

This is a “preproof” accepted article for *Journal of Clinical and Translational Science*.

This version may be subject to change during the production process.

10.1017/cts.2025.11

Connecting the Bibliographic Directed Citation Networks of Translational Research and Implementation Science

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Conflicts of Interest: Andrew Quanbeck has a shareholder interest in CHES Mobile Health, a public benefit corporation that disseminates technology to the specialty addiction treatment system. Dr. Quanbeck also provides consulting on implementation research through the non-profit NIATx Foundation. These relationships between the author and CHES Mobile Health is managed by the authors and the University of Wisconsin–Madison’s Conflict of Interest Committee. All other authors declare they have no competing interests.

Funding statement: Dr. Quanbeck, Dr. Hennessy Garza, and Ms. Burns received indirect funding supported by 1R01DA047279-01 NIH/NIDA. Dr. Mahoney and Dr. Quanbeck received indirect funding support by 1UL1TR002373-01 NIH/NCATS. The authors received no direct financial support for the research and authorship of this article.

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Introduction

Translational science and implementation science are two disciplines that focus on moving scientific knowledge from discovery into practice within healthcare organizations and public health. Translation is defined by the National Center for Advancing Translational Science (NCATS) as “the process of turning observations in the laboratory, clinic, and community into interventions that improve the health of individuals & the public [1],” and translational science is “the field of investigation which seeks to understand the scientific and operational principles underlying each step of the translational process [1].” Implementation is defined by the National Institutes of Health as, “the adoption and integration of evidence-based health interventions into clinical and community settings for the purposes of improving delivery, outcomes, and individual & population health [2],” and implementation science is “the scientific study of methods to promote the systematic uptake of research findings and other evidence-based practices into routine practice, and, hence, to improve the quality and effectiveness of health services [3].”

Together, translational and implementation sciences aim to bridge the gap between what *works* to address health and what is *done* to address health. Scientific inquiry using these overlapping disciplines remains essential to address the gap between the creation of clinical knowledge and its integration into healthcare. Bridging translational science and implementation science may facilitate improvement in health care delivery. These fields connect within NCATS’ translational science spectrum, a non-linear model depicting the progression of research from basic sciences to interventions that improve health [4]. Key stages of the spectrum include clinical implementation of health interventions and public health. These stages link implementation science directly to translational science, with implementation research considered one stage of translational research while also informing additional stages.

A progression of efforts to advance implementation science and translational science has occurred over the past 20 years. Since 2001, numerous financial contributions and grants have been made available for clinical implementation research [5], increasing knowledge production and helping to facilitate the launch of the journal *Implementation Science* in 2006 [3]. Beginning in 2010, components that influence the scale-up of evidence-based interventions across health systems were incorporated into the US Department of Health and Human Services strategic plan [6]. Currently, implementation science has been formally integrated in over half of the Clinical

and Translational Science Award recipients (CTSA hubs), with 34 hubs represented on the *Dissemination, Implementation, and Knowledge Translation Working Group* as of 2019[7] and continued recommendation by scholars to continue this trend [8]. The national working group *Advancing Dissemination and Implementation Sciences within CTSA*s advances translational research in CTSA hubs through capacity building to incorporate principles and strategies of implementation science [9]. In July 2020, the *Journal of Clinical and Translational Science* released its first themed issue highlighting implementation science to advance translational research [10]. Reflecting federal priorities, in July 2021 the funding award PAR-21-293 required all CTSA hubs to actively engage in implementation activities [11]. These and additional efforts are highlighted in Figure 1.

Our study examines the literature that connects translational science and implementation science to assist leaders at medical research centers throughout the U.S. implement their research findings into clinical practice. This work builds upon recommendations by McKibbin et al [12], who highlighted the need for easier access to literature across disciplines for knowledge translation to progress. The aim of this paper was to examine the bibliographic bridge between the sciences of translation and implementation by 1) determining key inter-connected literature in each field; and 2) documenting bridging publications between fields while quantifying the overlap of scientific inquiry within translational science and implementation science. Our overarching goal was to increase our understanding of how these two fields are connected in the literature by presenting a more visual, numeric, and tangible understanding of overlap and separation between the research fields and authors. Recognizing bibliographic overlap can provide resources to scholars in both fields to help cultivate a more cohesive academic community working in less isolation and more unity to streamline and share lessons learned in knowledge translation.

Materials and Methods

We used directed citation network analysis to create directed citation network maps of publications in translational science, publications in implementation science, and a combination of these publications to examine overlap in the literature of the two fields. While the overall aim of our paper differs in scope, our methodology parallels the work of Fort et al [13] to connect highly inter-cited literature within translational research. We expanded upon their work to examine connections between translational science and implementation science literature. Our

methods included four main components: (1) a systematic search to obtain literature in translational science and implementation science; (2) directed citation network analysis to create directed citation network maps that connect publications through shared citation links; (3) construction of heat maps to visually display global citation data for the most cited publications within translational science and implementation science; and (4) a quantitative comparison to assess interconnections between translational science and implementation science via citation links..

Systematic literature search

To obtain publications in translational science and implementation science we used identical search terms by Fort et al. [13] for translational science and adapted the search terms by Davis & D’Lima [14] for implementation science. Using database filters, articles, review articles, books, or book chapters published within 2022 or any year beforehand were identified in *Web of Science* by searching for key terms in the title, author-selected keywords, or Keywords Plus, which are words or phrases that frequently appear in the titles of an article’s references [15]. The translational science search yielded 6,111 publications of articles, reviews, books, and book chapters using identical search terms from Fort et al [13]: “translational science*” OR “clinical and translational science*” OR “CTSA*” OR “translational research” OR “translation research” OR “clinical and translational research” OR “translational medicine.” For each search term, we used the same proximity operator by Fort et al. [13] to find records where the terms were within five words of each other (ie- “translational NEAR/5 medicine” OR “translational NEAR/5 research). The proximity operator was added to yield the most comprehensive search of the field within the literature (i.e.- to capture an article entitled “The science of implementation”). All publications were included and no additional screening was employed.

The implementation science search yielded 7,003 articles, review articles, books, and book chapters using adapted implementation science search terms from a systematic review by Davis & D’Lima [14]: “implementation research” OR “implementation science*” OR "improvement research" OR "improvement science" OR "dissemination science" OR "knowledge mobilisation" OR “knowledge translation.” We expanded the search by adding the NEAR/5 proximity operator to mirror the translational science search (ie- “implementation NEAR/5 science”). Two terms from Davis & D’Lima’s [14] search were omitted: “knowledge

transfer” was excluded as our focus was on health science and related literature, and the addition of this term yielded literature in business, management, computer science, and information technology. “Quality improvement” was excluded because it led to a vast literature with publications beyond the scope of implementation, including specific medical recommendations and guidelines that lacked an implementation focus. “Knowledge translation” was included as it was described by Davis & D’Lima [14] as a related and synonymous term for implementation science.

