-Anan, 2012). Today, open science often encompasses *open access* (making published reports about scientific discoveries freely available) as well as *open materials*, *open methods*, and *open data* (making the tools for and data from the scientific process freely available). Put simply, while science has long been concerned with making its *results* more accessible, science is now beginning to grapple with making its *process* more accessible.

While increasing openness benefits all scientific areas (e.g., Boulton et al., 2012; Nosek & Bar-Anan, 2012), open science initiatives are particularly important to emerging *data-intensive perspectives*—types of research that leverage today’s increased data collection, storage, and processing capabilities (e.g., Hey, Tansley, & Tolle, 2009). Rapid expansions in technology

are enabling quantitative and qualitative shifts in the scientific process, not only allowing scientists to collect and analyze more data in traditional experiments but also enabling them create new ways to study their phenomena of interest. Data-intensive perspectives have emerged in nearly every research area—from medieval German (Hench, 2017) to omics (Gomez-Cabrero et al., 2014).

While not every scientific field handles terabytes of data, data-intensive perspectives open doors to larger, messier, and more diverse datasets than many areas have traditionally had available to them. Because openness advocates for increased sharing, it can facilitate transparency—or the ability of others to examine the process and data from which the results came—that can improve the public’s confidence in scientific rigor (e.g., Vazire, 2017) and empower more researchers to reuse valuable (and sometimes costly) data. As data, statistics, and modeling become more complex, openness can help data-intensive perspectives remain a viable complement to traditional perspectives—and not a black-box area accessible only to insiders.

Open *and* Data-Intensive Psychology and Cognitive Science

From physiological signals and fMRI data to search results and social media, data on human behavior and cognition are more readily available than ever. While open science principles have been of broad interest to psychology and cognitive science for some time (e.g., Alexander et al., 2012; Grahe, 2018; M. A. Pitt & Tang, 2013), open science provides some unique benefits to data-intensive psychology and cognitive science. The current article makes a case for the value of open science to data-intensive perspectives on human cognition and behavior and for the power of policymakers to improve widespread adoption of these open science principles.

To that end, the present work outlines specific policy proposals that could help open science grow through a multipronged approach. However, many of these proposals could benefit traditional perspectives as well, and the current article aims to fuel continued conversations about improving open science in psychology and cognitive science across all perspectives.

For brevity, “psychological science” here encompasses the range of research areas represented across cognitive science and psychology. Although some researchers distinguish these terms, the current work uses a single term only for simplicity. Ultimately, these recommendations are equally applicable to all data-intensive researchers who study the mind, its processes, and its situatedness within the world, whether they identify as cognitive scientists or psychologists.

Why Open Science Matters

Embracing open science in data-intensive psychological science perhaps most obviously benefits the pursuit of science, but it also benefits the public and public policy. Given public financial support for science, proponents of open science should not only convince scientists of its utility but should also demonstrate its value to the public.

Benefits to Data-Intensive Psychological Science

Improving resource-sharing. Data-intensive science often requires a significant investment in time and resources. Open science—especially open data and open materials—ensures that valuable scientific resources will not languish in old hard drives and file drawers. While APA guidelines have long required authors to share data upon request for seven years after publication, this norm has often failed, as researchers move, misplace data, or experience fires and floods (cf. Vanpaemel, Vermorgen, Deriemaeker, & Storms, 2015; Wicherts, Bakker, & Molenaar, 2011).

Researchers may balk at sharing data and materials that they spent significant time curating and developing, but widespread adoption of data- and material-sharing would allow those same researchers to find other resources that could benefit their own research program. This can be especially impactful for researchers with smaller or less well-funded labs that may be less able to collect large, complex datasets on their own, especially when coupled with tools to help researchers make the most of those data (e.g., Neurosynth for fMRI research; <http://neurosynth.org/>).

In addition to sharing data openly, emerging complementary initiatives are helping researchers pool their resources for inter-lab data collection (e.g., Psychological Science Accelerator [<https://psysciacc.org/>]; StudySwap [<https://osf.io/view/StudySwap/>]). In this model, each participating lab contributes some piece of a larger dataset. These collaborations enable the group to achieve goals at a scale that would be nearly impossible by any single lab and improve confidence in their findings by providing multiple independent replications within the project.

