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The National Robotics Initiative

A Five-Year Retrospective

By Daniel J. Hicks and Reid Simmons

The U.S. National Science Foundation (NSF), together with other federal agencies, launched the National Robotics Initiative (NRI) program in 2011. The aim of the NRI is to accelerate the development and use of collaborative robots (corobots), which work beside or cooperatively with people. To date, the NRI program has involved multiple directorates of the NSF (Computer and Information Science and Engineering; Engineering; Social, Behavioral, and Economic Sciences; and Education and Human Resources) and several other federal research funding agencies [the U.S. Department of Agriculture (USDA), the National Institutes of Health (NIH), the U.S. Department of Energy (DOE), NASA, and the U.S. Department of Defense (DOD)]. As the program prepared to announce its sixth round of awards in the summer of 2017, we took the opportunity to reflect on the impacts of the first five years of NRI funding.

Interdisciplinary research is central to the NRI's vision of collaborative robotics. As robots move from science fiction to reality, engineers and computer scientists must work closely with specialists in areas such as agriculture, materials science, clinical medicine, and psychology and even humanistic fields, such as ethics. Although the primary metric of success for the NRI program is its impact on robotics science and technology development, this article addresses the less-often considered question of the impact on collaborative research. Specifically, this article addresses three central questions about the portfolio of NRI awards:

1) What kinds of new collaborations has the NRI supported?
2) How have NRI-funded researchers drawn on different academic disciplines in their research?
3) How has the NRI encouraged researchers to publish outside traditional areas of robotics research?

To answer these questions, we constructed a data set of publications by NRI-funded researchers. We considered publications directly sponsored by the NRI program as well as the full publication record of NRI-funded researchers and the prior research cited by NRI-sponsored publications. Viewing NRI-funded publications in this broader context allows us to examine the effects that the NRI has had on researchers' publication patterns.

Regarding the first question, we find that approximately 22% of NRI-funded collaborations (pairs of coauthors) are

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novel. For the second question, we show that NRI papers in traditional robotics research areas (computer science, engineering, and mathematics) cite research in nonstandard robotics fields, such as medicine, neuroscience, social science, suborganismal biology, and physics. For 26 NRI awards (29% of those for which we find publications), more than 25% of citations are to at least one such nonrobotics field. Finally, our analysis of publication histories suggests that NRI funding increases the chance of publishing in several nontraditional robotics fields.

The NRI Research Community

The idea of a U.S. national funding program for robotics research emerged in a series of workshops sponsored by the Computing Community Consortium and the Computing Research Association in 2008 [1]. The workshops were organized by a group of nine universities (the Georgia Institute of Technology, the University of Southern California, Johns Hopkins University, the University of Pennsylvania, the University of California at Berkeley, Rensselaer Polytechnic Institute, the University of Massachusetts at Amherst, the University of Utah, and Carnegie Mellon University), as well as The Technology Collaborative. Three of the workshops focused on industry/application areas: manufacturing, medicine and healthcare, and service robotics, ranging from domestic cleaning or entertainment systems to assistive systems for impaired or elderly people. A fourth workshop focused on the fundamental technological capabilities that would be required for robots to be effective in each of these three areas. The findings of these workshops were collected in a 2009 report, *A Roadmap for US Robotics: From Internet to Robotics* [2].

As the title suggests, the 2009 report framed robotics as an imminent platform technology "likely to become as ubiquitous over the next few decades as computing technology is today" [2, p. 2]. The roadmap adopted a demand–pull model of innovation: there is a strong potential for substantial economic benefits as robotics is adopted in manufacturing, medicine and healthcare, and personal services. Thus, the technology should be developed to realize these benefits. This demand–pull model contrasts with the supply–push model of innovation, in which researchers pursue their idiosyncratic interests and societal benefits emerge serendipitously [3]. The report appealed to economic competitiveness to argue for a U.S. national funding program, pointing to existing programs for robotics research in the European Union, Japan, and Korea.

A distinctive feature of the NRI is its emphasis on corobots, robots "acting in direct support of and in a symbiotic relationship with human partners" [4]. In the context of the NRI, the notion of corobots was developed in 2010. In that year, a draft white paper provided to us by Henrik Christensen characterized robots 2.0 as coworkers, coprotectors, and coinhabitants. Also, at the 2010 Performance Metrics for Intelligence Systems Workshop, the National Institute of Standards and Technology organized a panel discussion on robots as coprotectors, coinhabitants, coworkers, cointegrants, or, more generically, co-x [5].