In this study we were interested in the *science* of translation and the *science* of implementation, as compared to translational research or implementation research. Since the seminal paper by Austin [1], the National Center for Advancing Translational Sciences (NCATS) has made a clear distinction between translational research and translational science – with research defined as “the endeavor to traverse a particular step of the translation process for a particular target or disease,” while science “seeks to understand the scientific and operational principles underlying each step of the translational process” [1]. Conclusively, translational research studies one disease/target while translational science focuses on applications in translation for any disease, such as common causes of inefficiency or failure in translational research projects [1]. Similarly, implementation science is the overall study of methods to promote the systematic uptake of research and evidence-based practices into practice [3], while implementation research seeks to understand processes and factors associated with the successful integration of specific research and evidence-based practices within a particular setting [16]. While the distinction in terminology has improved in recent years, historically many authors used the terms ‘science’ and ‘research’ interchangeably. Therefore, we included both search terms (science and research) in our literature search.

Directed citation network analysis

Citation data were obtained from the *Web of Science* title of each paper. The program *VosViewer* [17] was used to identify citation networks of publications that cite each other. A citation network is a structure of linked academic publications that uses citations from one document to connect to another. Per recommendations by Van Eck & Waltman [18], we used *VosViewer’s* default association strength normalization method within all constructed networks to normalize the strengths of the links between our publications [17]. Our directed citation

network maps showed *citation links* between publications, with a connecting line or link occurring when one publication cited another in the group [17]. Each publication was represented by a circular node, with node size representing the frequency of citation links between one publication and another. *VosViewer* mathematically assigns each publication to a cluster with a different color. Clusters are sets of documents included in the directed citation network map that are substantially more connected to each other compared to others in the group, with each publication belonging to only one cluster at most.

Three total directed citation network maps were constructed. The first and second directed citation network maps examined publications in translational science (Figure 2a) and implementation science (Figure 2b), respectively. All publications obtained in the literature search for each respective topic were used to create each directed citation network map. To compare the citation linkages between publications in translational science and implementation science, a third directed citation network map was created, which combined all publications from the literature searches in translational science and implementation science (Figure 3).

Heat maps of global citations

Two heat maps were constructed to visually indicate how frequently the 50 most cited papers in each field were annually cited. One heat map was created for implementation science and the other for translational science. Citations were tabulated from Web of Science and were presented annually and in cumulative totals through the end of 2022. Global citations arose from anywhere in the literature and are not limited to the directed citation network maps. Heat maps use color to represent higher values of data with darker colors and lower values with a lighter color, making it easier to detect patterns in the data [19,20]. The light-colored yellow boxes indicated less citations while dark-colored red boxes indicated more citations.

Percent change in citation links

To provide an understanding of how the most cited literature overall is cited in either translational science, implementation science, or among both fields, additional data were included in the heat maps. The number of citation links between each of the top 50 publications was provided to show the field-respective links in each directed citation network map and the number of links in the combined directed citation network map. The change in links was then calculated to demonstrate the percent increase in citation links. For example, a hypothetical

publication in translational science might be cited 1,000 times in the overall literature. There may be 400 citation links between this article and others in the translational science directed citation network map. When examining the article in the combined directed citation network map, there may be 450 citation links, demonstrating an additional 50 citation links between translational science and implementation science for this publication. This would translate to a 12.5% increase in this fictitious example.

Results

Separate citation networks

Figure 2a depicts the directed citation network map for translational science and Figure 2b depicts the directed citation network map for implementation science. The citation network of 6,111 possible publications in the search pool for translational science had a largest component that included 2,360 publications. Only these 2,360 were included in the analysis and the other 3,751 publications were not assigned to a cluster, following the analysis and reporting provided by Van Eck & Waltman, the developers of the VosViewer program used for the analysis and visualization [21]. (A publication is only included in the map if it is cited by another publication or cites another publication within the network.) There were 4,894 links, or shared citations, between the included publications. The largest nodes were publications that have the most citation links to others in the network and included Khory et al. [22] (n=118 links), followed by Rubio et al. [23] (n=101 links), and Harris et al. [24] (n=92 links) (See Supplementary Material Appendix A1 for the 50 most linked publications in this directed citation network along with total citations for each publication). Khory et al. [22] presented a four-phase framework for the continuum of translational research in genomics (i.e.- phase 1 through phase 4). Rubio et al. [23] considered the needs for a workforce in translational research, posited objectives for trainees, and provided considerations for evaluation of training programs. Harris et al. [24] was the seminal article describing the research electronic data capture program (REDCap) used to collect, store, and analyze data.

In Figure 2b, the citation network of 7,003 possible publications in the search pool for implementation science had a largest component that included 5,754 publications. Only these 5,754 were included in the analysis and the other 1,249 publications were not assigned to a cluster. There were 25,367 links between the included publications. The largest nodes in the network were publications by Damschroder et al. [25] (n=1,277 links), followed by Graham et al.

[26] (n=969 links), and Proctor et al. [27] (n=561 links) (See Supplementary Material Appendix A2 for the 50 most linked publications in this directed citation network along with total citations for each publication). Damschroder et al. [25] presented the development of the Consolidated Framework for Implementation Research (CFIR). Graham et al. [26] provided definitions for terminology related to moving knowledge into action and presented a conceptual framework to integrate knowledge creation with application. Proctor et al. [27] presented eight implementation outcomes to assist in the evaluation of implementation differently from service system or clinical treatment outcomes.

Combined Analysis: Comparing translational science and implementation science

As an aim of this study was to explore citation linkages between implementation science and translational science, all publications from the translational science literature search and implementation science literature search were combined to create a directed citation network map. In Figure 3, the citation network of 12,988 possible publications had a largest component that included 8,247 publications. Only these 8,247 were included in the analysis and the other 4,741 publications were not assigned to a cluster. Previously, there were 4,894 links in the translational science directed citation network map and 25,367 links in the implementation science network. The combined network yielded 31,400 citation links among the 8,247 publications that cited or were cited by at least one other publication in the combined pool, representing a 3.76% increase in linkages when combining the literature from the two separate fields. The visual representation within the combined directed citation network map depicts the publications in two larger groups that mirror the separate directed citation network maps for translational science from Figure 2a (solid-line circle in Figure 3) and implementation science from Figure 2b (dotted-line circle in Figure 3). While publications were more likely to be situated closer to those in their originating directed citation network, the visualization shows publications in the implementation science group that linked with publications in the translational science group, and vice versa.

Citation frequency

Two heat maps were created. The first included the top 50 most cited publications from the translational science literature search. The second included the top 50 most cited publications from the literature search for implementation science.

