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Bibliometric Study of Interdisciplinary Relations of Converging Technologies (Nano-Bio-Info-Cogno)

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Abstract

This study investigates the interdisciplinary relations of nanotechnology (Nano), biotechnology (Bio), information technology (Info), and cognitive science (Cogno) (together kwon as NBIC converging technologies) at the science level using a range of different bibliometric techniques and measures. The study applied journal citation, author citation, keyword analysis, and authorship analysis on all Iranian NBIC international articles (2001-2015). Spanning tree, inclusion index, import and export of concepts, and inward and outward interactions were used to measure the interdisciplinary relations. The results showed that Bio and Nano had the highest level of interdisciplinary relations in terms of journal citations, shared keywords, and the exchange of authorship. On the other hand, Cogno had no journal citation relation with Bio, and it had very low exchange of concepts with Bio. Cogno also had the weakest link to Nano in terms of authorship as well as author citations. The study suggests using a combination of techniques and measures for the study of interdisciplinarity and convergence.

Conference Topic

Science communication; Participation in science

Introduction

Interdisciplinary relations are interactions between two or more disciplines. These interactions could be as simple as the exchange of ideas or as complex as mutual integration of methods, terminologies, data and epistemology of disciplines. Interdisciplinary relations play an important role in the progress of science and the study of interdisciplinary relations has gained a great deal of importance in recent years. In the bibliometric tradition, interdisciplinarity has remained a difficult issue despite its high policy-relevance (Wagner *et al.*, 2011). However, access to high-volume and high-quality data sets of scientific output (e.g., publications, patents, grants) and computers and algorithms capable of handling this enormous stream of data has made it possible for bibliometricians to deeply study the phenomenon of interdisciplinarity (Borner, Maru and Goldstone, 2004).

Interdisciplinary research is considered a kind of convergence phenomenon (Jeong, Kim and Choi, 2015). There are four areas that their convergence is particularly considered important, especially in terms of technology convergence. They include nanotechnology, biotechnology, information technology, and cognitive science (together known with the acronym of NBIC) (Jeong, Kim and Choi, 2015). This technological convergence might manifest itself in the early stages as the interdisciplinary relations and interactions among these four fields. Technology convergence has different levels that starts with convergence in science and moves to convergence in technology, market and then in industry (Jeong, Kim and Choi, 2015). Although, individual fields from NBIC, especially nanotechnology and nanoscience, have received considerable attention in bibliometric studies, there is not much research on the

interdisciplinary relations of these four areas. It is critical to know how these converging fields rely on each other, how similar they are and how much scientific exchange and interactions occur among them. All of these four fields have been especially emphasised in the Iranian Scientific Roadmap and the Iranian government has invested in research in these areas. This article aims to investigate the convergence of these four fields at the science level by focusing on the relations between them. The focus of the article is on Iranian international publications in these areas. There are different bibliometric techniques for studying interdisciplinary relations and this article uses a combination of techniques including journal citations, author citations and keyword analysis.

Literature review

Techniques and methods for measuring similarity and interdisciplinary relations in science have been laboriously developed over the past several decades using bibliometric analysis (Rafols, Porter and Leydesdorff, 2010). There have been already a few reviews and discussions of the methods used for this purpose including Van Raan (1999) and Wagner *et al*. (2011).

Generally, we can divide studies on the interdisciplinary relations of scientific fields into five groups based on the techniques they have used.

The first group include studies that have used citation analysis. These studies focus on the cross references between scientific fields with the assumption that if two fields of science cite publications of one another, they are related. For instance Goldstone and Leydesdorff (2006) studied how much cognitive science cite other fields of science and how much it is cited by other fields. The results showed that cognitive science cited neurology (13.4%) more than other fields and it received the highest rate of interdisciplinary citations from computer and artificial intelligence (15.2%). In another study Porter and Youtie (2009) studied interdisciplinarity of nanotechnology and found that nanotechnology had some level of convergence with medicine, biotechnology, neurosciences, physics and maths. In a more recent study on nanotechnology and nanoscience, Stopar *et al*. (2016) found out that nanosciences showed characteristics of a distinct discipline.

