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The state of science convergence in implantable brain-computer interface clinical trials

K Michelle Patrick-Krueger[1,3,*], **Ioannis Pavlidis**[2] **and J L Contreras-Vidal**[3]

[1] Texas institute of Restorative Neurotechnology, Department of Neurology, McGovern School of Medicine, University of Texas Health Sciences Houston, Houston, TX 77030, United States of America
[2] Affective and Data Computing Laboratory, University of Houston, Houston, TX 77204, United States of America
[3] Laboratory for Non-invasive Brain-Machine Interface Systems, Department of Electrical and Computer Engineering, IUCRC BRAIN, University of Houston, Houston, TX 77204, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: KPatrick3@uh.edu

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Abstract

Objective. Advances in implantable brain-computer interfaces (iBCI) have rapidly accelerated in the last decade that promises to improve the quality of life of patients with communications, sensory, and motor control disabilities. *Approach.* In this Perspective, we quantify the extent and nature of scientific convergence across 21 research groups conducting iBCI clinical trials worldwide. Using medical subject headers and Classification of Instructional Programs taxonomies, we analyze topical and disciplinary integration within 161 publications from 1998–2023 to assess how deeply team composition aligns with research themes and translational impact. *Main Results.* Our findings indicate uneven patterns of convergence, with many teams combining engineering and clinical expertise yet omitting ethical, legal, and social dimensions. This represents what we term short-cut convergence. *Significance.* We propose an operational definition of this phenomenon and identify practical steps for researchers and funders to strengthen full convergence to accelerate iBCI translation and implementation.

1. Introduction

Over the past century, some of the most significant scientific achievements have emerged from interdisciplinary teams. Notable examples include the mastery of nuclear fission [1], the lunar landing [2], and the human genome mapping [3]. In 2014, the Brain Research Through Advancing Innovative Neurotechnologies (BRAINs) Initiative in the US and the Human Brain Project (HBP) in the EU launched substantial funding initiatives to advance neuroscience research [4, 5]. These initiatives have accelerated the development of implanted brain computer interface (iBCI) systems for individuals with communication or sensorimotor control disabilities [6].

In parallel, there has been growing interest in the field of convergent research, a broader policy and science-of-science field which describes the deep integration of multifaceted disciplines around a compelling problem [7, 8]. Unlike traditional interdisciplinarity, convergence research explicitly aims for shared conceptual frameworks that span life, physical, humanities, and social sciences as iBCIs can be best considered as a sociotechnological system with ethical and legal ramifications [6]. This distinction provides a useful lens for evaluating the maturity of emerging fields such as iBCI.

A recent knowledge integration review of clinical trials in the iBCI field identified 21 iBCI groups worldwide, 28 clinical trials, and 67 iBCI patients resulting in 161 publications from 1998 to 2023 [6]. This work shows a notable increase in clinical trials initiated after the implementation of funding initiatives, with the total number of research groups increasing five-fold and an increase in clinical trial participants of 157%, with 49.3% of all participant implantations happening between 2019–2023 and 31 participants (61% of those implanted after 2014) active at the end of 2023. Recognizing the critical role of interdisciplinarity and scientific convergence in addressing grand societal challenges, our study aims to quantify the levels of topical and disciplinary expertise represented