Figure 4 depicts the heat map of the top 50 overall most-cited publications from the translational science literature pool (See Supplementary Material Appendix A1 for the 50 most linked publications in the translational science directed citation network of Figure 2A along with total citations for each publication). In total, the 6,111 translational science publications were cited 182,747 times. The top 50-most cited publications were cited 51,173 times, with a median of 356 citations per publication (min=247, max=23,253). The top most cited publications were Harris et al. [24] (n=23,253 citations) and Harris et al. [28] (3,372), two publications that describe the research electronic data capture (REDCap) and the REDCap consortium. Seok et al. [29] (n=2,040 citations), the third most cited publication, demonstrated a poor correlation in genomic responses between mouse models and human inflammatory diseases. Five additional publications were cited more than 1,000 times, including Hoojimans et al. [30], Bellg et al. [31], Morris et al. [32], Meyer-Lindenberg et al. [33], and Workman et al. [34].

Figure 5 depicts the heat map of the top 50 most-cited publications from the implementation science literature search pool (See Supplementary Material Appendix A2 for the 50 most linked publications in the translational science directed citation network of Figure 2B along with total citations for each publication). In total, the 7,003 publications were cited 156,363 times. Overall, the 50 most-cited publications were cited 41,635 times, with a median of 474 citations per paper (min=255, max=5,799). Damschroder et al [25] was the most cited paper within the group (n=5,799 citations), followed by Palinkas et al. [35] (n=2,950), and Proctor et al. [27] (n=2,619). Palinkas et al. [35] reviewed purposeful sampling strategies in implementation research and provided recommendations for mixed methods research. Eight additional publications were cited more than 1,000 times, including Graham et al. [26], Cane et al. [36], Curran et al. [37], Nilsen et al. [38], Powell et al. [39], Morris et al. [32], Grimshaw et al. [40], and Cooper et al. [41].

Interconnections between translational science and implementation science via citation links

To quantify the overlap in citation links of publications between fields, we included three data points each for the top 50 most-cited publications in both translational science and implementation science. (1) At the end of the Figure 4 heat map (of the top 50 most cited translational science publications), the number of citation links in the translational network from Figure 2a was included. (2) The number of citation links for each publication in the combined

network in Figure 3 was listed next. (3) The percentage change was calculated between the citation links in the translational science directed citation network map and the combined directed citation network map. For example, the first article in the heat map of Figure 4 is Harris et al. [24]. This article was cited 23,253 times anywhere in the global literature: (1) It shared 92 citation links with other publications in the translational science directed citation network map, and (2) it shared 209 citation links with publications in the combined directed citation network map. (3) The additional links to implementation science publications represented an increase of 127.2%. The same process and calculation of percent change was repeated for the implementation science heat map in Figure 5.

In the translational science heat map (Figure 4), 21 of the 50 publications did not have any citation links in either directed citation network map. This signifies that while these 21 publications are cited highly in the overall literature, they are not cited by or citing other publications included in the translational science or implementation science search pool (based on our search criteria). This suggests that 42% of the top cited publications in translational science are being cited by disciplines other than translational science or implementation science. Seven of the top 50 publications from the translational science search pool had over a 100% increase in citation links when combined with publications from the implementation science search pool: Braithwaite et al. (1300% increase) [42], Glasgow et al. [43] (400% increase), Morris et al. [32] (324% increase), Bellg et al. [31] (200% increase), Moore et al. [44] (150% increase), Harris et al. [28] (133% increase), and Harris et al. [24] (127% increase). The remaining publications in the translational science heat map (n=22) had a 2.4% average percentage increase in citation links when combined with the implementation science publications in the combined directed citation network map (mode=0%, median=0%, max=16.7%).

From the implementation science heat map (Figure 5), only two publications were not included in the implementation science directed citation network map. One of these publications, Moritz & Woodward [45], lacked citation links with other implementation science publications, but gained one citation link when combined with the translational science literature. McGaghie et al. [46] was the only publication with a 100%+ increase in citation links between the implementation science directed citation network map and the combined directed citation network map (from n=4 citation links to n=10 citation links). The remaining publications in the

implementation science heat map (n=47) had an average percentage increase of 3.3% in citation links when combined with the translational science literature (mode=0%, median=1.2%, max=26.2%).

Discussion

This paper examined the most highly cited publications within and across implementation science and translational science to assess shared links, identify top cited publications, and understand how the literature is connected. While previous studies have used citation network analysis to assess other aspects of these fields [47,48], this study was novel in using directed citation network analyses to identify the extent to which publications in implementation science and publications in translational science were linked through citations. Our study provides a contribution to the scant literature assessing the relationship between translational and implementation sciences. Leppin et al. [49] proposed an integrated framework to characterize how implementation science is situated within translational research while Mehta et al. [8] explored the relatedness of the fields from a practical standpoint, but neither publication provided a quantifiable analysis to examine the degree of relatedness as seen in citations of the literature between the two fields.

Overall, when publications from the translational science and implementation science literature were merged within a combined directed citation network map, we found shared citation links between fields, but were still able to identify two groupings of publications, one derived from translational science keywords and one from implementation science keywords (Figure 3). Our results demonstrated mostly small percentage increases in citation linkages among (1) commonly cited articles and (2) when combining the individual literature in translational and implementation science to create a combined directed citation network map (<4%). However, there were cases of commonly cited publications with greater increases in the percentage of linkages across fields, some with percent increases in citation links over 100% ([24,28,31,32,42–44,46].

We interpret these findings to suggest there is modest bibliographic overlap between the fields based on authors citing each other.

There are two clear examples of publications that are highly cited in the combined directed citation network map that arise from the literature in both translational science and implementation science. Harris et al. 2009 [24] is a centralized node in the combined directed

citation network map that discusses the REDCap tool used in implementation and translational science research. REDCap is an example of how a tool, methodology, or framework that is highly relevant for translational research is also highly relevant for implementation research.