In addition to open data and materials, open-access publishing is another means for resource-sharing by ensuring that the products of scholarly activity are universally available. Open access includes journals that are exclusively open access or journals that provide open-access options, but in either case, authors are required to pay open-access publication fees—typically several thousand dollars (US) for a single journal article. While finding funding for open-access fees for non-grant-funded research is an open question (unfortunately outside of the scope of the current article), open-access publishing of grant-funded research would allow everyone—whether members of the public, of the scientific community, or of policy-making bodies—to have greater access to the end result of the scientific process.

Improving robustness. Open science can improve the robustness of specific findings and of scientific inquiry broadly. However, data-intensive science—because of the quantity, complexity, or messiness of the data—can pose unique concerns when evaluating the quality of results. Such work can be opaque to those who are unfamiliar with data-intensive perspectives (especially the public), making it difficult for others to judge the value and validity of the work. However, without clear reporting and sharing, even other data-intensive psychological scientists can have difficulty judging data-intensive studies because of the countless decisions that shape each study’s scope, method, and analyses—decisions that may not be immediately apparent and may be driven by a host of factors, including theory and personal preference (cf. Luck & Gaspelin, 2017; Simmons, Nelson, & Simonsohn, 2011; Vul, Harris, Winkielman, & Pashler, 2017). Open data and open materials—especially coupled with careful documentation—can help open the “black box” of data-intensive science to promote constructive critical evaluation of studies’ theoretical impact.

While open data and open materials help evaluate individual published studies, other open-science initiatives improve the health of the overall scientific pipeline in several ways. Broadly, these promote reproducibility and reduce the risk of publishing spurious findings by allowing reviewers to fully inspect the quality of the scientific process before publication. First, open methods and materials facilitate both conceptual and direct replication by giving other researchers full access to study protocols (e.g., Simons, 2014; Zwaan, Etz, Lucas, & Donnellan, 2018).

Second, the *preregistration* initiative encourages accountability by asking researchers to declare their research plans in advance: Researchers describe how they will collect, prepare, and analyze their data (a *preregistration plan*), often on a public website that cannot be edited after

being shared (like the Open Science Foundation; <https://osf.io/prereg/>). Creating preregistration plans can reduce the likelihood that researchers will make accidental or well-intentioned choices that lead to false positives (e.g., Gelman & Loken, 2013)—a particularly relevant concern for data-intensive perspectives, as mentioned above. Preregistration does not prevent researchers from doing exploratory analyses or reanalysis of existing data, but it does call for researchers to clearly delineate between explicitly recorded *a priori* hypotheses and later *ad hoc* analyses. The goal of preregistration is not to limit data-driven exploration but rather to make the analysis process more transparent and limit false positives by preventing cherry-picking of significant results.

Finally, by emphasizing rigor over novelty or statistical significance, the open science movement has even inspired a new type of journal article: The “registered report” (e.g., Nosek & Lakens, 2014) initiates peer review before data are collected and analyzed, rewarding high-quality scientific work by publishing even null results. Removing incentives for significant results frees scientists to remain agnostic to results and to prioritize accuracy when communicating with policymakers and the public.

Benefits to Public Policy

Informing policy debates. Open science—especially open-access publishing—informs public policy debates by allowing lawmakers, citizens, and other stakeholders to consider scientific studies relevant to policy proposals. Scientists may have valuable data-supported insights into important public questions, but subscription-based publishing models close these findings from those with the power to act on them. By committing to open-science practices like open data, open materials, and open methods, scientists can expand their reach even further by allowing public policy experts to see the strength and quality of pertinent findings. With

implications from child development to social structures, psychological science is especially impactful to public policy. Opening scientific resources ensures that policymakers have direct access to relevant scientific evidence.

Improving impact of government-funded research. The public's investment in science mandates maximizing the reach of grant-funded research. Open data, open materials, open methods, and open access exponentially increase the yield from each dollar invested: Open materials and methods can be reused, open data can be reanalyzed, and open-access publication can be read by all. Not only does sharing improve the reach of specific grant-funded deliverables, but it can spark a virtuous cycle of grant-funded open-science research by demonstrating the benefits of publicly funded science. By prioritizing funding for projects committed to open science, government funding agencies can make valuable taxpayer dollars go further.