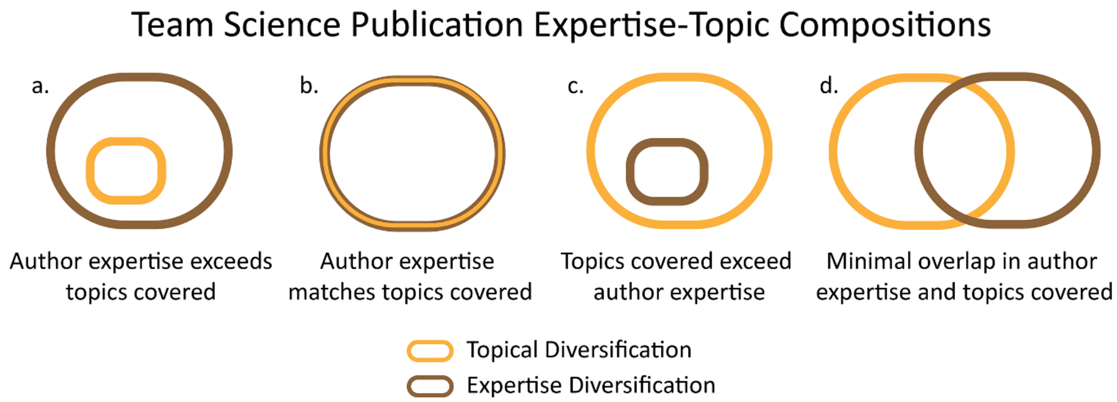

Figure 1. The types of team science publications based on author expertise and publication topics. Figures (a) and (b) representing optimal author discipline-to-publication topics configurations, with figures (c) and (d) describing sub-optimal combinations of authors and topics.

in the iBCI teams in relation to the impact of related publications as a measure of success.

This work extends previous bibliographic analysis [9, 10] by explicitly testing whether the iBCI publications reflect full convergence with deep disciplinary integration across technical, clinical, and societal domains, or short-cut convergence in which teams integrate only partially, focusing on engineering and clinical aspects while omitting ethical or translational expertise. It also evaluates the levels of sub-optimal expertise-topic compositions, assessing the levels of correlation of publication topic and author disciplinary expertise, as illustrated in figure 1. By comparing the topical and disciplinary heterogeneity with normalized citation and NIH translation metrics, we evaluate how convergence patterns related to publication impact and discuss mechanisms that promote or hinder full convergence.

2. Methodology

The convergence metrics for iBCI have been quantified based on previous work used in analyzing the Human Brain Sciences [9]. We adopted the bibliometric framework to jointly estimate topical and disciplinary heterogeneity for each peer reviewed iBCI publication [10]. This dual-axis approach captures the conceptual breadth of research topic discussed and the disciplinary range of expertise represented among the authors.

Data sources. The publication corpus comprised 161 articles identified in the 2024 knowledge-integration review [6]. Each record was validated using PubMed identifiers (PMIDs) and major U.S. National Library of medical subject headings (MeSHs) associated with the PMID, identified by an included asterisk [11]. Of the corpus, 43 did not have identified MeSH terms, thus, the NIH MeSH on Demand tool [12] was used to ensure complete topical mapping. However, the use of this tool introduces quantitative limitations as it does not assign a 'major topic' and the MeSH terms are assigned by algorithm rather than curated by expert teams. Limitations may include: higher risk of irrelevant terms, missing emerging or context-dependent concepts, no hierarchical depth control, and less interpretive nuance than expert human curators.

Topical heterogeneity. Topical heterogeneity was quantified using the hierarchal structure of the U.S. National Library of MeSHs taxonomy [11]. Each publication's major MeSH branches were used to assign topics into the six macro-domains of Anatomy & Organisms, Phenomena & Processes, Techniques & Equipment, Health, Technology & Information Science, and Psychiatry & Psychology, consistent with prior convergence frameworks.

Disciplinary heterogeneity. Author expertise was categorized using the U.S. National Center for Education Statistics Classification of Instructional Programs (CIP) codes [13]. Each author's primary disciplinary affiliation, extracted from the publication metadata, was matched to the corresponding CIP two-digit category. The resulting disciplinary profile for each paper was then compared to its MeSH-based topical profile to determine the overlap and heterogeneity.