A second publication that is well cited in translational science and implementation science is Morris et al. [32]. This is a top cited publication in both fields. The title, “The answer is 17 years, but what is the question: understanding time lags in translational research,” directly pertains to translational research but references the 17 year-gap, which clearly emphasizes implementation science. In contrast to the REDCap article, which addresses a widely recognized tool used across numerous scientific disciplines, we find that Morris et al. [32] conceptually links fields and highlights shared concerns across translational science and implementation science. While Harris et al. [23], Morris et al. [32], and six other publications [28,31,42–44,46] from among the top 50 cited publications in each separate scientific field demonstrated a large increase in citations among the combined citation network (>100% increase), many publications do not share any citation links between fields: 76% of the top 50 cited publications in translational science and 36% of the top 50 cited publications in the implementation science network reported no increases in citations when combined (this includes articles with no original linkages within their own networks)

Finally, the comparison of the separate heat maps and citation networks provided additional information on the state of these fields for consideration. Implementation science publications were more interconnected than were translational science publications based on (1) how many publications cited each other within each field and (2) how many shared links there were between fields: (1) 82.2% of publications in the implementation science directed citation network map cited each other (n= 5,754 publications from a pool of 7,003) compared to only 38.6% of publications from the translational science directed citation network map (n=2,360 publications from a pool of 6,111). (2) Implementation science publications shared over five times as many citation links as translational science publications (n= 25,367 implementation science links; n=4,894 translational science links). One possible explanation for fewer connections within the translational science citation network may be the wide range of research that falls within translational research. Less interconnectedness in translational science, compared to implementation science, may also be explained by Van der Laan et al [50], who states it is misleading to label all translational activities as one field, because “it suggests that it

would suffice to perform and stimulate one type of research” to accomplish all translational aims. In contrast, implementation science in general has dealt with the later stages of research in the translational research spectrum and therefore may be expected to have a more interlinked literature.

In summary, this study adds to what is known about the literature on the inter-relatedness of citations in translational and implementation sciences [10]. We see room for growth between shared citation links in the academic literature of translational science and implementation science to align the fields together more strategically [49].

Implications

Our study brings into question what a successful benchmark would be to represent useful integration between translational and implementation sciences based on directed citation network analysis. Unlike a methodology such as a meta-analysis that can estimate the strength of an association [51], we do not expect to see 100% increases in citations across every publication, as translational science and implementation science are not identical fields. Further, there will always be literature that is critical to advance specific research topics but is less relevant to the overall fields of translation and implementation, such as “Exosome Theranostics: Biology and Translational Medicine” [52], the 15th most cited publication in our translational science literature search. However, highlighting publications that are highly cited in both search pools and identifying publications that could be applicable across fields to share tools and lessons learned could help bridge important gaps and keep the fields from developing in academic isolation.

With the July 2021 release of funding award PAR-21-293, which requires all CTSA hubs to actively engage in implementation activities, among others, this publication is timely. We believe that enhanced collaboration between translational science and implementation science can increase the efficiency of these fields to develop and translate health healthcare innovations into practice. Expanded integration of implementation science within CTSA hubs is one critical step to help accomplish this mission, in line with the recommendation by Leppin et al [49] that implementation science should be an integral sub-science of translational science [8]. Guided by Mehta et al [8], we reinforce and expand upon three recommendations made by Hwang et al [53] to advance the mission of the CTSA program using implementation science:

- 1) *Integrate implementation methods and designs into CTSA hubs' existing processes that support translational research.* Our study highlights key publications of interest in implementation science that could provide opportunities for integration within translational science, including work that outlines common implementation theories, models, and frameworks [25,36,54–57]; assists in the selection and use of these in practice [38,58]; provides considerations for research design and methodology in the field [35,37,59,60] [44]; and highlights outcome and evaluation metrics [27,61–63]. Publications providing information on implementation strategies and how to select them are also available for integration into CTSA hubs [39,64–66]. This literature can assist CTSA hubs to find and utilize tools from implementation science more easily.
- 2) *Lead the advancement of implementation science through collaboration.* Hwang et al [53] focus on collaboration of implementation scientists with other NIH institutes. We also acknowledge the need for partnerships across disciplines, institutes, and stakeholders to maximize the usefulness of implementation science in CTSA hubs [8,53,67]. Implementation publications focused on specific clinical application areas can assist with partnerships in specific areas, for example, mental health services [68,69] or education [61,70]. Lessons learned in participatory research [71,72] may assist in collaboration across institutions and provide assistance on centering patients and end-use stakeholders in translational research. Publications across both fields also provide different perspectives to navigate shared challenges, such as complexity [42,73,74].
- 3) *Provide training in implementation science.* Top cited literature in implementation science provides key background knowledge and training for audiences new to implementation science. Publications by Straus et al. [75] and Rabin et al.[16] define common terminology in implementation science, providing key foundational concepts. Additional publications provide guidance for specific goals, such as improving guideline use [57] or policy implementation [76]. Training in translational research [23] can be modified to incorporate implementation science. One particular opportunity for integration may be the provision of implementation science seminars for KL2 scholars run by CTSA hubs, which currently happens at some universities.

Limitations

Our study results are limited to publications we obtained from a Web of Science search for titles, keywords, or Keywords Plus that represent terms commonly associated within translational science and implementation science. In our initial search we did not include the term “research” in any search terms. However, we found that many scholars have previously used “research” and “science” interchangeably and that it was necessary to include the terminology for “translational research” and “implementation research” to obtain a wide breadth of articles that also discuss science. Other publications in these fields may not include our search terms in their titles, keywords, or Keywords Plus and may have been excluded. Further, we conducted our review based on search terms from previous scholars, but misclassification of articles may still have occurred due to inconsistent use of terminology and imperfect search filters in implementation and translational sciences [16,77]. Publications that are not indexed in Web of Science would not have been obtained in our literature search, potentially excluding pertinent literature of interest. Our study was subject to a limitation that impacts all bibliographic research, i.e. citation network “lag,” in which newer publications have less time to accumulate citations. In addition to lags, a lack of normalization of citation data can lead to bias; this is particularly true for the heat maps assessing the most-cited literature overall within each field. The directed citation networks in our study used a normalization method to help correct for these issues as a preliminary start, but future research could expand this work with more advanced techniques that involve indirect citations and bibliographic coupling [78], or new metrics like *weighted direct citations* that integrate direct citations with references and co-citations [79]. Within VosViewer, we were limited to use the “largest component” for analysis within our networks, and future work would benefit from the “main component” to address the boundary specification issue in network studies. Despite these potential limitations, this study provided an initial and novel visual manner to assess citation overlap between the fields of implementation science and translational along with a quantifiable perspective of how the academic disciplines intersect in the literature.

Conclusions

Translational science and implementation science are two disciplines that aim to integrate scientific findings into healthcare and public health. As our findings show, the disciplines overlap bibliographically across some publications, with opportunities to increase citation links

across fields. Our network analysis reinforces the established notion that translational science and implementation science are conceptually integrated, and that there is continued opportunity for collaboration between authors in the two fields. Future research could also assess clustering of bibliographic directed citation network maps within these fields to explore connectedness, themes over time, and further leverage opportunities for collaboration. We hope this paper provides a continued platform to support bibliographic integration of the two fields, shares resources to further this effort, and advances collaboration to subsequently improve clinical practice and the public's health.