Improving public confidence in science. Cross-domain research is currently working to understand how the public views science, including some groups' decreased trust in science (Fiske & Dupree, 2014; Sherkat, 2017). Conflicting findings within the scientific community are a major source of public distrust in science regardless of party affiliation (Nisbet, Cooper, & Kelly Garrett, 2015), but debates over theory, data, and interpretation among scientists are relatively common. Explaining the value of these debates may be more in the purview of scientific education, but scientists can facilitate these conversations by making data, materials, methods, and publications open. Open science also fosters public trust by facilitating the vetting of scientific findings—allowing for criticism, re-analysis, and replication—and thereby improves self-correction within psychological science.

Open science sheds light on the underlying reasons for scientific debates, providing opportunities to compare data and methods behind dissonant findings. If policymakers continue to rely on scientific evidence for decision-making and to invest public funds in scientific inquiry, policymakers should work to bolstering the public's trust in science; embracing open-science principles and practices is a valuable aid in that effort.

Benefits to the Public

Improving the quality of science. The utility of empirically based policy rests entirely on the quality of the data that formed the base for those policies. As open science practices improve scientific robustness and reliability, scientific contributions to the public will correspondingly improve. By informing policies from medical standards to economic policy, science is a public good that touches everyone's everyday lives. Improving the quality of science—both its practices *and* its findings—maximizes public benefits and minimizes public risks.

Improving ownership over publicly funded science. Federal grants play a massive role in modern science, ultimately making science not only a public good but also public property. Locking away data, methods, materials, and publications behind paywalls or in file drawers ultimately silos valuable goods that taxpayer dollars helped create. While due consideration must first be given to the ethics of human-subjects data-sharing, governments fund science to improve the body of public knowledge—not to keep it for the privileged few with peer-reviewed journal subscriptions or personal connections to data or materials. As scientists expand best practices to include open-science principles, the public should expect to see their access to scientific findings, outcomes, and resources expand, too.

Improving access to science. Whether a specific study is publicly funded or not, open science allows the public to engage more directly with science than ever before. This creates a host of educational opportunities: Access to primary-source articles can improve scientific literacy, and access to materials, methods, and data can spark new ways for educators to help learners understand the scientific process. Sharing data, materials, and methods can even empower more advanced learners to engage in hands-on exploration—like a recent graduate-level course in which students worked to reproduce results from an open-access journal article using open raw data and reported methods (original article: J. H. Pitt & Hill, 2016; course syllabus: Stark, 2016; course description: Tennant, 2017). Outside of the classroom, direct engagement can facilitate innovation, giving entrepreneurs and inventors access to science that could shape new companies and new technology.

Proposals and Policy Implications

No “silver bullet” will improve the state of open science, whether in data-intensive psychological science or any other field. With a variety of stakeholders with sometimes-competing incentives, achieving widespread adoption of open-science practices will require a multi-pronged approach and the persistent efforts of open-science advocates. However, policymakers can make significant headway in two domains: changing academic incentives and improving the education pipeline.

Changing Academic Incentives

Given the importance of grants to academic careers, grant-funding agencies hold significant power to improve the uptake of open science practices. Here, we outline specific recommendations for changing academic incentives to promote open science (see also Nosek,

Spies, & Motyl, 2012). These proposals relate most directly to funding agencies, but other agencies, departments, and government actors can also make valuable contributions.

RECOMMENDATION 1: UNIFY OPEN SCIENCE REQUIREMENTS FOR ALL FEDERAL FUNDERS INTO A SINGLE FRAMEWORK THAT INCLUDES STRONG ENFORCEMENT MECHANISMS.

Many granting agencies already have policies governing data sharing and open-access publication. For example, the National Science Foundation (NSF) requires that grant recipients make data and materials from grant activities available to other researchers upon request (National Science Foundation, 2017), and some NSF directorates have created additional guidelines (National Science Foundation, n.d.). Additionally, the National Institutes of Health (NIH) has required some form of open access since 2008, with more recent requirements for preregistration, open materials, and open data (National Institutes of Health, n.d.).

Beyond funding agencies, other government actors have expressed interest in implementing open-science initiatives. Congress has repeatedly introduced legislation that would require various funding agencies to mandate open-access publication, but these bills—the Federal Research Public Access Act (in 2006¹, 2010², and 2012³) and the Fair Access to Science and Technology Research Act (in 2013⁴, 2015⁵, and 2017⁶)—never passed into law. The White House Office of Science and Technology issued a policy directive in 2013 that mandated public access to research output (including publication and data) from most publicly funded projects.