The second group are studies that focus on co-classification analysis which looks at the co-occurrence of different subject-classification headings assigned to research publications. An example from this group is the study by Rafols and Meyer (2010) on bionanoscience.

The third group have used co-word analysis. Milojević (2012) in his study of nanotechnology found that some 85% of Nano research was multidisciplinary. Wang, Notten and Surpatean (2013) in their study of nanotechnology also found that nanotechnology has developed to a relatively mature stage and has become a standardized and codified technology.

The fourth group have used co-authorship analysis techniques. Bergmann *et al*. (2016) investigated how interdisciplinary collaboration in cognitive science was and they found a high level of interdisciplinary collaboration in cognitive sciences.

The fifth group are those that have applied co-citation and bibliographic coupling analysis techniques. For instance, Bassecoulard, Lelu and Zitt (2007) used bibliographic coupling analysis for nanosciences and found out that observed moderate multi-disciplinarity is based on a real inter-disciplinarity at the paper level. Chen *et al*. (2015) used a co-citation matrix to study the interdisciplinary evolution of biochemistry and molecular biology. Their study showed that interdisciplinarity evolves mainly from neighbouring fields to distant cognitive areas and provides evidence of an increasing tendency of biochemistry and molecular biology researchers to cite literature from other disciplines.

Overall, there is a wide range of research on interdisciplinary relations as well as on identifying converging fields (such as Buter, Noyons and Van Raan, 2010). Several studies in the past have focused on nanotechnology and nanoscience and a few on cognitive sciences. However, there

seems to be no study on the relations between all of the four areas of NBIC and the present study contributes in this area.

Methods and measures

Data for the Iranian articles were obtained from Scopus database. Any English article with at least one author affiliated to an Iranian institute was retrieved in four fields of nanotechnology (Nano), biotechnology (Bio), information technology (Info), and cognitive science (Cogno) for the period 2001-2015. The data were searched and obtained in 6 September 2016 as batches of 2000 records (the maximum number Scopus allows downloading). The year of publication was used to break the search results into smaller sets in order to be able to download the records. They were then imported into a database for the analysis. Table 1 shows the number of Iranian records for each subject area.

Table 1. Number of Iranian publications for the four subject fields in Scopus.

Field	*No of publications*
Nanotechnology	21,393
Biotechnology	27,578
Information technology	16,358
Cognitive science	3,535

Four analysis techniques were used: journal citations, author citations, keyword analysis and authorship.

- Journal citations: citations to journals by publications of each field were analyzed and then the amount of overlap between the cited journals (journals jointly cited by each pair of fields) was calculated.
- Author citations: citations to authors by publications of each field were analyzed and then the amount of overlap between the cited authors (authors jointly cited by each pair of fields) was calculated
- Keywords analysis: VOSviewer (vosviewer.com) was used to do a keyword analysis on the titles of the articles for each field. For each field, keywords with at least five occurrences were extracted and then the amount of keywords shared by each pair of fields was calculated. VOSviewer was used to extract the keywords from titles of each field. The results were presented to a panel of experts who identified common terms to be removed. The remaining sets were used for comparison of the four fields as pairs or triads.
- Authorship analysis: the number of authors who have published articles in each pair of fields were calculated. Author analysis was only done on Iranian authors and foreign co-authors were removed from the sets. Affiliations were used to do some control for homonyms.

Four measures were used in this study: inclusion index, import/export of concepts, inward/outward interactions and spanning tree.

- Spanning tree: spanning tree calculation was used to show the strongest (maximum spanning tree) and weakest (minimum spanning tree) ties between the subject fields.
- Inclusion index: inclusion index is a simple measure for asymmetric similarity. It was used because among three indexes that have been suggested for measuring similarity of

documents (including Salton's Cosine formula, the Jaccard Index, and the Inclusion Index), inclusion index reveals better results (Sternitzke & Bergmann, 2009). In asymmetric similarity, the similarity of set A to set B is different from the similarity of set B to set A (Qin, 2000). Inclusion index here indicate the extent by which keywords from one field have been used in a second field. The formula used here was 100*A/M in which A is the number of keywords common in both fields of B and C, and M is the number of keywords from field B that do not exist in field C.