Impact normalization and threshold definition. Publication impact was assessed using normalized citation counts derived from the NIH iCite and Scopus data queried on 10 October 2025 [14]. Citations for each paper were normalized within publication year to account for differences in exposure time. For years with fewer than 5 papers, normalization was applied at the multi-year block level to maintain statistical stability. The publications from each era (pre-2014, 2014–2018, 2019–2023) having a normalized citation values of one or greater, corresponding to greater than one standard deviation

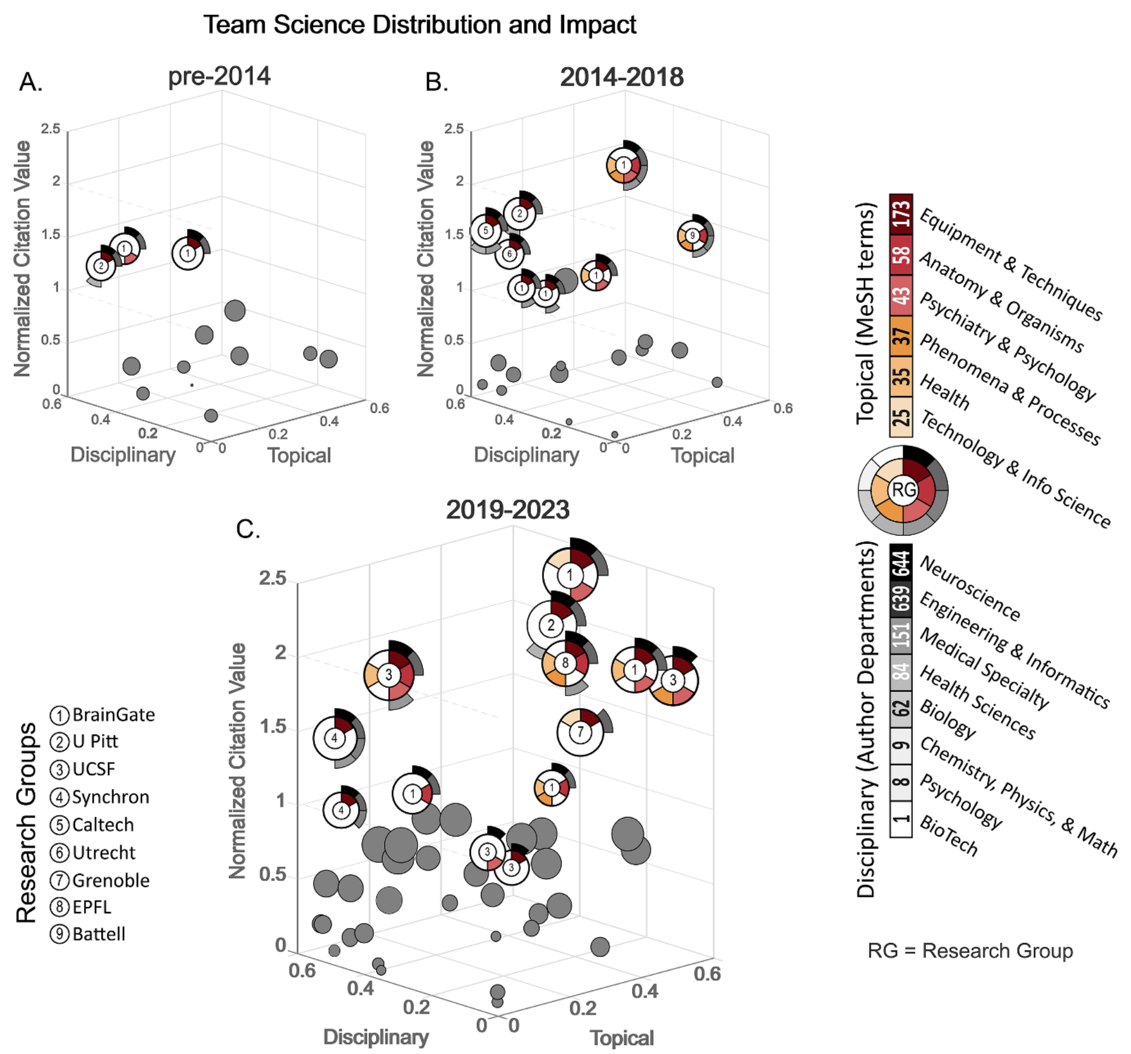

Figure 2. Level of scientific convergence in iBCI. Three periods were assessed: The time prior to the BRAIN/HBP initiatives and the early and late time segment of BRAIN/HBP research investments. Those publications with above average citation normalization values are displayed, with the disc circumference proportional to the normalized value. Those publications with a normalized citation value greater than 1 are designated 'high impact' publications, with inner discs showing the major topics covered using the categories of publication MeSH terms, and outer segments showing the disciplinary specialties of the publication authors using CIP categories for the author's institution. The publications are separated into 3 segments: (A). The era from 2000–2014, (B). The first segment of the neuroscience funding initiatives 2014–2018, and (C). The later segment of the neuroscience funding initiatives 2019–2023. The citation counts were determined using PubMed iCite on 10 October 2025.

above the norm, were designated as 'high-impact.' This cutoff provides a consistent benchmark across the eras.

Supplementary NIH metrics. The NIH provided metrics of relative citation ration (RCR), Approximate Potential to Translate (APT), and NIH Percentile Rank relative to all NIH-funded works of the same year were assessed to evaluate for the publications identified as high-impact vs the full corpus. These indicators were used to explore potential links between convergence and translational potential.