The NRI initially included four funding agencies: the NSF, the NIH, NASA, and the USDA. Two other agencies—the DOE and DOD—also participated in recent rounds of funding. The first round of applications was submitted on 1 October 2011, and the first round of awards was announced in the summer of 2012. Therefore, the summer of 2016 marked the fifth round of NRI awards. A renewed solicitation for NRI 2.0 was announced in the fall of 2016 [6]. NRI 2.0 builds on the corobot concept and aims to promote "ubiquitous corobots, where robots are as commonplace as today's automobiles, computers, and cell phones." Corobots are expanded to corobot teams of robots working together or with multiple people. This expanded vision of corobot teams introduces demands for greater scalability and variety—for example, swarms of unpiloted aerial vehicles (UAVs), rather than a single machine, or systems that include both ground-based robots and UAVs. NRI 2.0 also emphasizes systems that can be customized and personalized, with the goal of allowing off-the-shelf robotic systems to be deployed at scale in a wide variety of real-world settings. Furthermore, it specifically requests proposals to develop infrastructure to lower the barriers for entry into the robotics research field.

Robots raise both intrinsic and systemic ethical issues. *Intrinsic ethics* refers to the behavior of a robotic system itself, as in the many discussions of the trolley problem that have emerged over the last five years [7], [8]; *systemic ethics* refers to the broader social impacts of robotics, such as job market effects [9] or what Shannon Vallor has called *moral deskilling* [10]. Every version of the NRI solicitation has recognized the importance of these issues and so has specifically requested proposals for social science and humanistic ethics research, including proposals that will advance the use of robotics in education and workforce development.

The NRI projects span a wide variety of technical areas, including manipulation and locomotion, task and motion planning, perception, navigation and localization, human–robot interaction, swarms and multirobot coordination, dynamics and control, teleoperation, and soft robotics. The projects also cover a wide variety of applications, including environmental monitoring, oceanography, medicine, service and assistive robots, education, agriculture, search and rescue, disaster recovery, manufacturing, inspection, surveillance, and space. Over the course of fiscal years 2012–2016, NRI funding agencies have allocated approximately US$241 million to fund 310 awards, supporting 490 researchers [principal investigators (PIs) or co-PIs] at 152 institutions. The NSF funds 259 of these awards. Figure 1 shows the number of NRI awards by proposal submission year and funding agency through 2016.

Methods and Data: Bibliometrics

Bibliometrics is a field of quantitative science of science research; that is, bibliometrics is a scientific field that studies the products of scientific research. As its name suggests, bibliometrics relies heavily on publication metadata, especially citation data. For example, many researchers will be familiar

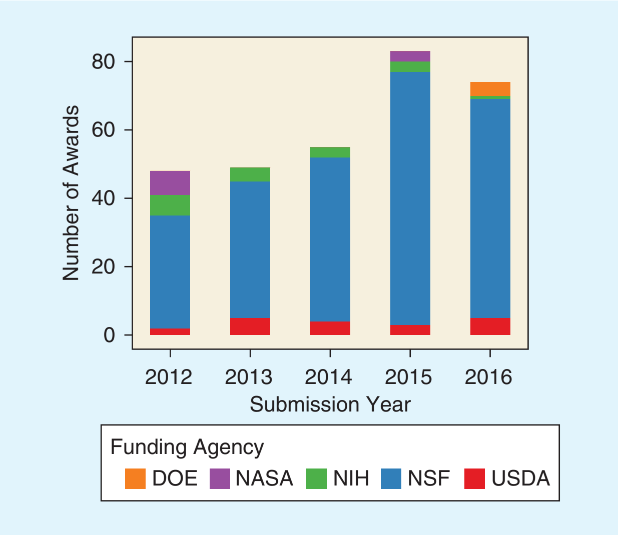

Figure 1. The number of NRI awards, by submission year and funding agency.

with simple citation counts as well as aggregate statistics based on citation counts, such as the h-index and journal impact factors. However, it takes several years for papers to accumulate citations, which limits the utility of citation counts for evaluating the impact of a relatively young and interdisciplinary program, such as the NRI. Similarly, it is too soon to expect substantial dissemination of NRI-sponsored research into society. Instead, we focus here on the impacts of the program on funded researchers themselves.

Given the interdisciplinary nature of the program objectives, one might ask whether the NRI has, in fact, fostered novel collaborations and brought together researchers from different fields to tackle major challenges in the development of corobots. Thus, early indications that the program is successful in this regard might include evidence of novel collaborations, citations by NRI-funded publications to fields that are not traditional areas of robotics research (that is, citations to fields other than computer science and electrical engineering), and increased publication in journals that are not traditional venues for robotics research.