Disclosures

Dr. Quanbeck, Dr. Hennessy Garza, and Ms. Burns received indirect funding supported by 1R01DA047279-01 NIH/NIDA. Dr. Mahoney and Dr. Quanbeck received indirect funding support by 1UL1TR002373-01 NIH/NCATS. The authors received no direct financial support for the research and authorship of this article. Andrew Quanbeck has a shareholder interest in CHESS Mobile Health, a public benefit corporation that disseminates technology to the specialty addiction treatment system. Dr. Quanbeck also provides consulting on implementation research through the non-profit NIATx Foundation. These relationships between the author and CHESS Mobile Health is managed by the authors and the University of Wisconsin–Madison's Conflict of Interest Committee. All other authors declare they have no competing interests.

Author contributions statement: Dr. Andrew Quanbeck is the senior author and conceptualized the overall paper, provided background information and key considerations for the discussion, and conducted substantial revisions. Dr. Rose Hennessy Garza is the first author and conducted the data analysis, wrote the main body of the paper, and led paper revisions. Dr. Jane Mahoney provided initial feedback to the original paper contribution, provided key insights into the background and interpretation of findings in the discussion, and thoroughly reviewed and revised the original manuscript and revisions. Morgan Burns created data figures, and assisted with references, citations, editing, and overall feedback on readability to improve the manuscript.

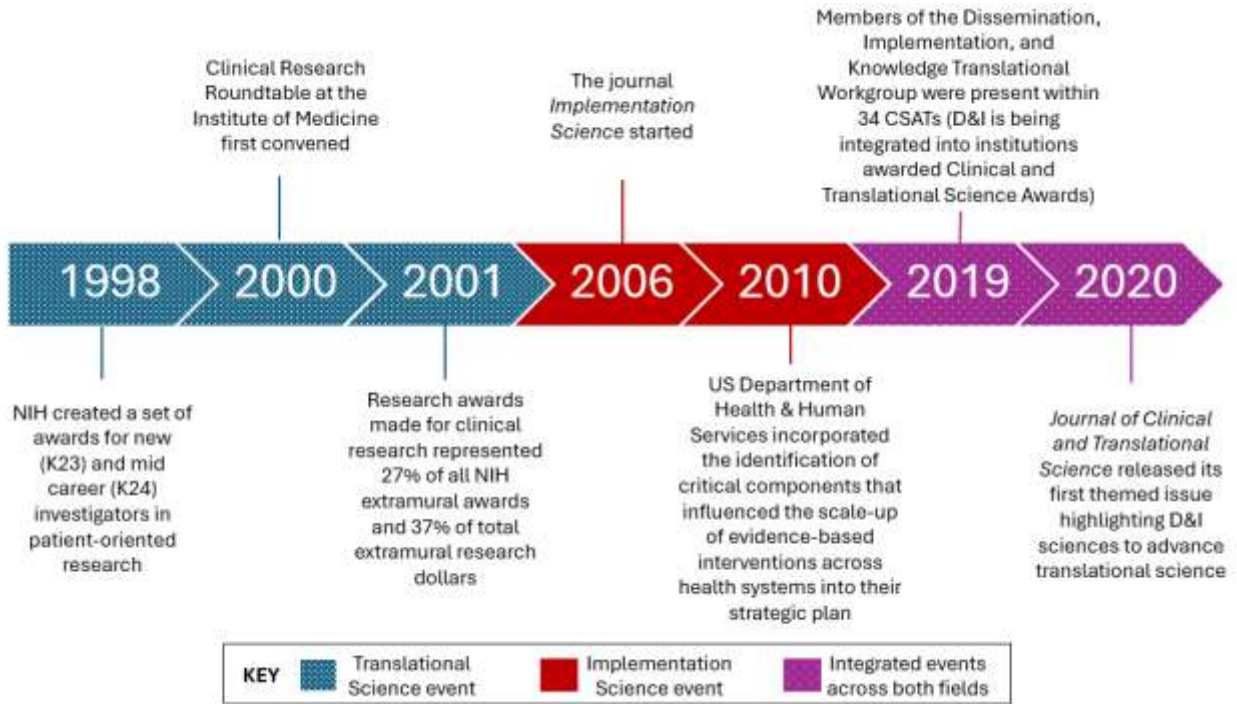
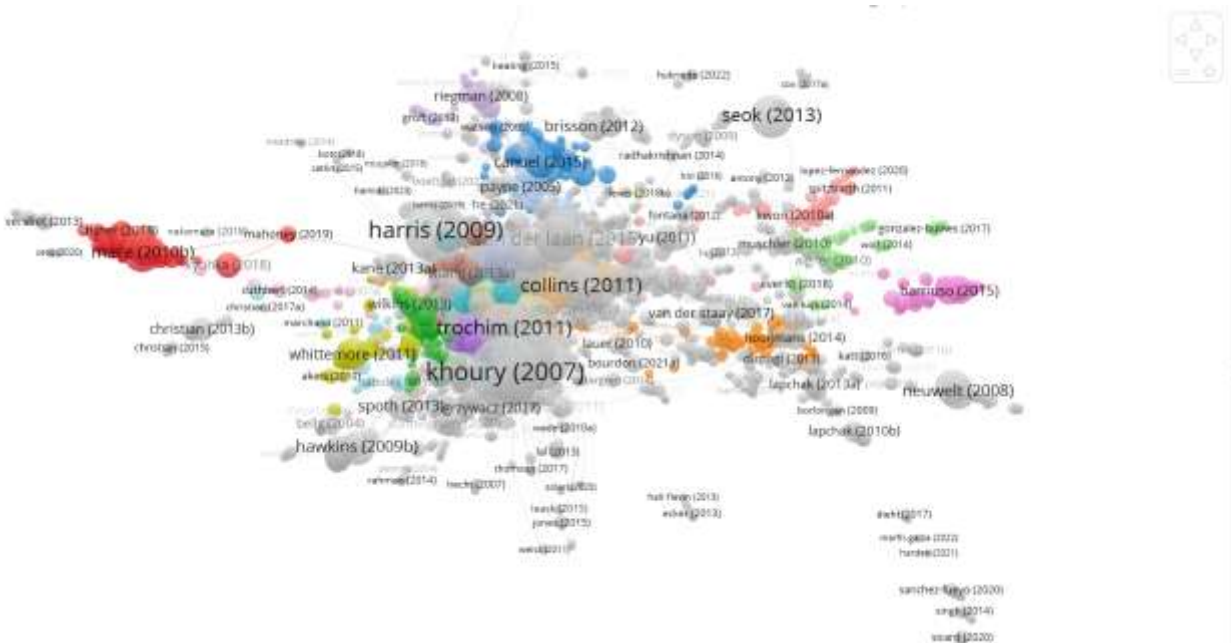