- Import and export of concepts: this measures (used only for keyword analysis) shows how many concepts from one field are used in other fields (exporting) and how many concepts from other fields are used in the given field (importing). Concepts here are represented with keywords.
- Inward and outward interactions: this measure (used only for author analysis) was used to see the percentage of authors of a given field that have authored articles in other fields (outward interaction) and the percentage of authors from other fields that have authored articles in the given field (inward interactions).

Findings

Journal citations

Table 2 shows the amount of overlap in each pair of fields in their citations to journals. For instance the first row shows the overlap between Nano and Cogno. It shows that 17 journals have been cited by the articles of both fields. There have been 223 citations to these 17 journals in Nano articles, accounting for 9.9 per cent of all of citations. Cogno articles included 4,424 citations (12%) to these 17 journals. The largest number of journals jointly cited by two fields belongs to Nano and Bio with 297 journals cited by both fields. While these journals accounted for 65.4 percentage of citations from Bio articles, they only were 18 per cent of citations from Nano articles. The smallest overlap is between Bio and Cogno (no overlap) and then between Info and Bio, and Info and Cogno respectively.

Figure 1 shows the weighted graph of the spanning tree representing the journal citation similarities between the four fields. The numbers shown for edges are percentages. The number inside nodes are the total number of journals cited in the articles of that field. The maximum spanning tree is shown with dashed line and the minimum spanning tree is shown with dotted line. The strongest relation is between Bio and Nano where 65.4 per cent of citations in Bio articles are to sources that have been cited in Nano articles too. The weakest relation is between Bio and Cogno where Bio has no common cited sources with Cogno articles.

Table 2. Overlap of citations to journals in each pair of subjects

Combination	*No of journals cited by both fields*	*First field*	*No of citations to journals*	*% of citations*	*Second field*	*No of citations to journals*	*% of citations*
Nano & Cogno	17	Nano	223	9.9	Cogno	4,424	12
Nano & Bio	297	Nano	40,521	18	Bio	168,265	65.4
Nano & Info	101	Nano	55,102	24.6	Info	6,081	4.4
Info & Cogno	13	Info	1,612	1.2	Cogno	1,588	4.4
Info & Bio	35	Info	6,397	4.7	Bio	3,787	1.5
Cogno & Bio	6	Cogno	7	0.01	Bio	7	0.00

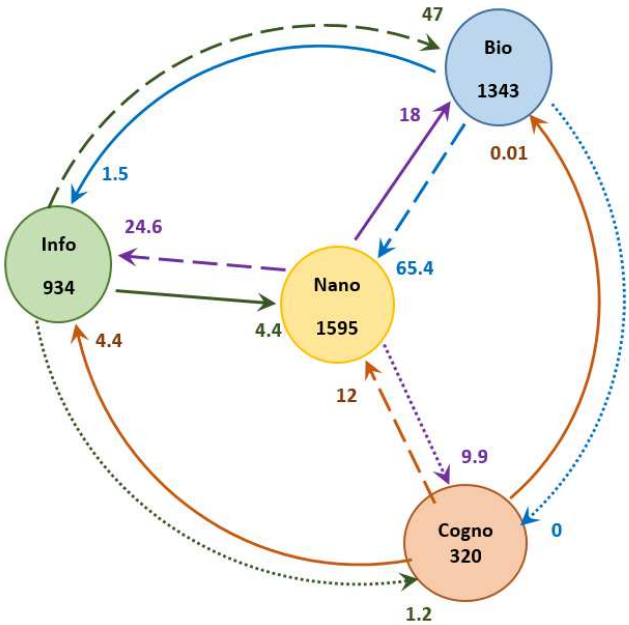

Figure 1. Spanning tree of the relations of four fields based on journal citations

Inclusion index was calculated for overlap in citations to journals. Table 3 shows that for instance the similarity of journal citations in Nano articles to Bio articles (2nd row) is 18.6%, while the similarity of journal citations in Bio articles to Nano articles is higher (22.1%). The smallest number is the similarity of journal citations in Cogno articles to journal citations in Bio articles.

