Classifying Scientific Disciplines in Slovenia: A Study of the Evolution of Collaboration Structures

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We explore classifying scientific disciplines including their temporal features by focusing on their collaboration structures over time. Bibliometric data for Slovenian researchers registered at the Slovenian Research Agency were used. These data were obtained from the Slovenian National Current Research Information System. We applied a recently developed hierarchical clustering procedure for symbolic data to the coauthorship structure of scientific disciplines. To track temporal changes, we divided data for the period 1986–2010 into five 5-year time periods. The clusters of disciplines for the Slovene science system revealed 5 clusters of scientific disciplines that, in large measure, correspond with the official national classification of sciences. However, there were also some significant differences pointing to the need for a dynamic classification system of sciences to better characterize them. Implications stemming from these results, especially with regard to classifying scientific disciplines, understanding the collaborative structure of science, and research and development policies, are discussed.

Introduction

Since its creation, science has become a powerful way of understanding both the physical and the social worlds. Many disciplines were created to study a diverse set of phenomena. These disciplines evolved over time to create an ever more complicated scientific domain. Classification is often the first step in scientific efforts to establish a basic understanding of empirical phenomena. Whether different types of science are best suited to different goals could hardly be solved without the use of classification systems. This approach has been extended to classifying sciences and academic disciplines. Some of classification criteria include nomothetic versus ideographic sciences (Weber, 1988)[1]; quantitative versus qualitative sciences or, more accurately, quantitative and qualitative activities within science (Creswell, 2003)[2]; and natural-technical versus social-humanities sciences (Szostak, 2004). There are also "popular" simple dichotomies such as hard sciences versus soft sciences (Fuller, 1997; Whitley, 1984). Such broad classifications of modern scientific knowledge are, essentially, static and are present in many science, technologies and society (STS) studies. As a result, to the extent that these classifications are used, these studies are unable to explain huge *transformations* in the social and cognitive structure of modern science.

As a way of grappling with the dynamic aspects of science as disciplines change, we focus on two inherently dynamic and related characteristics of modern scientific phenomena, even though they are often regarded as static and independent of each other: (a) disciplinarity; and (b) collectivism, the collaboration practices of science both within and between disciplines.

Disciplinarity

It is useful to take the disciplinary context of science as a starting point for bibliometric analyses because academic disciplines still represent the crucial institutional and organizational framework within which scientific activities take place. In historical and sociological studies of science it is usually assumed that the disciplinary structure of science originating in the 18th century has persisted: "Like police

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guards patrolling national borders, scientists decreed which topics should lie inside the large domain they ruled over, and which ones should be outlawed" (Fara, 2009, p. 194). The 19th and 20th centuries saw a tremendous proliferation of scientific disciplines. These processes and the conditions of knowledge growth have been described as either the promotion of disciplinary differentiation (Storer & Parsons, 1968), segmentation and differentiation processes (Hagstrom, 1965), or as a model of branching (Mulkay, 1975).

Even today, intellectual substances are mainly connected to the social structures, modes, and organization of knowledge production represented by the disciplinary organization of science. "Academic disciplines are the type of knowledge production which unify reputation networks, employment structures, and the training programs in the scientific communities of many countries" (Whitley, 1984, p. 7).

STS authors mostly converge in an opinion about the constitutive nature of scientific disciplines embracing epistemological and sociohistorical dimensions. The first is concerned with intellectual substance and truth claims, whereas the latter deals with the organization of intellectual substance into social institutions. The intellectual or epistemological dimension tends to display permanent and universal characteristics, whereas the sociological component of scientific disciplines tends to exhibit changing and contingent characteristics (Becher & Trowler, 2001; Manzon, 2011; Stichweh, 1994; Whitley, 1984).

Disciplinary membership is not just a matter of occasional and personal preference for an individual researcher. It is a privilege earned by laborious apprenticeship and maintained by lifelong commitment to disciplinary values and network memberships. Modern academic life for researchers is strongly dependent on disciplinary networking[3] for professional socialization, keeping up with their research areas, judging the merits of the work of others and their own work,[4] learning the (changing) status of scientific journals, looking for various kinds of research funding opportunities, finding publication outlets, hearing about conferences, and learning of job opportunities are all vital parts of the academic life of scientists who rely on disciplinary networking. Specific scientific disciplines are seen as distinct intellectual and social organizational contexts that have their own norms and values forming disciplinary cultures. These cultures are "internal" systems for regulating knowledge production and validating knowledge. Moreover, these cultures change over time, albeit at varying speeds.

Scientific Collaboration

An old-fashioned, even mythological interpretation of scientific careers is one where scientists are seen as dedicated and often isolated personalities who grapple with problems they set. Such isolated and parochial types of scientific communication no longer can serve as a suitable environment for modern science. Although the new forms of the globalized connections of science reflect Ziman's idea that "the traditional parochial individualism of science is rapidly being transformed in what might be described as transnational collectivism" (Ziman, 1994, p. 218); in our case, collaboration is operationalized as coauthorship of publications.[5] Recent trends show a very clear change in collaboration practices in the 1990s. Figure 1 presents the absolute number of single-authored and coauthored scientific publications published in Slovenia since 1986.[6] Although the number of single-authored publications published each year remained essentially the same after 1995, the number of coauthored publications steadily increased by about 500 units each year. Similar trends have been observed in different scientific communities by many different authors (see Babchuk, Keith, & Peters, 1999; Glänzel, Schubert, & Hans-Jürgen, 1999).