¹ <https://www.congress.gov/bill/109th-congress/senate-bill/2695>

² <https://www.congress.gov/bill/111th-congress/senate-bill/1373/text>

³ <https://www.congress.gov/bill/112th-congress/house-bill/4004/text>

⁴ <https://www.congress.gov/bill/113th-congress/house-bill/708>;
<https://www.congress.gov/bill/113th-congress/senate-bill/350>

⁵ <https://www.congress.gov/bill/114th-congress/house-bill/1477>;
<https://www.congress.gov/bill/114th-congress/senate-bill/779>

⁶ <https://www.congress.gov/bill/115th-congress/house-bill/3427>;
<https://www.congress.gov/bill/115th-congress/senate-bill/1701/>

To replace this piecemeal approach, we recommend that **funding agencies and Congressional lawmakers work with scientists from a variety of fields to develop a unified open science policy framework** that would govern all federally funded research. At a minimum, this should **include open-access publishing** (whether in open-access journals or journals with open-access options)⁷, **open data** (see Recommendation 2 below), **and open materials and methods** (including code), although additional requirements may also be worth considering (cf. Transparency and Openness Promotion guidelines; Nosek et al., 2015).

Because of the high costs associated with open-access publishing (often \$1,000-\$3,000 USD per article), explicit funding or funding policies should be put in place to provide for publishing fees⁸ and repository costs—perhaps by requiring that grant awardees explicitly anticipate these costs within proposed budgets. In addition to providing clear and uniform guidelines across agencies, these recommendations should also include enforcement mechanisms to ensure compliance. While ongoing persuasion campaigns and changing norms are unquestionably important to self-sustaining change, enacting enforcement mechanisms could serve as a kind of guard rail against the now-meager structural incentives for individual researchers to adopt open-science practices (see Recommendation 4)⁹. The current lack of enforcement implicitly disfavors open-science practices by effectively disadvantaging researchers who embrace open science practices: These researchers invest valuable time and

⁷ Top journals in some fields may not have open-access options, but public ownership over publicly funded research is vital. Moreover, migration from closed journals may compel those journals to offer open-access options.

⁸ This could quickly become a rather high burden, given the cost of open-access publishing in many journals. With funding agencies creating opportunities for thousands of articles each year, the total cost of open-access fees could easily rise to millions of dollars. Generally, despite most journals relying largely on volunteer labor, the business model for open-access publishing has not yet been settled, and any recommendations in this regard are beyond the scope of this article.

⁹ Additional steps should be taken by universities and departments to further incentivize and acknowledge open science activities; however, such recommendations are outside the scope of the current work.

resources in sharing, while those who choose not to follow voluntary requirements are able to invest in further productivity gains. A unified open science policy framework would pave the way toward wider adoption of open science practices because of the important role that federal funders play in shaping scientific expectations.

RECOMMENDATION 2: CREATE CLEAR GUIDELINES FOR OPEN DATA BEST-PRACTICES.

Given recent and growing concerns about data security and privacy, data-intensive psychological scientists should be more mindful than ever about the impact and ethics of sharing data (cf. Paxton & Griffiths, 2017). Sharing data should be a pillar of the scientific community, but even human-subjects researchers willing to share their data worry about whether, how, and to what extent they can do so—especially for multivariate datasets that include potentially identifiable information about individual participants. The U.S. Department of Health and Human Services (<https://www.hhs.gov/>)—already responsible for overseeing human-subjects research (U.S. Department of Health and Human Services, n.d.)—would be well-poised to update its guidelines and regulations to cover these emerging concerns.

Therefore, we recommend that **funding agencies and HHS Office for Human Research Protections work with scientists from a variety of fields to create clear guidelines for open data best-practices**. At a minimum, this should include how varying levels of sensitive data can be shared, how open-data concerns should be presented in the informed consent process, and how researchers should de-identify data to best protect participant privacy (since insufficiently de-identified data can be re-identified; Narayanan & Shmatikov, 2008). Achieving these goals will likely require agencies to consult a number of experts from across domains and data types but would be well worth the effort.