Table 3. Inclusion index for overlap of citations to journals

Combinations	*First field*	*Inclusion index (%)*	*Second field*	*Inclusion index (%)*
Nano & Cogno	Nano	1.06	Cogno	5.3
Nano & Bio	Nano	18.6	Bio	22.1
Nano & Info	Nano	6.3	Info	10.8
Info & Cogno	Info	1.4	Cogno	4
Info & Bio	Info	3.7	Bio	2.6
Cogno & Bio	Cogno	0.45	Bio	1.9

Author citations

Another way of measuring the relation between two fields or their similarity is to look at their overlap in citations to authors. Table 4 shows the overlap between each pair of fields in their author citations. For instance there were 1,494 authors that were cited by articles in both Nano and Cogno articles. In Nano articles, 32,391 citations (3.4% of all of citations in Nano articles) were made to these 1,494 authors, while this figure for Cogno science articles was 45,334 citations (23.5% of all of citations in Cogno articles). The strongest relation is where 72.5 per cent of citations in Nano articles were made to 9,479 authors who also were cited by articles in Bio. The data are also illustrated in the spanning tree graph (Figure 2). The number inside nodes are the total number of citations to authors in the articles of that field.

Table 4. Overlap of citations to authors in each pair of subjects

Combinations	*No of authors*	*First field*	*No of citations*	*Percentage of citations to*	*Second field*	*No of citations*	*Percentage of citations to*

	cited by both fields		*to authors cited by both fields*	*authors cited by both fields*		*to authors cited by both fields*	*authors cited by both fields*
Nano & Cogno	1,494	Nano	32,391	3.4	Cogno	45,334	23.5
Nano & Bio	9,479	Nano	589,533	72.5	Bio	582,463	41.9
Nano & Info	4,130	Nano	310,040	38.1	Info	124,038	31.4
Info & Cogno	1,494	Info	110,199	27.9	Cogno	41,716	21.6
Info & Bio	5,372	Info	56,782	14.4	Bio	113,906	8.2
Cogno & Bio	1,343	Cogno	43,678	22.7	Bio	108,609	7.8

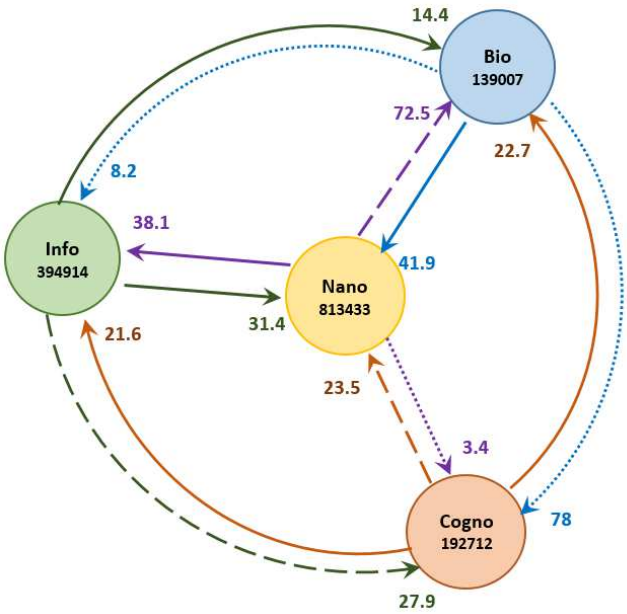

Figure 2. Spanning tree for the relations of four subjects based on author citations

Inclusion index for author citations is presented in Table 5. We can see that the similarity of Nano articles to Cogno articles in terms of citing the same authors is 4.6 per cent while Cogno articles are only 3.3 per cent similar to Nano in this regard. The highest similarity is the similarity of Info articles to Bio articles (9.4%).