Coauthorship networks and citation networks[7] are very useful instruments for studying collaboration in science. Both have positive impacts on scientific productivity. They have been studied by numerous authors including Price (1965), Beaver and Rosen (1979), Katz and Hicks (1997), Börner, Dall'Asta, Ke, and Vespignani (2005), and Abbasi, Altmann, and Hossain (2011), who all conclude that publications with higher numbers of authors gain higher visibility and have a greater impact on subsequent research.

According to in-depth analyses of collaboration styles of researchers belonging to different scientific disciplines and fields (Kronegger et al., 2011, 2012; Larivière, Gingras, & Archambault, 2006; Mali et al., 2010), the presence of coauthorship and coauthorship structures presents important differentiating indicators between scientific disciplines and fields. The differences in proportions of coauthored publications among seven broad scientific fields in Slovenia are shown in Figure 2. There is a large gap between the average levels in the proportions of collaboration between natural, technical, and medical sciences and the average proportions of collaboration in humanities and social sciences. Although six trajectories show a steady increase during 1986–2010, the trajectory for interdisciplinary studies indicates a high level of instability. Humanities and the social sciences have the lowest percentages of coauthored publications throughout this period.

Examining General Descriptors of Fields

Our main goal is to examine the trajectories of scientific areas shown in Figure 2. To this end, we present an empirical clustering[8] of disciplines based on their collaboration structures and discuss the contrast between scientific areas defined in an official classification system and empirically obtained clusters of scientific disciplines.

Hitherto, various types of scientific classification have been developed for internal (academic) and external (science policy) purposes; a recent partial review of these is provided by Börner, Klavans, et al. (2012). The main categories of the classification used by the Slovenian Research

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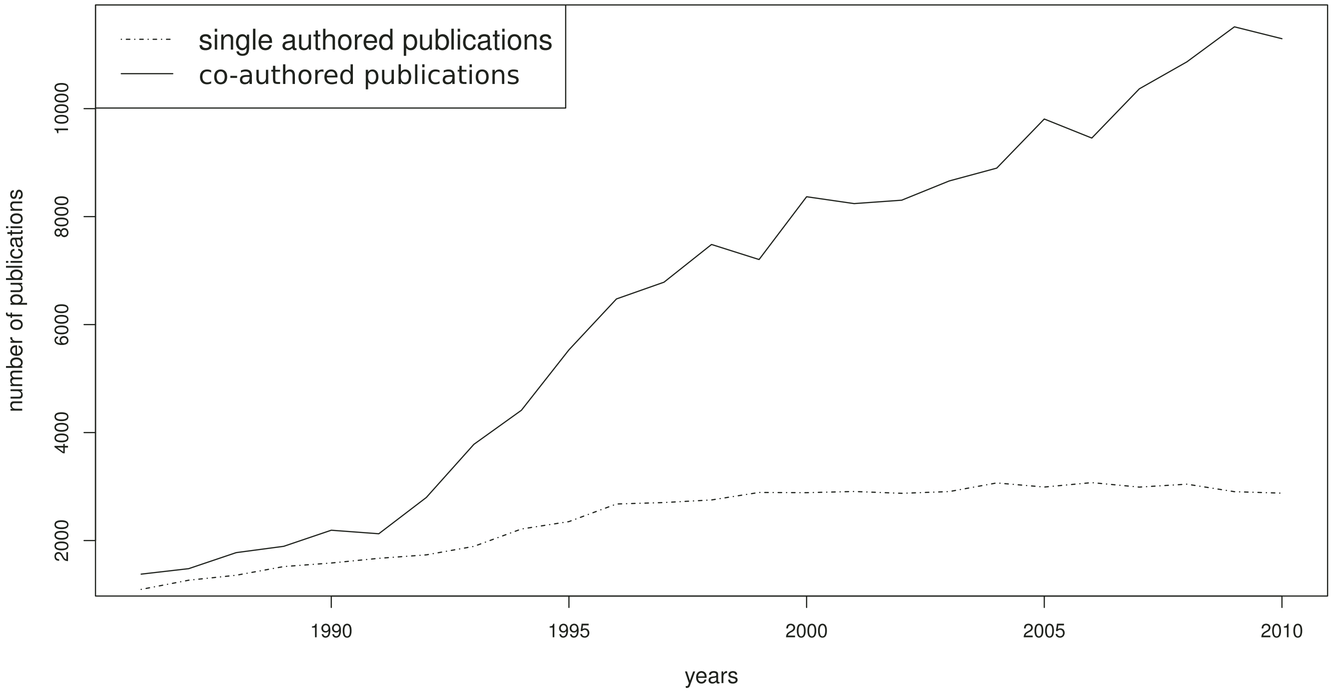

FIG. 1. Absolute numbers of single-authored and coauthored productions published from 1986 to 2010.