Figure 1. Timeline of key events in implementation science and translational science

a) Translational science directed citation network



b) Implementation science directed citation network

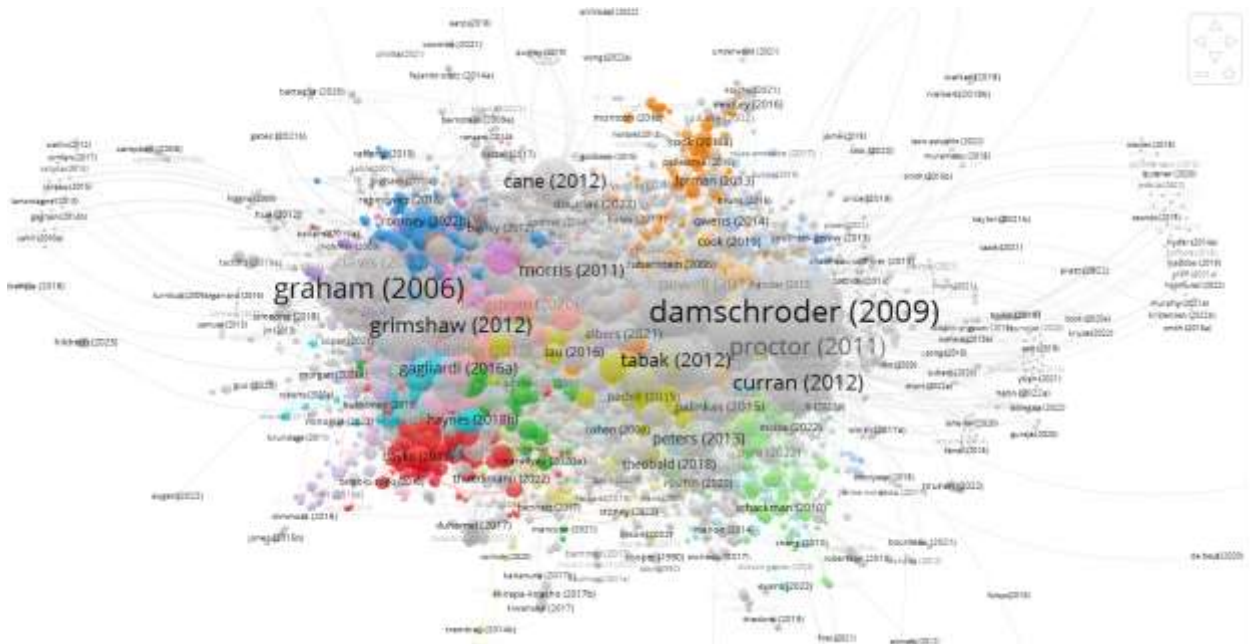


Figure 2. Separate citation networks with citation links between publications
**Colors indicate clusters determined by VosViewer. Node size is based on the number of citation links with other publications in the network (ie- bigger nodes have more citation links with the other publications in the network)*

Implementation science publications*

Translational science publications*

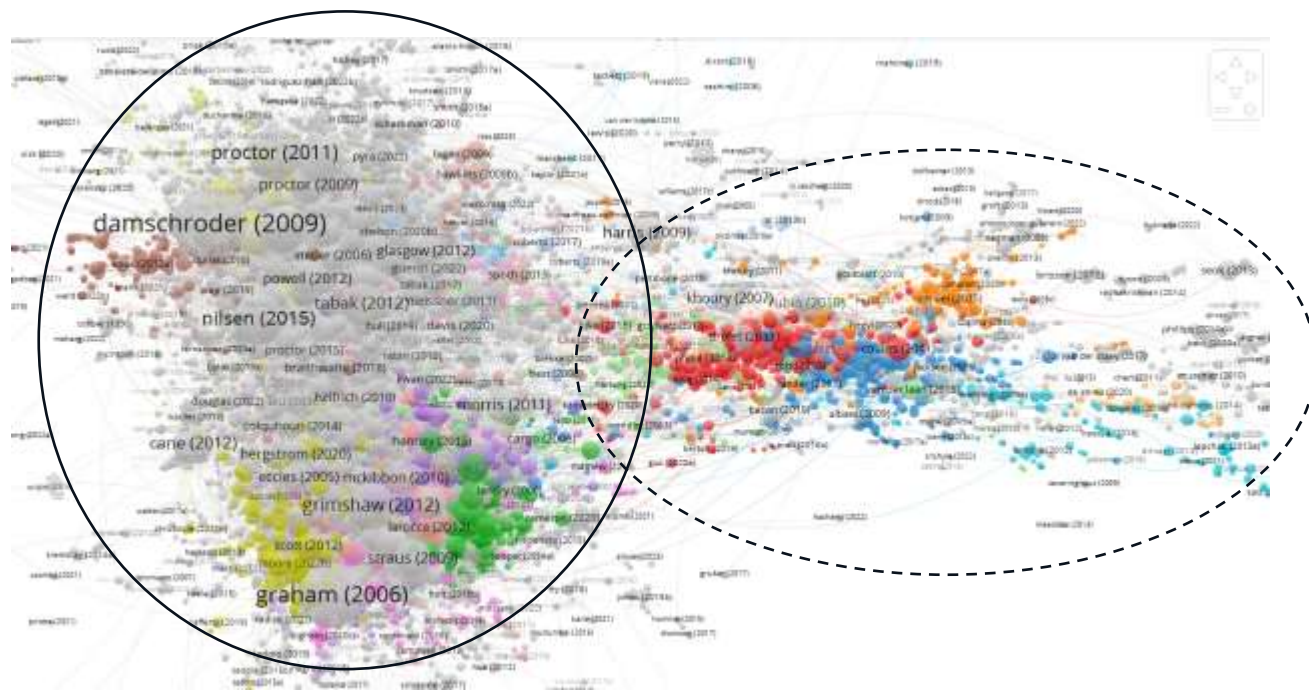


Figure 3. Combined implementation science and translational science citation network

**The majority of publications in the enclosed circles come from the separate implementation science (solid) and translational science (dashed) network analyses. Colors indicate clusters determined by VosViewer. Node size is based on the number of citation links with other publications in the network (ie- bigger nodes have more citation links with the other publications in the network)*

Figure 4. Annual overall citations for top-50 most cited publications in the translational science network