RECOMMENDATION 3: CONTINUE LONG-TERM SUPPORT FOR CYBERINFRASTRUCTURE THAT FACILITATES DATA-INTENSIVE RESEARCH AND OPEN SCIENCE PRACTICES. Although funding pioneering new scientific infrastructure should still be a priority, funding agencies should keep in mind the long-term viability of already-funded initiatives. Funding operating expenses is less glamorous than funding new initiatives, but agencies should prioritize sustaining projects that have been transformative to the scientific process and that broaden access to research innovations beyond top-tier universities. Specifically, continued funding in two areas—cyberinfrastructure and sharing initiatives—would provide outsized benefit to the broader scientific community.

Robust cyberinfrastructure is crucial to today’s research—especially for data-intensive science—and funding agencies have been pivotal in democratizing access. For example, XSEDE (<https://xsede.org>; Towns et al., 2014) provides researchers with access to scalable cloud computing with curated software and programming environments. XSEDE facilitates cutting-edge work across discipline, and its network of experts helps even novice researchers make the most these resources. Rather than requiring payment for access, XSEDE operates on a use-grant model that allows researchers to apply for computing resources for specific projects. As a result, XSEDE is invaluable for data-intensive researchers from smaller or less well-funded institutions and may be the only way for them to access the resources they need.

Sharing data, code, and other materials is a pillar of the open science movement, and many repositories—often supported by funding agencies—have sprung up to support it. This has created a patchwork of repositories with different constraints, groups, and data types (the latter being particularly important given the ethics of sharing human-subjects data). Although a variety

of pressures has led to the state of open data, this siloed approach can limit data discovery and reuse across domains.

Some initiatives—like the Open Science Framework (<https://osf.io>)—aim to break down these walls by creating all-in-one collaborative platforms for researchers to share data, methods, materials, and output. By unifying and simplifying the sharing process, platforms like the OSF have significantly lowered barriers to entry into open science. However, without support for these initiatives and without considering how they can be expanded to accommodate the spectrum of ethical restrictions for sharing data, it will be difficult for scientists to unite behind them.

Therefore, we recommend that **funding agencies prioritize (1) continued support for critical scientific cyberinfrastructure and (2) supporting efforts to unify open data repositories that can accommodate human-subjects ethics considerations**. Especially for data-intensive psychological science, the need for large-scale open data *and* the computing power to analyze them are inseparable. We recommend that such **repositories have multiple levels of access**, allowing anyone to access non-sensitive data while allowing any researcher with appropriate ethical clearance to access sensitive data—similar to models already in place at the ICPSR (<https://www.icpsr.umich.edu/icpsrweb/>). Agencies and funders could improve impact by **allowing grant applicants to allocate funds for research IT personnel**, who serve as champions of cyberinfrastructure and open-science best-practices in academic institutions but who often have no formal mechanism to receive compensation for consultation work on grants. By prioritizing wider access of cyberinfrastructure and data within the context of human-subjects ethics, federal funding agencies would empower and democratize data-driven discovery for data-intensive psychological science and beyond.

RECOMMENDATION 4: VALUE APPLICANTS’ OPEN SCIENCE CONTRIBUTIONS WHEN CONSIDERING GRANT APPLICATIONS. Open science relies on contributions from individual researchers who invest time, effort, and funds to share their materials, code, data, and research deliverables. This might include paying thousands of dollars in open-access publication fees, spending hours cleaning up data files before sharing them, or dedicating time to maintaining academic software or programming libraries. Taken together, these activities can lead a single researcher to have a massive impact on the work of countless other researchers—even enabling research that would have been otherwise impossible.

Unfortunately, these invaluable community contributions often go un- or under-appreciated by formal academic structures like hiring, tenure, and grants. This devaluation not only is problematic for individual researchers who are not rewarded for their time and efforts but also leads to perverse incentives that actively discourage open-science activities—by signaling to researchers that their time would be better spent on efforts that are recognized, such as grants and publications.

Therefore, we recommend that **funding agencies explicitly consider grant applicants’ previous and current efforts to facilitate open science.** Funders may not be able to compel academic institutions to consider open-science contributions in their incentive structures, but by rewarding community-minded dedication to open science in the grant process, funding agencies can ensure that open-science researchers are the standard-bearers for ongoing scientific inquiry. Not only will this serve as a valuable **incentive to continued participation in open science**, but it will also **improve the reach of grant-funded research**—ensuring that publicly funded research materials and deliverables make it back into the public domain.

Improving the Education Pipeline

Policymakers can shape the present and future of open science directly through the educational pipeline at federal and state levels. Here, we outline several initiatives that could encourage open science in science generally and in data-intensive psychological science specifically.