Table 5. Inclusion index for overlap of citations to authors

Combinations	*First field*	*Inclusion index (%)*	*Second field*	*Inclusion index (%)*
Nano & Cogno	Nano	4.6	Cogno	3.3
Nano & Bio	Nano	1.6	Bio	1.6
Nano & Info	Nano	1.3	Info	3.3
Info & Cogno	Info	1.3	Cogno	3.5
Info & Bio	Info	9.4	Bio	4.7
Cogno & Bio	Cogno	3	Bio	1.2

Shared keywords

The third way of looking at the relation or similarity of two fields here is keyword analysis. Table 6 shows the keyword similarity between pairs of subjects. In the strongest similarity we can see that 483 keywords had a total frequency of 15,855 (28.6%) in Nano articles. These 483 keywords were also used in Bio articles and they accounted for 38 per cent of keyword frequencies in Bio articles. The weakest relation is between Cogno and Bio articles, where

Cogno articles have the smallest number of shared keywords with Bio articles. Figure 3 shows the spanning tree of shared keywords. The number inside nodes are the total number of keywords in the given field.

Table 6. Overlap of title keywords (shared keywords) in each pair of subjects

Combinations	*No of shared keywords*	*First field*	*No of keywords*	*% of keywords*	*Second field*	*No of keywords*	*% of keywords*
Nano & Cogno	25	Nano	755	1.4	Cogno	871	15.2
Nano & Bio	483	Nano	15,855	28.6	Bio	8,664	38
Nano & Info	141	Nano	11,526	20.8	Info	4,799	20.4
Info & Cogno	16	Info	1,216	1.2	Cogno	669	11.7
Info & Bio	56	Info	1,198	4.7	Bio	1,513	6.6
Cogno & Bio	68	Cogno	3,006	0.01	Bio	1,241	5.4

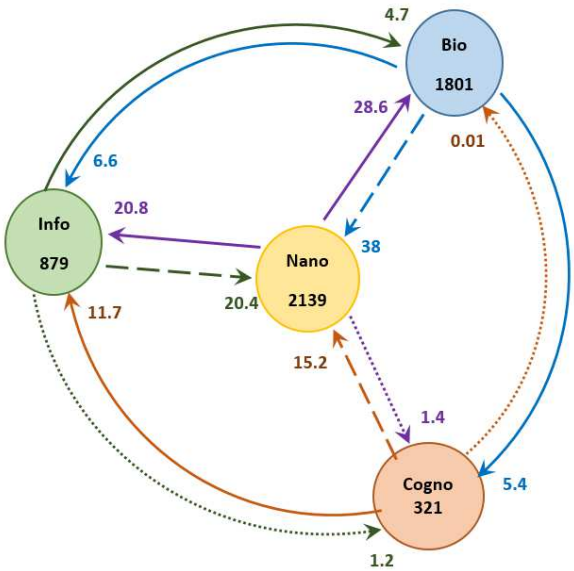

Figure 3. Spanning tree for the relations of four subjects based on shared keywords

Inclusion index for the similarity of pairs of subjects in terms of shared keywords is presented in Table 7. The highest quantity is the similarity of Bio articles' keywords (5.6%) to those of Nano articles. The lowest quantity belongs to similarity of Nano articles' keywords (1.2%) to those of Info articles.

Table 7. Inclusion index for overlap of keywords for pairs of subjects

Combinations	*First field*	*Inclusion index (%)*	*Second field*	*Inclusion index (%)*
Nano & Cogno	Nano	3.3	Cogno	2.8
Nano & Bio	Nano	3.04	Bio	5.6
Nano & Info	Nano	1.2	Info	2.9
Info & Cogno	Info	1.3	Cogno	2.4
Info & Bio	Info	4.7	Bio	3.7
Cogno & Bio	Cogno	2.3	Bio	5.5

For keywords, we can also consider how each field imports concepts from or exports concepts to the other fields. Exporting here indicates the percentage of keywords of a given field that have been used by other fields. The percentage of concept export for Cogno articles here is 56

per cent ((i.e. 1241+1216+755)/5725*100 = 56%). To calculate import percentage for Cogno articles, the sum of all of its join keywords with the other three fields is divided by the total number of its keywords. The concept import percentage for Cogno articles is 79 per cent. The ratio of import to export (59/79) is 0.7 for Cogno. This ratio indicates that Cogno exports more concepts to the other fields than it imports. Nano seems to have the largest import to export ratio.