To search for these kinds of trends, we used publication metadata maintained by the research indexing service Scopus [11]. Scopus offers a large and highly inclusive database of publication metadata from numerous scientific fields, and it has been validated by bibliometricians as an appropriate source for bibliometric data [12]. Furthermore, Scopus offers an application programming interface that allowed us to automatically retrieve metadata for tens of thousands of publications.

We began with a core set of 958 NRI-funded journal articles and peer-reviewed conference presentations. These papers were identified in March 2017 by a combination of Scopus searches. We matched each paper to a particular NRI award, and we matched paper authors to NRI PIs and co-PIs. All together, we retrieved publications for 138 (out of 310 total) distinct awards. We found no publications for 131 (out of 259 total) NSF-funded awards. For these 131 awards, 61 were recent awards (initiated in the summer/fall of 2016, approximately six months before we began our literature search), 57 were supplements or transfers to other awards, and seven were for nonresearch awards, such as conferences. For six awards, we were unable to locate any relevant publications. We were also able to retrieve partial lists of publications for NIH-, DOE-, and USDA-funded awards, and these publications were included in the core set.

To place this core set in context, we also retrieved metadata on 1) all papers cited by papers in the core set (when available) and 2) all papers authored by at least one NRI-funded researcher. The first set allows us to examine the research fields cited by NRI papers; it comprises 13,132 papers. The second set allows us to examine research topics, collaboration relationships between NRI-funded researchers, and changes in publication patterns over time; it comprises 20,800 papers. There are 2,279 papers in both sets. In other words, 2,279 papers were both cited by NRI papers and written by NRI-funded researchers. All together, we analyze data from 31,653 papers.

Supporting New Collaborations

We first investigated what kinds of new collaborations the NRI has supported. To identify new collaborations, we focused on NRI PIs or co-PIs who had at least two papers in their publication record. We identified 143 pairs of these researchers (161 individual researchers) who had collaborated together on at least one NRI-funded publication. Figure 2 shows the coauthorship relations among these 143 pairs. Each individual researcher is represented by a single node; red and blue edges represent a paper coauthored by the two given researchers. Blue lines are NRI-funded publications; red lines are non-NRI papers that were published before the pair's first NRI publication. The intensity of shading indicates when the paper was published: darker lines represent more recent publication. The network is divided into 48 connected components; these are given arbitrary index numbers to facilitate cross-referencing. Although most components comprise only two or three researchers, components 1, 2, and 10 are relatively large. These components, respectively, comprise 18, 13, and eight of the 161 total researchers (24% combined) and 23, 19, and 10 of the 143 total collaboration pairs (36% combined).

We also considered the possibility that researchers at the same institution would be likely to collaborate even without NRI funding. In Figure 2, two researchers with the same institutional affiliation at the time of a given paper are indicated with a dashed line. A solid line means that the coauthor pair had different institutional affiliations. Altogether, the NRI has funded 143 coauthor pairs. Figure 2 clearly indicates that the NRI has helped to continue a number of longstanding collaborations (see, for example, components 8, 12, 30, 37, and 41). These research pairs have a few NRI-funded publications (blue lines) but many more prior publications (red lines). The NRI has also funded new collaborations between researchers with the same affiliation (dashed blue lines). See, for example, components 7, 17, 24, 33, and 35.