Publications	Citations															Citations	Links within each network		
	<2009	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022		TS Links	Comb-ined TS/IS Links	% Increase
Harris 2009	0	0	12	40	14	31	54	82	11	15	19	26	37	49	52	2325	92	209	127.2
Harris 2019	0	0	0	0	0	0	0	0	0	0	0	14	8	30	20	3372	12	28	133.3
Seok 2013	0	0	0	0	0	15	31	30	22	22	19	17	14	15	14	2040	44	45	2.3
Hooijmans 2014	0	0	0	0	0	9	5	4	9	1	6	2	9	0	5	1392	12	12	0.0
Bellg 2004	70	34	34	42	60	80	89	87	98	96	2	2	1	3	9	1397	11	33	200.0
Morris 2011	0	0	0	0	8	8	28	37	67	8	8	7	4	7	5	1267	55	233	323.6
Meyer-Lindenberg 2011	0	0	0	2	76	5	9	1	5	3	7	94	83	86	78	1129	0	0	NA
Workman 2010	0	0	5	35	79	80	86	71	9	6	1	87	85	88	78	1010	3	3	0.0
Cheever 2009	0	2	41	52	59	74	77	4	81	77	78	60	86	69	59	919	3	3	0.0
Dantzer 2007	55	53	42	49	52	52	59	82	65	68	71	70	73	65	54	910	3	3	0.0
Spizzo 2012	0	0	0	0	1	31	49	79	78	8	6	3	2	81	56	844	0	0	NA
Cuthbert 2014	0	0	0	0	0	0	33	83	96	83	75	99	77	0	93	749	6	7	16.7
Anselmo 2019	0	0	0	0	0	0	0	0	0	0	0	5	1	4	1	631	0	0	NA
Kalueff 2014	0	0	0	0	0	0	17	38	39	59	70	81	94	3	94	605	11	11	0.0

Publications		Citations														Links within each network				
Author	Year	<2009	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Citations	TS Links	Comb-ined TS/IS Links	% Increase
He	2018	0	0	0	0	0	0	0	0	0	0	13	46	92	5	2	488	0	0	NA
Zhao	2017	0	0	0	0	0	0	0	0	0	11	70	93	7	9	0	520	0	0	NA
Khoury	2007	17	40	52	58	38	51	41	32	39	41	20	38	16	16	12	511	118	132	11.9
Glasgow	2012	0	0	0	0	5	30	34	35	40	52	47	54	70	57	52	476	30	150	400.0
Goodman	2011	0	0	0	13	42	47	31	46	38	37	35	51	39	50	39	468	0	0	NA
Vervliet	2013	0	0	0	0	0	0	24	44	42	43	50	61	46	60	53	423	7	7	0.0
Chen	2015	0	0	0	0	0	0	0	7	33	42	60	44	72	70	65	393	1	1	0.0
Tetzlaff	2011	0	0	0	9	28	38	38	54	41	44	42	25	27	26	25	397	8	8	0.0
Neuwelt	2011	0	0	0	13	48	42	28	32	36	30	39	33	26	32	29	388	29	29	0.0
Dodge	2006	15	12	16	17	19	28	25	25	16	30	32	27	42	37	32	373	0	0	NA
Catalano	2012	0	0	0	0	7	18	34	34	56	40	26	52	43	33	26	369	8	9	12.5
Byers	2015	0	0	0	0	0	0	0	7	30	39	30	50	44	71	61	332	0	0	NA
Lorito	2010	0	0	0	10	22	24	25	24	33	22	31	37	43	42	30	343	0	0	NA
Neuwelt	2008	14	24	14	24	25	29	23	35	18	30	25	23	22	24	13	343	30	30	0.0
Phillips	2014	0	0	0	0	0	0	3	16	23	35	36	45	49	70	52	329	14	14	0.0
Holzappel	2013	0	0	0	0	0	8	30	38	39	51	31	31	35	33	29	325	0	0	NA
Bossert	2013	0	0	0	0	0	1	19	53	36	53	34	38	36	31	17	318	7	7	0.0
Cicchetti	2009	0	4	14	30	29	24	34	30	20	24	25	24	18	18	20	314	4	4	0.0
Gillet	2011	0	0	0	0	11	19	20	28	32	36	31	41	37	25	25	305	6	6	0.0
Moore	2011	0	0	0	0	2	7	1	9	8	23	28	43	51	59	72	303	2	5	150.0
Rubio	2010	0	0	1	5	9	17	22	25	30	42	42	32	27	33	20	305	101	108	6.9
Collins	2011	0	0	0	16	51	62	39	31	21	23	21	13	16	9	7	309	60	62	3.3

Publications		Citations														Links within each network				
Author	Year	<2 009	20 09	20 10	20 11	20 12	20 13	20 14	20 15	20 16	20 17	20 18	20 19	20 20	20 21	20 22	Citat ions	TS Link s	Comb-ined TS/IS Links	% Increa se
Vendrell	2013	0	0	0	0	0	3	28	41	34	49	33	41	23	24	27	303	0	0	NA
Lee	2000	136	23	11	19	13	14	14	14	11	13	5	7	7	14	3	304	0	0	NA
Loescher	2010	0	0	1	13	21	29	30	33	33	31	18	27	21	23	18	298	0	0	NA
Ivashkevich	2012	0	0	0	0	0	20	16	27	28	38	27	26	40	27	39	288	0	0	NA
Dong	2014	0	0	0	0	0	0	10	28	35	36	24	30	30	45	37	275	0	0	NA
Libby	2018	0	0	0	0	0	0	0	0	0	0	0	38	88	84	63	273	0	0	NA
Archer	2000	148	18	14	16	23	12	10	9	10	5	7	2	4	4	3	285	0	0	NA
DiBona	2010	0	0	6	14	32	38	48	26	22	25	15	14	14	16	10	280	0	0	NA
Ziemke	2010	0	0	12	38	37	38	24	25	12	17	16	10	11	13	18	271	0	0	NA
Maes	2008	0	11	18	26	16	22	23	19	20	26	16	29	22	14	12	274	1	1	0.0
Curtin	2013	0	0	0	0	0	5	22	41	32	39	20	27	29	29	24	268	0	0	NA
Griner	2014	0	0	0	0	0	0	15	28	37	38	42	31	25	30	20	266	3	3	0.0
Braithwaite	2018	0	0	0	0	0	0	0	0	0	7	45	61	68	69	250	4	56	1300.0	
Garg	2015	0	0	0	0	0	0	0	22	34	41	32	48	31	39	247	0	0	NA	

Figure 5. Annual overall citations for the top 50 most-cited publications in the implementation science network

Publications	Citations																Links within each network		
	<20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	To	IS	Comb-ined	Incr
Author	09	09	10	11	12	13	14	15	16	17	18	19	20	21	22	tal	Link	TS/IS Links	ease
Damschroder						11	18	26	35	43	53	73	89	10	11	57			
2009	0	2	17	51	67	8	5	1	1	6	7	7	1	41	05	99	1277	1299	1.7
Palinkas										10	21	40	57	72	87	29			
2015	0	0	0	0	0	0	1	16	36	2	4	2	4	8	7	50	67	67	0.0
Proctor 2011									10	14	20	32	44	54	63	26			
Graham				11	12	14	14	17	16	15	22	23	25	28	23	24			
2006	50	63	87	4	4	0	4	6	1	3	3	5	6	4	4	44	969	986	1.8
Cane 2012									11	12	19	27	28	38	38	19			
	0	0	0	0	4	31	49	76	7	7	3	4	0	2	9	22	243	245	0.8
Curran 2012										10	14	21	28	32	35	16			
	0	0	0	0	7	25	34	53	57	2	7	1	3	9	8	06	405	416	2.7
Nilsen 2015										12	18	24	29	30	32	15			
	0	0	0	0	0	0	0	11	52	9	7	2	1	8	8	48	491	497	1.2
Powell 2015											11	18	25	33	39	14			
	0	0	0	0	0	0	0	6	38	68	4	9	7	1	8	01	422	425	0.7
Morris 2011																12	187	233	24.6