Analytic workflow. The analysis proceeded in three steps. (1) Topic-discipline matrices were constructed for each publication period to visualize integration patterns (figure 2). (2) Aggregated distributions of single- vs multi-topic papers and their corresponding disciplinary breadth were computed (figure 3). (3) Topical-disciplinary overlap was compared between the full corpus and the high-impact subset (figure 4). Publication distribution across NIH metrics were summarized (figure 5).

Interpretive framework. Following Petersen *et al* [9], publications were classified as equal disciplines when the number of disciplinary areas matched the number of topics covered, greater disciplines when author disciplines exceeded topics, and fewer disciplines when the topical range exceeded disciplinary coverage. These categories enable quantitative differentiation between full convergence and sub-optimal convergence, defined as cases where topical scope is broad but disciplinary expertise remains limited or uneven.

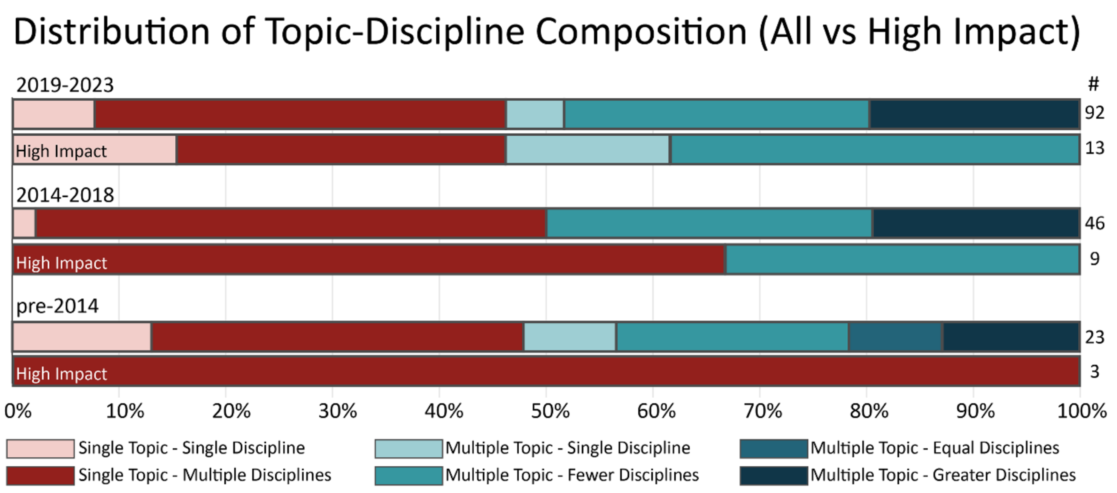

Figure 3. Comparison of the distribution of topical-disciplinary convergence between the full publication set and those identified as high impact. Single topic publications are shades of red, multi topic publications are shades of teal. For multiple topic publications, those with topics not represented by author disciplines are described as 'fewer disciplines.' Those with authors in more disciplines than topics covered by the publication are described as 'greater disciplines.' Those with author disciplines covering all of the publications topics are described as 'equal disciplines.' The numeric value on the right represents the total number of publications in the subgroup represented by the bar.