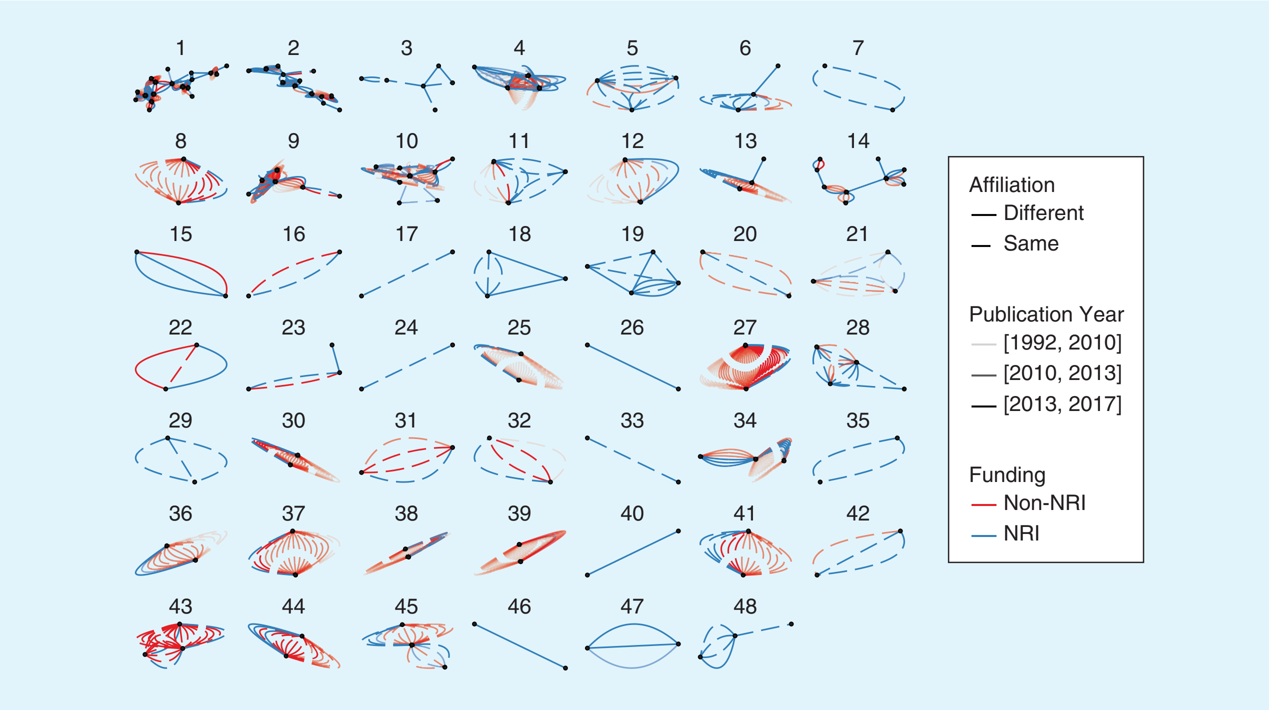

Figure 2. Collaborations between NRI-funded researchers.

By contrast, we are particularly interested in pairs of researchers who are connected by solid blue lines and who have no red connections. These pairs have never published together with the same institutional affiliation and first published together in an NRI-funded paper. These are novel, NRI-sponsored collaborations. Note that our analysis looks at only common institutional affiliations in coauthored publications. We have no way to detect longstanding professional friendships, for example, or researchers who were in graduate school together and later collaborated for the first time.

Figure 3 shows the 31 novel NRI-funded collaborations (22.4% of all NRI-funded coauthor pairs) in context. Colored edges show pairs of NRI-funded PIs or co-PIs whose first collaborative publication was NRI-funded and who have never had the same affiliation in any coauthored publication; edge colors give the year the pair first published an NRI-funded paper. Thin gray edges show collaborations that do not satisfy these criteria for novel collaborations but are included to illustrate the broader context of collaboration among robotics researchers. The large connected component shows that some of these collaborations take place in the context of an extended robotics research community (e.g., researchers A and B have worked together, and researchers B and C have worked together, and the NRI funds a novel collaboration between A and C). Others appear to exist on the margins or outside of this extended community. All together, these collaborations are funded by 23 distinct awards, or 16.7% of all awards for which we have publications, and they amount to 22.4% of all NRI-funded coauthor pairs. This shows that the NRI program has funded and continues to fund novel research collaborations at a fairly high rate.

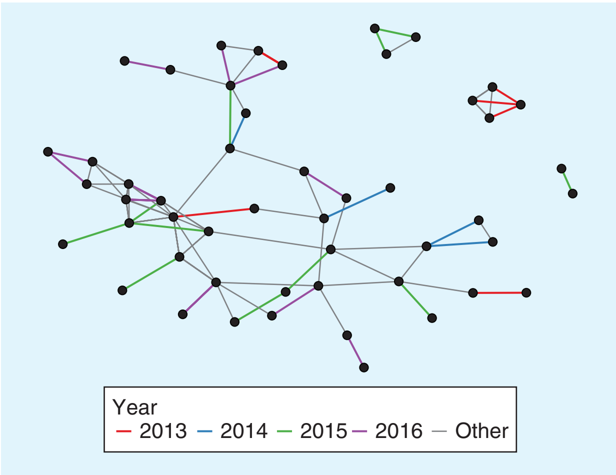

Figure 3. Novel NRI-funded collaborations in context.

An Interdisciplinary Knowledge Base

Our next research question considers how NRI-funded researchers have drawn on different academic disciplines in their research. To address this question, we focus on the set of 13,132 papers cited by NRI publications. Scopus classifies journals (and other publication venues, such as peer-reviewed conference proceedings) into 26 general areas of scientific research (see Table 1). A given journal can have more than one area, and these areas can change over time. An individual paper inherits the areas from the journal in which it is published at the time of its publication.