Publications	Citations																Links within each network			
	Author	<20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	To	IS	Link	Comb-ined
Year	09	09	10	11	12	13	14	15	16	17	18	19	20	21	22	tal	s	TS/IS Links	ease	
										8	8	7	4	7	6	68				
Grimshaw								12	12	14	14	15	12	15	13	12				
2012	0	0	0	0	3	44	96	9	5	2	7	3	8	1	2	50	400	408	2.0	
Cooper 1990	421	62	74	64	78	63	70	67	62	50	56	56	47	40	51	12	8	8	0.0	
Proctor 2009	0	2	13	27	41	49	81	54	69	81	82	6	0	0	98	3	229	235	2.6	
Thorne 2016	0	0	2	0	0	0	1	0	3	18	74	4	6	6	3	7	7	7	0.0	
Warburton													18	25	27	82				
2017	0	0	0	0	0	0	0	0	0	2	20	89	4	9	1	5	6	6	0.0	
Ferrer 2014	0	0	0	0	0	0	16	62	80	5	94	0	1	6	9	3	1	1	0.0	
Spillane										10		11	14	11	10	83				
2002	56	27	21	31	35	40	44	49	60	57	65	90	85	81	57	8	16	16	0.0	
Tabak 2012	0	0	0	0	2	15	28	60	56	75	84	4	2	87	69	2	279	290	3.9	
Proctor 2013	0	0	0	0	0	0	8	31	27	48	86	74	47	14	20	67	235	238	1.3	

Publications	Citations																Links within each network		
	Author	<2009	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	IS Links	Comb-ined TS/IS Links
														4	7	2			
Cargo 2008	0	14	22	23	34	36	35	48	43	45	45	58	52	57	58	570	42	53	26.2
Eccles 2005	60	36	37	26	37	34	42	34	38	33	26	34	38	41	28	544	111	114	2.7
Palinkas 2011	0	0	0	6	12	20	22	29	32	31	47	62	70	85	90	506	112	116	3.6
Powell 2012	0	0	0	0	4	20	22	35	37	48	54	62	69	74	69	494	148	149	0.7
Meyers 2012	0	0	0	0	1	7	27	29	39	46	60	56	84	70	64	349	111	117	5.4
Kitson 2013	0	0	0	0	0	6	14	28	48	57	72	77	78	65	46	141	4	4	0.0
Weiner 2017	0	0	0	0	0	0	0	0	0	1	9	35	57	9	20	428	81	83	2.5
Glasgow 2012	0	0	0	0	5	30	34	35	40	52	47	54	70	57	52	476	130	150	15.4
Grimshaw	32	31	41	49	39	35	46	47	27	28	25	29	17	13	13	474	82	82	0.0

Publications	Citations																Links within each network		
	<20 09	20 09	20 10	20 11	20 12	20 13	20 14	20 15	20 16	20 17	20 18	20 19	20 20	20 21	20 22	Total	IS Link s	Comb-ined TS/IS Links	Incr ease
2006																2			
Glisson 2008	3	20	21	26	41	37	43	24	39	43	46	36	32	13	14	8	45	47	4.4
Ergina 2009	0	2	19	26	33	36	44	30	36	28	34	42	25	42	32	9	4	5	25.0
Davis 2003	117	37	24	24	28	34	27	22	22	18	10	21	21	19	7	1	162	170	4.9
Mensah 2017	0	0	0	0	0	0	0	0	0	5	41	54	77	8	94	9	1	1	0.0
Duckworth 2015	0	0	0	0	0	0	0	3	27	42	59	73	56	65	56	1	0	0	NA
Cook 2013	0	0	0	0	0	11	22	17	27	42	36	66	55	59	37	2	33	33	0.0
Pfadenhauer 2017	0	0	0	0	0	0	0	0	0	7	33	51	68	79	83	1	66	66	0.0
Stetler 2006	22	8	11	12	16	17	20	21	18	25	30	32	36	36	24	8	77	79	2.6
Straus 2009	0	1	18	19	23	18	21	23	16	27	27	26	24	45	34	32	198	203	2.5

Publications	Citations																Links within each network			
	Author	<20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	To	IS	Link	Comb-ined
Year	09	09	10	11	12	13	14	15	16	17	18	19	20	21	22	tal	s	TS/IS	Links	ease
Rabin 2008	2	6	5	12	13	19	21	33	24	27	35	27	34	44	30	2	109	111	1.8	
Rycroft- Malone 2012	0	0	0	0	1	11	12	16	20	31	28	39	34	53	61	6	17	17	0.0	
McGaghie 2014	0	0	0	0	0	0	1	24	27	30	43	50	52	44	44	5	4	10	150.0	
Straus, 2013	0	0	0	0	0	2	8	25	26	24	32	35	34	49	63	8	0	0	NA	
Greenhalgh 2011	0	0	0	1	3	21	19	40	33	39	36	40	31	24	17	4	128	128	0.0	
Kirk 2016	0	0	0	0	0	0	0	0	1	9	17	37	50	65	99	8	121	122	0.8	
Hanney 2015	51	17	8	14	9	6	10	17	19	18	27	22	22	30	26	6	57	58	1.8	
Waltz 2015	0	0	0	0	0	0	0	0	11	25	22	36	48	57	77	6	100	101	1.0	
Baskerville	0	0	0	0	3	15	21	28	17	30	34	41	38	29	31	28	49	50	2.0	

Author	Publications Citations																Links within each network		
	<2009	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	IS Links	Combined TS/IS Links	Increase
2012																7			
Mdege 2011	0	0	0	0	9	13	19	45	40	35	29	30	33	18	21	27	18	18	0.0
Hawe 2015	0	0	0	0	0	0	0	5	26	21	32	56	52	50	33	27	23	24	4.3
Moritz 2007	7	14	13	18	17	16	22	14	16	14	25	25	24	21	30	27	0	1	NA
Gagliardi 2011	0	0	0	6	16	24	17	32	24	25	20	33	23	27	25	2	39	39	0.0
Damschroder 2013	0	0	0	0	0	2	9	15	17	22	22	21	28	57	62	5	103	104	1.0

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