3. Results

The full set of 161 publications were included in the analysis following the successful assignment of MeSH terms using the NIH MeSH on Demand tool for those without terms assigned by PubMed [12]. This dataset spans publications from 1998–2023 and covers 21 distinct research groups conducting iBCI clinical trials worldwide. The corpus has a mean publication year of 2018 ± 4.5 with 85.7% published after 2014, reflecting the acceleration of the field following the BRAIN and HBP initiatives. The average number of authors per paper increased from 6.3 ± 3.4 (pre-2014) to 11.2 ± 6.8 (2019–2023), consistent with the growth in team-based science.

Figure 2 illustrates the results of the convergence analysis for the iBCI publications, with each disc representing a publication with greater than average impact and a circumference proportional to the normalized citation value. Publications with normalized citation values greater than one standard deviation above the mean correspond to the 'high-impact' subset used for comparative analysis throughout the Results section. The high-impact publications are highlighted in figure 2, showing detailed topical and disciplinary information. The internal segments of each identifies the publication topics covered using a red color gradient combined with radial position, while the outer greyscale radial segments represent areas of author disciplinary expertise. The inner number identifies the research group. Information on the full set of papers is summarized in figures 3 and 4.

Topical and disciplinary breadth. Among the 161 papers, 27% covered a single MeSH macro-topic, 57% covered 2–3, and 16% covered 4 or more. The average number of disciplinary areas represented among authors was 2.7 ± 1, ranging from strictly technical to transdisciplinary teams including members from medical specialties and health sciences. Across all publications, 91.7% include at least one author with disciplinary expertise corresponding to each of the publication's MeSH topics, indicating a high level of topic-discipline alignment.

Temporal Patterns of Convergence. Figure 3 compares the three eras as defined by Patrick-Krueger (2024), (A) 2000–2013, (B) 2014–2018, and (C) 2019–2023. Throughout all three eras, publications have similar topical diversities with means of 2.3 ± 1.2 topics for era A, 2.3 ± 1.3 for era B, and 2.4 ± 1.2 for era C. However, the era with the largest disciplinary breadth occurred during era B, with a mean of 3.0 ± 0.8 disciplines per publication, while era A had 2.1 ± 0.8 and era C had 2.6 ± 1.1. This may correspond to the rapid increase in iBCI clinical trials research in that era due to the implementation of the funding initiatives. The ratio of publications with greater or equal numbers of author disciplines than publication topics follows a similar trend, with 57% in era A, 67% in era B, and 58% in era C.

In comparing the high-impact publications, the topical breadth increase as the field develops, with means of 2.2 ± 1.2 for era A, 2.4 ± 1.5 for era B, and 2.5 ± 1.3 for era C. Disciplinary heterogeneity follows a similar pattern as that of the full corpus, with the greatest value occurring during era B with a mean of 3.1 ± 0.8, while era A had 2.2 ± 0.8 and era C had 2.6 ± 1.1. When evaluating the ratio of publications with author disciplines which are greater or equal in number to publication topics, the high-impact publications display a noticeable decrease, with all 100%