Figure 4 shows the flow of citations among research areas. Cited paper research areas are on the left-hand side of each

Table 1. Scopus four-letter research area codes and definitions [11].

Code	Research Area
AGRI	Agricultural and biological sciences (including ecology and organismal biology)
ARTS	Arts and humanities (including linguistics)
BUSI	Business, management, and accounting
BIOC	Biochemistry, genetics, and molecular biology
CENG	Chemical engineering
CHEM	Chemistry
COMP	Computer science
DECI	Decision sciences (including information systems and statistics)
DENT	Dentistry
EART	Earth and planetary sciences
ECON	Economics, econometrics, and finance
ENER	Energy
ENGI	Engineering
ENVI	Environmental science (including ecology)
HEAL	Health professions
MATE	Materials science
MATH	Mathematics
MEDI	Medicine
MULT	Multidisciplinary
NEUR	Neuroscience
NURS	Nursing
PHAR	Pharmacology, toxicology, and pharmaceutics
PHYS	Physics and astronomy
PSYC	Psychology
SOCI	Social sciences
VETE	Veterinary

panel; NRI papers are on the right-hand side. Ribbons connect pairs of research areas in proportion to the number of citations in NRI papers. The panels are split by NRI research area, with traditional robotics areas— computer science, engineering, and mathematics—on the left.

Figure 4(a) shows that, although NRI papers in traditional robotics areas primarily cite other research in traditional robotics areas (namely, computer science, engineering, and mathematics), there are substantial numbers of citations to less traditional fields, most noticeably medicine as well as neuroscience, social science, suborganismal biology, and physics. Figure 4(b) shows that NRI papers published in less-traditional robotics areas cite a more even mix of fields. Engineering and computer science are still prominent, but they are much less prominent than in Figure 4(a). For example, biomedical fields are more prominent than in Figure 4(a). This suggests that some NRI awards are making substantial use of previous research well outside the traditional robotics domain. Figure 5 shows dot plots of the percentage of citations from NRI awards to selected fields. For example, a dot at 50% over biochemistry, genetics, and molecular biology (BIOC) indicates that, for one NRI award, 50% of that award's citations are to papers classified as BIOC. Although many awards have a small number of citations to nontraditional robotics fields, a number of awards cite these fields for 20% or more of their references. In particular, for 26 awards (29% of those for which we have publications), more than 25% of the citations are to at least one nontraditional robotics field.

Expanding the Scope of Robotics Research

The previous section showed that NRI researchers are drawing on prior work outside traditional robotics. What about dissemination? Given the interdisciplinary aims of the NRI, is it also encouraging researchers to publish outside traditional robotics journals? To address this question, we focus on nine research areas: suborganismal biology, decision sciences, Earth sciences, materials science, medicine, neuroscience, physics, psychology, and social sciences. For each of these research areas, a moderate number of NRI-funded authors (more than five and fewer than 50) have published at least one NRI-funded paper in the area. We consider the publication record of each of these authors, looking at all papers they have published since 2000, including those that were not funded by the NRI and those published outside the target areas. The sizes of these data sets are given in Table 2.

For each research area, we fit a multilevel Bayesian logistic regression model for the probability that a given paper will be published in the area, conditional on publication year and whether the paper was NRI-funded. We partially pool the intercept term and NRI effect across authors (within a given area). By *partially pool*, we mean that we estimate intercept and NRI effects for each individual author but model these effects as draws from a common, unobserved distribution. Intuitively, partial pooling means that the author-level effects should be similar (they are connected by the unobserved distribution) but not constrained too tightly (they are not identical, for example). This allows us to make informed estimates even when a given author has only a small number of publications in the data set [13].

More precisely, our models are all specified as a generalized linear regression

$$p(y_i = 1) = \text{logit}^{-1}(\beta_{\text{year}}\,\text{year}_i + \beta_j + \beta_{nri,j}\,nri_i), \qquad (1)$$

where $y_i = 1$ indicates that publication i is in the research area, logit is the logistic function, β_{year} is a random effect for the publication year, j is the author of publication i, β_j is an intercept term (constant or baseline effect) for author j, nri_i indicates whether publication i is NRI-funded, and $\beta_{nri,j}$ is an author-specific NRI effect. In these models, the intercept term β_j can be interpreted as the probability (more precisely, the