Table 8. Import and export of concepts

Fields	*Importing concepts (%)*	*Exporting concepts (%)*	*Ratio of import to export*
Nano	50.7	25.8	1.9
Bio	88	50.1	1.7
Info	30.8	58.5	0.51
Cogno	79	56	0.7

Authorship analysis

Authors of one subject field might publish articles in the journals of another subject field. Table 9 shows the number and percentage of authors who published in each pair of subject fields. In the pair of Nano and Bio, 9,478 authors published in the journals of both fields. These authors, given the frequency of their appearance in the articles (counting was not unique counting) were 67.4 per cent (or 50,131 authorships) of Nano articles. The same 9,478 authors accounted for 40.7 per cent or 50,915 authorships in Cogno articles. Figure 4 shows the spanning tree graph of authorship. The number inside nodes are the total number of authors in the given field.

Table 9. Overlap of authors in each pair of subjects

Combinations	*No of authors publishing in both fields*	*First field*	*No of authors*	*% of authors*	*Second field*	*No of authors*	*% of authors*
Nano & Cogno	1,494	Nano	4,373	5.8	Cogno	2,774	16.2
Nano & Bio	9,478	Nano	50,131	67.4	Bio	50,915	40.7
Nano & Info	4,130	Nano	28,416	38.2	Info	14,434	31.2
Info & Cogno	1,494	Info	9,972	21.5	Cogno	4,140	24.2
Info & Bio	5,372	Info	6,,262	13.5	Bio	10,905	8.7
Cogno & Bio	1,343	Cogno	4,176	24.3	Bio	10,535	8.4

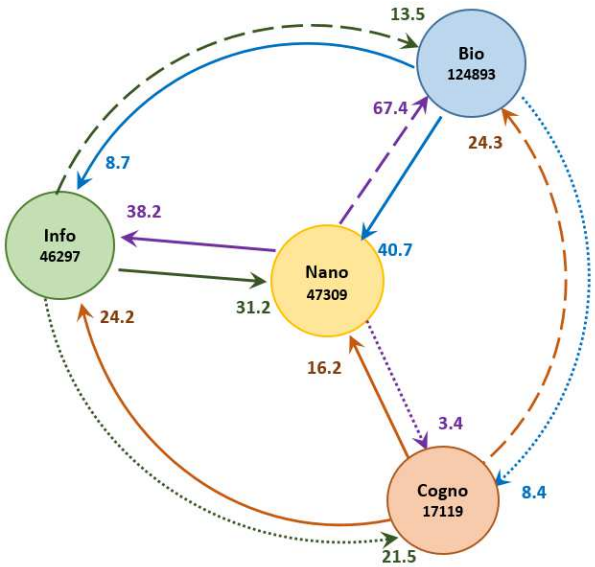

Figure 4. Spanning tree for the relations of four subjects based on authorship

Table 10 gives the *Inclusion index* for the similarity of pairs of subjects in terms of shared authors. The smallest number is the similarity of Nano article's authorship (2.01%) to that of Cogno articles. The largest number is the similarity of Nano articles' authorship to that of Bio articles.

Table 10. Inclusion index for overlap of authors for pairs of subjects

Combinations	*First field*	*Inclusion index (%)*	*Second field*	*Inclusion index (%)*
Nano & cogno	Nano	2.01	Cogno	8.72
Nano & bio	Nano	12.75	Bio	6.63
Nano & info	Nano	5.55	Info	8.92
Info& cogno	Info	3.22	Cogno	8.72
Info& bio	Info	11.61	Bio	4.31
Cogno & bio	Cogno	7.8	Bio	1.07