RECOMMENDATION 5: EMBRACE COMPUTATIONALLY MINDED EDUCATION AND COLLABORATIVE SCIENCE EARLY. Teachers and parents increasingly recognize the value of computational skills—including computer programming—even before kindergarten (e.g., Fessakis, Gouli, & Mavroudi, 2013; Portelance, Strawhacker, & Bers, 2016). While experts are still debating precisely what computational curricula should feature (e.g., Manches & Plowman, 2017; Weintrop et al., 2016), these skills are too important to the future of science, industry, and government to wait to take action. Early access and empowerment is key to improving science and math skills (e.g., Eshach & Fried, 2005; Tai, Liu, Maltese, & Fan, 2006; Wang, 2013), especially for students from groups that are underrepresented in scientific fields (e.g., Oakes, Ormseth, Bell, & Camp, 1990; Zeldin & Pajares, 2000).

Beyond simply learning computational skills, students must learn computational skills *as part of a team*. As the world becomes more interconnected, science becomes more collaborative (Wagner, Whetsell, & Leydesdorff, 2017). Since careers in industry have long relied on effective teamwork (Vicentini & Nasta, 2018), even computational work outside of academia will mandate collaboration. Mastering the intersection of computational and collaborative tools, then, will be critical to students' success, no matter their eventual career paths. Staples of open science—like GitHub (<https://github.com>) and the Open Science Framework (<https://osf.io>)—can provide such opportunities.

Therefore, we recommend that **policymakers broaden education standards to include programming, improve foundational statistical knowledge, and encourage collaboration with state-of-the-art open science tools as early as possible.** We see no downside to incorporating these recommendations even for students who do not become scientists: These skills are critical for 21st-century public- and private-sector careers—including cybersecurity jobs vital to national security (Raytheon & National Cyber Security Alliance, 2016). However, for science generally and data-intensive science specifically, **growing up with both computational and data literacy** will allow future scientists to spend more time innovating scientific methods and pursuing scientific discoveries—and less time learning foundational computational skills.

RECOMMENDATION 6: IMPROVE SUPPORT TO CREATE INNOVATIVE, INTERDISCIPLINARY EDUCATION AND TRAINING PROGRAMS THAT CAN PROVIDE NEW MODELS FOR DATA-INTENSIVE PSYCHOLOGICAL SCIENCE. Addressing Recommendation 5 would empower tomorrow’s scientists to embrace data-intensive perspectives, but additional steps should be taken to empower today’s data-intensive scientists. In addition to providing current researchers with learning opportunities in data-intensive perspectives (especially those from underrepresented groups and those in later stages of their scientific careers), training and education programs should encourage collaboration across disciplinary lines. The complexity of large-scale data is not unique to psychological science; looking to other fields—like graph theory, topology, and biology—could prove revolutionary to understanding human data.

Therefore, we recommend that **education-oriented funding agencies fund initiatives to create sustainable models for interdisciplinary education and training opportunities** that expand the toolbox for data-intensive psychological science. As scientific endeavors and grant

opportunities increasingly prize interdisciplinarity, education and training pipelines must adapt. These initiatives should **prioritize diversity** in data-intensive and collaborative training by reaching out across demographic characteristics, research areas, and career stages. Of course, these initiatives should be **founded in open-science principles** of collaboration, transparency, and openness. By encouraging cross-disciplinary contact, education and funding agencies will position psychological scientists to leverage large-scale data and advanced methodologies and discover new paradigms to study human behavior and cognition.

Conclusion

Despite a bright future for open science in data-intensive psychological science, some researchers are concerned with aspects of open science. For example, researchers who do not share their data or methods may feel as though they are implicitly accused of unethical practices, and researchers who rely on exploratory analysis may feel as though the preregistration movement has no room for them. Some of these concerns emerge from unfortunate realities of today's incentive structures in publication and academic systems. However, recent efforts to change these structures—such as rewarding open-science practices (e.g., Kidwell et al., 2016) and modifying open-science practices for secondary data analysis and non-traditional designs (e.g., Ritchie, Weston, Przybylski, & Rohrer, 2017)—leave us optimistic that open science can accommodate the needs of different areas of cognitive science and psychology. As scientists continue to refine open-science practices, policymakers can be important allies in promoting the adoption of open science principles.

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