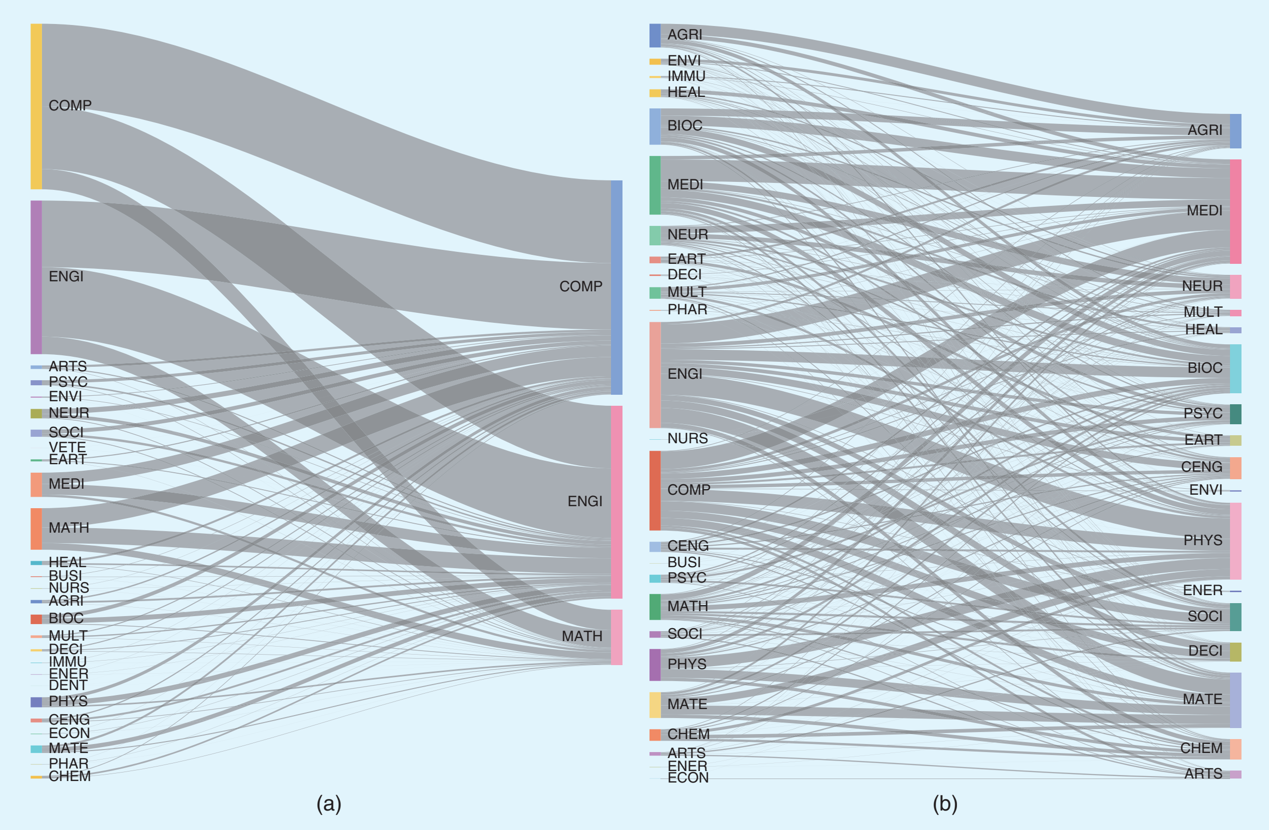

Figure 4. The citation links among research areas: (a) citation links for NRI papers in traditional robotics research areas (computer science, engineering, and mathematics); (b) citation links for NRI papers published outside traditional robotics research areas. The ribbon width represents the number of citation links between the given research areas. Ribbon widths are scaled separately between panels.