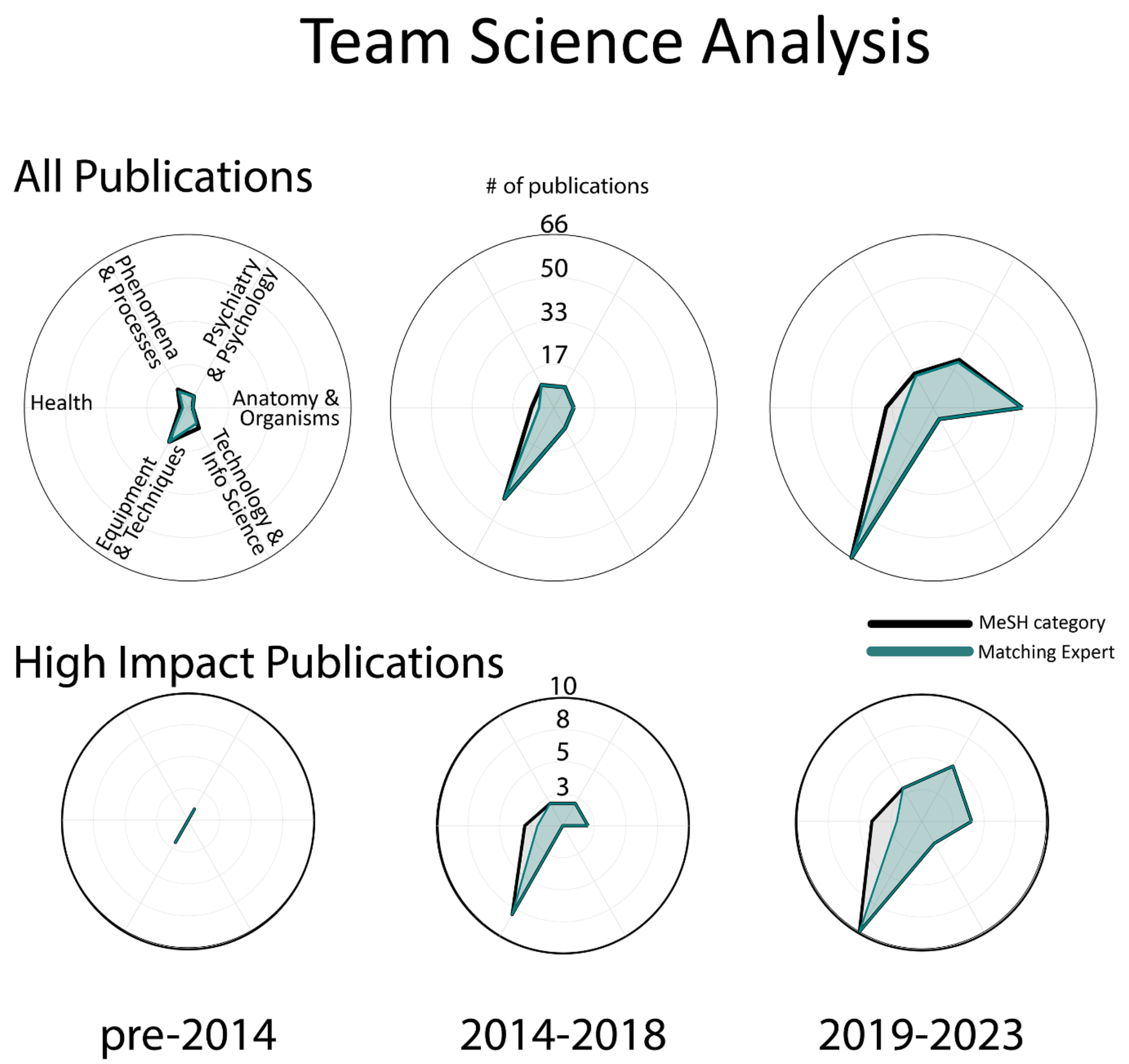

Figure 4. Team science analysis. The radar plots illustrate the prevalence of the six MeSH Categories used in the publications by plotting the number of papers with MeSH terms from each of the categories marked in blue. For each MeSH category, the red segment indicates the number of publications with author expertise matching that MeSH category. The larger radars are for all included publications, the smaller provides results for the High Impact publications.

of publications in era A, 67% in era B, and 31% in era C, which may reflect an increasing attention to progressing technical capabilities as corporations began to enter the field.