For authorship, we can also consider inward and outward interactions. Outward interaction is the percentage of authors from a given field that have contributed in the articles of any of the other three fields. Inward interaction is the percentage of authors from any of the other three fields that have contributed in the articles of the given field. Table 11 presents the data. We can see that inward interaction of authors in Nano is 91.6 which was calculated by dividing the sum of contributions of authors of the other fields in Nano articles by the total number of authors of Nano articles. Nano has a larger percentage of outward interactions. The ratio of inward to outward interactions (inward/outward) shows whether the authors of a field contribute to the other fields more than other receiving contribution from the other three fields or it is the opposite. In the case of Nano, 0.82 shows that authors of this field contribute more in the articles of the other three fields than the field receives contribution from the other three fields.

Table 11. Inward and outward activity of authors

Fields	*Inward(%)*	*Outward(%)*	*Ratio of inward to outward*
Nano	91.6	111.5	0.82
Bio	48.5	17.2	2.8
Info	93.9	66.2	1.4
Cogno	58.2	64.8	0.89

Discussion and conclusions

This study is one of the few studies, if not the only, that have looked at the interdisciplinary relations between the four fields of NBIC (nanotechnology, biotechnology, information technology, and cognitive science). These are known as converging (or convergent) technologies and there is a great deal of hope that their synergy will result in great progress in science. The first level of their convergence is at the science level, which is manifested in interdisciplinary relations. These relations were investigated in this study using a set of different techniques and measures. These combination of techniques and measures together (e.g. inclusion index and spanning tree) have not been used much in the past. The use of different techniques reveals different aspects of interdisciplinary relations. For instance while keyword analysis shows the exchange of concepts between two fields, citation analysis reveals how much

they have in common in terms of sources of information; and authorship analysis shows something about their human interaction.

The results of the study showed that the highest exchange of citations occurs between Bio and Nano. Bio and Nano also had the strongest link in terms of shared keywords. The highest exchange of authorship was also between Nano and Bio. These results show that Bio and Nano have probably a higher level of convergence and they are more likely to be able to do joint projects. This should not be surprising as there is already a field of research named bionanoscience (Rafols and Meyer, 2010) that indicates the convergence of Nano and Bio. This result is aligned with the findings of past studies (Porter and Youtie, 2009) on high interdisciplinarity of Nano and its convergence with some other fields.

The results also showed that Cogno articles did not have any citations to the journals cited in Bio articles and the two fields of Cogno and Bio did not have any relation in this regard. Cogno also had the weakest link to Nano in terms of authorship as well as author citations. The lowest rate of exchange of concepts also belonged to Cogno and Bio. All of these indicate that cognitive science in the context of Iranian science has not been very successful in establishing relations with the other three fields in NBIC and its interdisciplinary relation with the other three fields are not as strong as it should be. The low integration of Cogno with other fields in this study was not expected for past studies (Bergman *et al*., 2016) found cognitive science to be very interdisciplinary.

We should note that this study has its own limitations as the data used in the study were only the data of Iranian publications. Interactions between scientific fields in the context of Iranian science is influenced by the way science is managed in Iran. There are two independent and separate ministries in Iran in charge of research. Ministry of Science, Research and Technology manages most areas of science except Medical sciences that are managed by the Ministry of Health. This might create some hindrances for the relations of certain subfield of cognitive science (such as certain areas of neuroscience that falls under the administration of the Ministry of Health) with other areas (i.e. Nano, Bio and Info). This governance aspect of science might explain the weak relationship of Cogno with the other fields in this study. It will be interesting to do the same kind of analyses on the global data to see if the relations in Iranian NBIC are different from those in the international science. The other issue is that most of the analyses in this study, similar to many other bibliometrics studies, relied on the subject categorizations of journals in Scopus database. In spite of these limitations, use of different techniques and measures helped create a better picture of the interdisciplinary relations between NBIC. Spanning tree could show the weakest and strongest connections and inclusion index showed the similarity. It is recommended that future studies use a combination of techniques for the study of interdisciplinary relations. The study also focused only on publications, and there is a need to investigate the convergence of NBIC at the technology (e.g. patent), market, and industry levels.

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