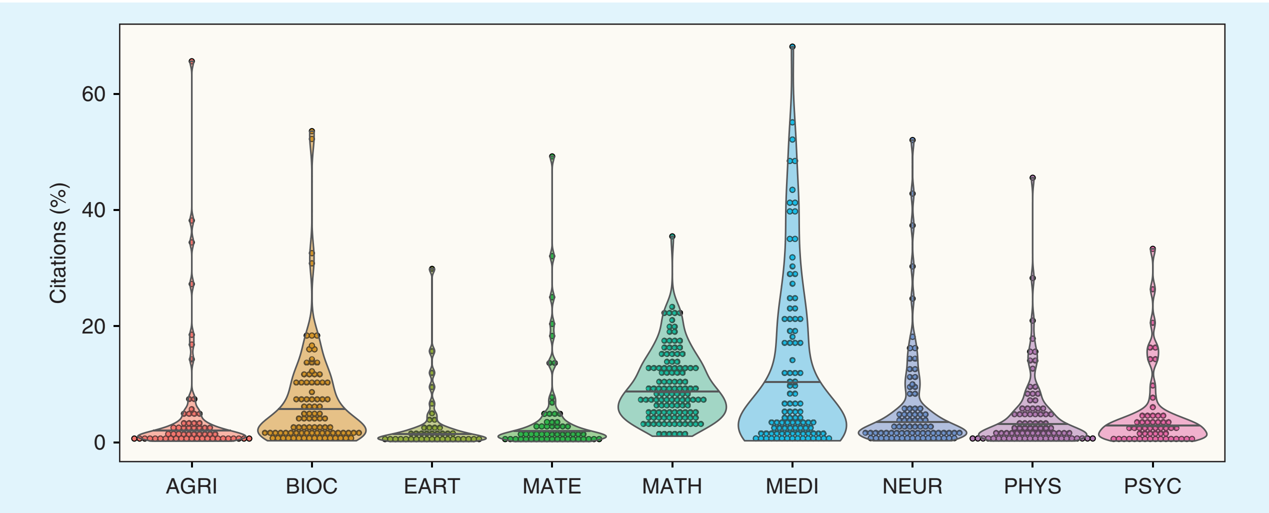

Figure 5. Citations to selected research areas. Each point represents a single NRI award; awards can be included more than once above different research areas. The point height indicates the percentage of citations from that award to previous publications in the research area. The horizontal bars in violin plots indicate medians. Awards with no citations to the research area are not included here.

log odds) that author j publishes in the given area outside the NRI program, and $\beta_{nri,j}$ is the change in this probability when author j publishes under the NRI program. Therefore, positive values of $\beta_{nri,j}$ indicate that the NRI increases publishing in the target research areas.

We fit the models independently for each of the nine research areas using the R package rstanarm as an interface to the C++ library Stan [14], [15]. For the prior distribution on the covariance matrix among the author-level effects β_j, $\beta_{nri,j}$, we used a moderately skeptical, nonuniform distribution with a mode at the identity matrix. Following Gelman and Hill [13], we evaluated the fit of these models using posterior predictive checks. We examined predictions for both individual articles and the overall publication rate in the target research area, generating posterior distributions for a number of test statistics. We found that all of the models accurately predicted the overall publication rate in their area, with a standard error of two percentage points or fewer, although the posterior distributions for decision sciences, neuroscience, and psychology were visibly non-Gaussian. At the individual article level, in almost every case, each model was highly confident (posterior probability $p > 90\%$) that it performed better than chance in terms of accuracy, sensitivity, and specificity. Decision sciences, neuroscience, and psychology were more confident than not (posterior probability $p > 50\%$) that their accuracies were better than chance, but not highly confident; all three of these models were highly confident that they performed better than chance in terms of sensitivity and specificity.

Table 2. The data sets used in each regression model.

Area	Authors	Papers in Area	NRI Papers	Total Papers
BIOC	Eight	40	50	505
DECI	13	26	65	1,310
EART	Eight	86	26	788
MATE	18	308	133	1,869
MEDI	36	358	261	2,948
NEUR	Six	24	47	716
PHYS	19	349	139	2,181
PSYC	Eight	18	52	636
SOCI	17	82	127	1,607

Paper counts refer to papers in the combined publication record since 2000 of the authors identified for each area. For example, eight authors published at least one paper in a BIOC venue; they have a combined 40 papers in BIOC, 50 papers funded by NRI, and 505 papers total.

Figure 6 shows the posterior estimates for the intercept term (β_j, top row) and NRI effect ($\beta_{nri,j}$, bottom row) for each author in each research area (columns). On the log odds scale used in Figure 5, a value of 0 means that the odds are 1:1 or that the probability is 50% that a given paper will be published in the area; a value of 2 means that the odds are 10^2:1 (100:1) or that the probability is more than 99% that a given paper will be published in the area. Values greater than 0 indicate a positive baseline/effect. They mean that the probability of publishing in a given area is greater than 50%. Values less than 0 mean that the probability is less than 50%. The dashed lines indicate odds of 1:2 (probability 33%) with the lower dashed line (1:1 at 0) and 2:1 (probability 67%) with the upper dashed line.