Topic-Discipline Alignment and Impact. The relationship between team composition and impact is further shown in figure 4, which summarizes the number of publications covering each major MeSH macro-topic used in the corpus, identifying those that include at least one topical expert. Both high-impact and the full publication set show a strong alignment between topical coverage and author expertise, with the most frequent topical categories being Equipment & Techniques (79% of publications), followed by Anatomy & Organisms (29% of publications).

Citation and Translational Metrics. The normalized citations for high-impact publications increase in mean, standard deviation, and maximum for each era, with values of 1.54 ± 0.16 (max: 1.70) in era A, 1.58 ± 0.28 (max: 1.96) in era B, and 1.60 ± 0.47 (max:2.42) in era C. This tracks the increasing numbers of publications per era with increasing participation and interest in the field.

Figure 5 compares the NIH metrics of the full publication set to the high-impact set. The mean normalized citation for the high-impact set is 1.59 ± 0.38 and a mean RCR of 20.67 ± 13.11, compared with the corpus normalized citation of 0 ± 1 and RCR of 5.12 ± 8.62. The average APT values (0.63 ± 0.06 for high-impact vs 0.60 ± 0.28 overall) indicate that greater convergence correlates with higher translational potential, however variance within each group underscores that convergence is one of several factors influencing impact.

Together, these results demonstrate a steady increase in topical and disciplinary convergence with iBCI research since 2014 and show that teams with more balanced coverage across domains tend to

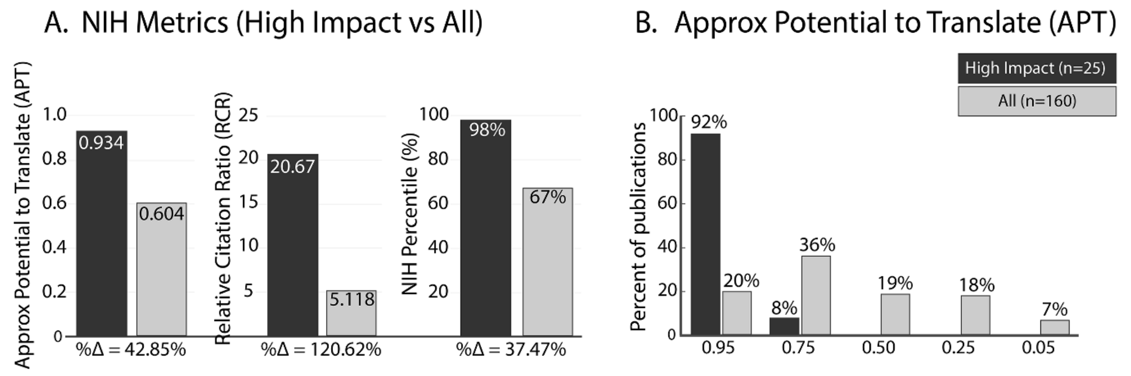

Figure 5. (A). A comparison of NIH publication metrics for high impact publications vs the full set of publications. (B). The APT score distribution for the high impact publications vs the complete set.

produce publications with higher normalized impact and translational potential.

4. Discussion

Prior research [1–3, 15] suggests that solving major societal and/or technological challenges requires teams of researchers spanning multiple disciplinary fields of expertise. Our analysis confirms that iBCI research reflects this pattern, but it also reveals analytically meaningful gaps in disciplinary integration. Although the field combines engineering, neuroscience, and clinical expertise effectively, the ethical, legal, social, and implementation-focused perspectives remain inconsistently incorporated. This imbalance underscores a form of short-cut convergence, where teams integrate around immediate technical priorities while omitting expertise needed for longer-term sociotechnical readiness.

Over 50% of iBCI publications demonstrate balanced or greater disciplinary representation relative to their topical scope (figure 3), suggesting an encouraging trend toward integrative team composition. Yet a substantial portion still exhibit fewer-discipline configurations. This quantitative pattern shows that while integrative team composition is emerging, convergence depth remains uneven. These findings highlight that disciplinary alignment rather than simply the presence of multiple disciplines is the key determinant of coherent knowledge integration.

Mechanisms and institutional constraints. Our findings align with broader convergence-science literature showing that structural barriers such as disciplinary funding silos, incentive systems, and governance misalignment, can impede sustained integration [16–21]. The uneven disciplinary composition observed across iBCI publications reflects the systemic constraint that even when funding programs promote cross-disciplinary collaborations, institutional incentives remain largely domain-specific, shaping who participates and how expertise is integrated.

Causal complexity. While convergence and publication impact are strongly correlated, causality is bidirectional. Teams with early visibility often attract additional collaborators, with the higher disciplinary variance may itself enhance novelty and citation rates. Our results indicate that convergence functions both as a driver and a consequence of impact, underscoring the need for longitudinal studies to understand how team formation dynamics shape translational outcomes.

5. Practical implications and policy recommendations

Research teams may strengthen convergence by intentionally recruiting social sciences, ethics, law, implementation science, and persons with lived experience, as well as including data-sharing plans.

Funding agencies may require explicit convergence plans that include mechanisms for cross-disciplinary leadership roles and co-training.

Regulatory bodies and payers may benefit from early engagement with convergence-structured teams to ensure usability, safety, and ethical considerations align with real-world deployment needs.

Journals and societies may further reinforce convergence by encouraging transparent reporting of author-discipline composition and recognizing contributions from non-traditional collaborators.

6. Limits and future directions

This analysis relies on the bibliometric proxies of MeSH terms and CIP classifications that cannot fully capture informal, emerging, or interdisciplinary expertise. Notably, the MeSH on Demand tool increases the probability of returning irrelevant terms, does not provide a ‘major’ designation, may under-index nascent topics, and does not provide the nuanced understanding of the expert human curators determining the MeSH terms assigned by PubMed. In addition, the corpus is limited to clinical-trial publications, which may underrepresent the inclusion of ethical, legal, or sociotechnical work. In addition, the corpus is limited to clinical-trial publications, which may underrepresent the inclusion of ethical, legal, or sociotechnical work. Future studies should incorporate qualitative or network analytic approaches to better characterize how convergence unfolds at the team and institutional levels.

Toward full convergence in iBCI. Scientific convergence in iBCI research has steadily increased over the past 25 years, particularly as translational goals have become more prominent. Recent coordinated actions by industry, academia, and regulatory agencies reflect growing recognition of the need for broader expertise, including legal, ethical, user-experience, and lived-experience perspectives, with the 2024 organization of the iBCI collaborative community being a notable example. Yet our findings show that full convergence across technical, clinical, and societal domains has not yet been realized. This gap may restrict translation and contribute to the persistent ethical, cultural, and sociotechnological challenges noted in recent reviews of iBCI clinical trials.

7. Conclusion

In summary, our analysis shows iBCI research exhibits increasing but uneven convergence, with persistent gaps in societal and translational expertise. The core contribution of this work is an empirically grounded characterization of short-cut versus full convergence, offering a framework for diagnosing where integration is advancing and where it remains incomplete. Looking forward, intentional structural and institutional support for deeper cross-domain integration, including expertise in the ethical, societal and cultural implications of iBCIs, will be essential for realizing the responsible and effective translation of iBCI technologies.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:. URL/DOI: https://doi.org/10.1038/s44222-024-00239-5.

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Conflict of interest

The authors report no conflict of interest.

Data access

The publications used to perform this study are contained in Reference 4, with the list contained in Supplementary Information, Table 1.

Ethics statement

This study did not use human subjects therefore did not require an ethics review.

Author contributions

K Michelle Patrick-Krueger 0000-0001-5207-2020
Writing – original draft (lead), Writing – review & editing (lead), Formal analysis (lead), Investigation (lead), Software (lead), Visualization (lead), Data curation (lead)

Ioannis Pavlidis 0000-0001-8025-2600
Methodology (supporting), Validation (supporting), Writing – review & editing (supporting)

J L Contreras-Vidal 0000-0002-6499-1208
Methodology (supporting), Validation (supporting), Writing – review & editing (supporting), Funding acquisition (lead)

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