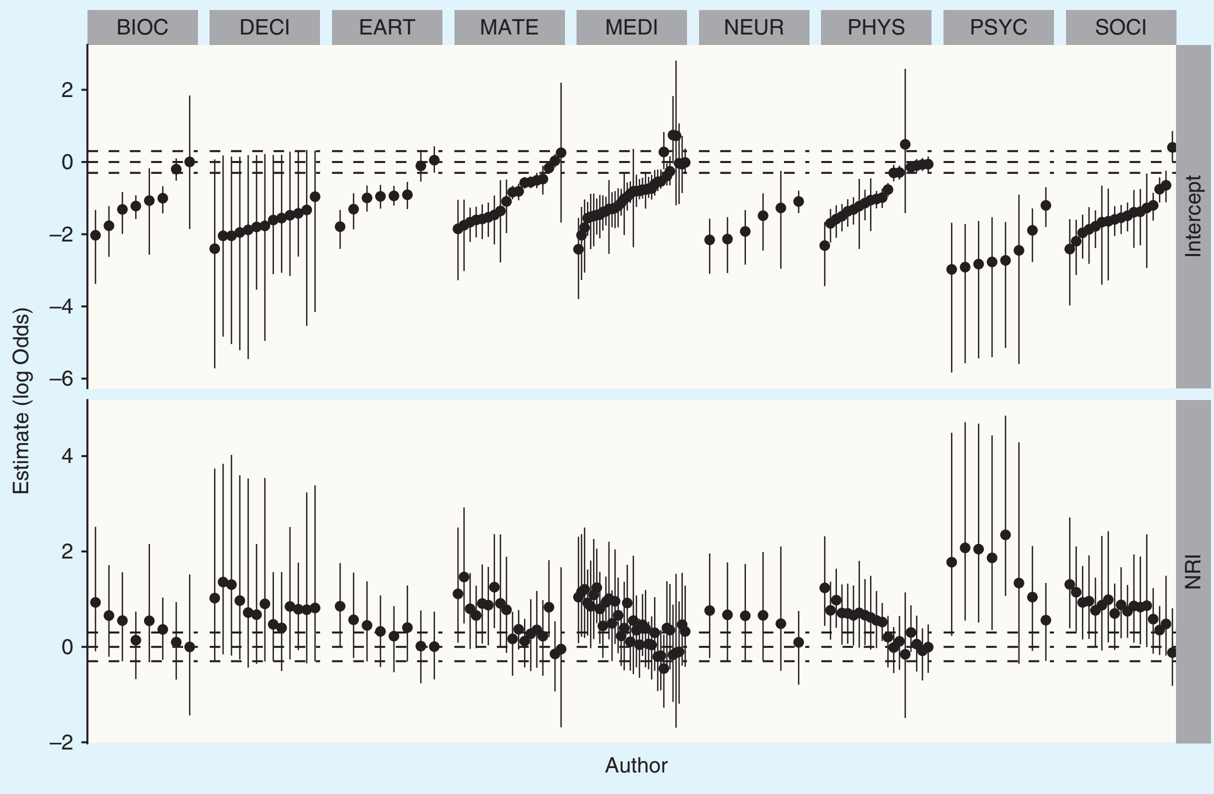

Figure 6. The effects estimates for the regression models. Posterior median and 95% credibility estimates are given for the intercept (baseline rate and upper row) and NRI effect (lower row) for each author in each of the nine research areas (columns). Within each research area, the authors are ordered (left to right) by increasing intercept; the same order is used in both rows. The estimates are given on a log odds scale (base 10).

For almost all authors across all research areas, the model is extremely confident ($p > .95$) that the intercept is less than 1:1 (below 0 on the log odds scale and within the bounds of the vertical line). This means that, outside of the NRI, almost all authors are unlikely to publish in these areas. At the same time, for many authors across the research areas, the model is confident ($p > .75$) or at least more confident than not ($p > .5$) of a positive NRI effect. In some cases, the model is confident of a substantial positive effect, corresponding to a change of 2:1 odds or greater. For several areas—most especially decision science and psychology—the model is highly confident of large effects, but the uncertainty over these estimates ranges over several orders of magnitude.

Discussion

Based on our bibliometric analysis, in its first five years of funding, the NRI has supported novel collaborations and stimulated interdisciplinary collaboration and publishing. We found that 31 pairs of NRI-funded collaborators at different institutions have never published together before (22% of all NRI-funded collaborations). Additionally, 26 NRI awards (8% of all awards) make substantial references to prior research in fields such as biology, medicine, neuroscience, Earth science, materials science, physics, and psychology. NRI-funded researchers also tend to publish more in these nonrobotics fields.

Our findings indicate that the NRI has begun to influence the robotics research community, supporting novel collaborations and interdisciplinary research. NRI 2.0's central themes—ubiquitous corobots, greater scalability and variety, and lowered barriers to robotics research—mean that the program will require still more novel and interdisciplinary collaboration. We therefore expect the trends we have identified here to continue. In addition, over the next decade, we expect that the NRI will start to have a significant societal impact as foundational research is translated into consumer products.

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