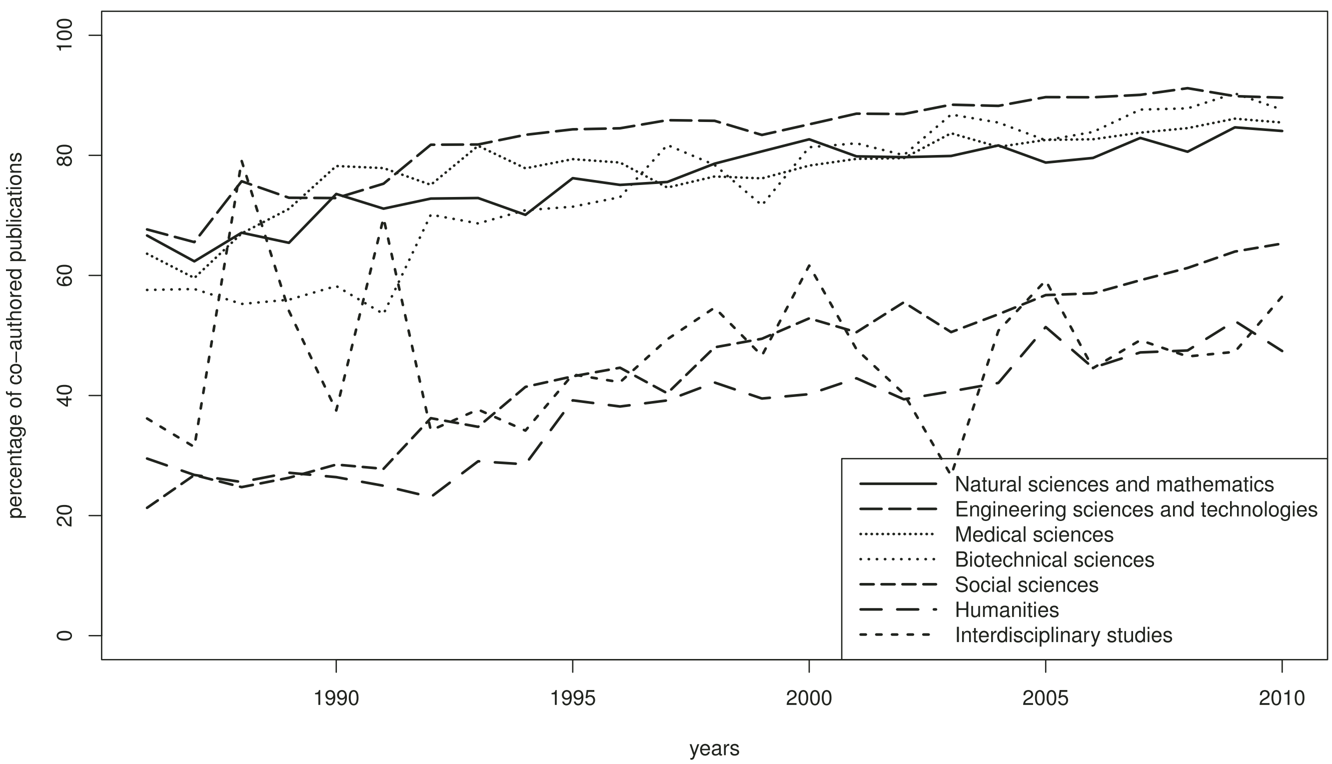

FIG. 2. Percentages of coauthored publications in six scientific fields for Slovenian researchers.

Agency, the main policy authority in science, are presented in Table 1. In the research and development (R&D) policy context in Slovenia, the first four scientific fields (1–4) in Table 1 are usually accepted as sciences for which research topics focus on natural and technical phenomena and nature in general, whereas the next two scientific fields (5, 6) primarily deal with different aspects of society and humanity. The final scientific field (7) has never really gained full

TABLE 1. Seven scientific fields (main scientific areas) in the classification system of the Slovenian Research Agency with the number of disciplines.

ID	Scientific field	No. of disciplines
1	Natural sciences and mathematics	9
2	Engineering sciences and technologies	19
3	Medical sciences	9
4	Biotechnical sciences	6
5	Social sciences	11
6	Humanities	12
7	Interdisciplinary studies	2

recognition as a separate field in the R&D policy context in Slovenia because R&D policy has remained conservative concerning interdisciplinary-oriented research. Over the last few decades, scientific interdisciplinarity has increased dramatically around the world. The increasing tendency of modern science, as well as R&D policy discourses in the leading economic powers, is to bridge narrow disciplinarities in science and to form heterogeneous (interdisciplinary) links to solve pressing social problems (Börner, Boyack, Milojević, & Morris, 2012; Mali, 2010). Unfortunately, in Slovenian R&D policy discourse, the category "interdisciplinary studies" remains unexploited, without solid long-range policy vision for the future. In the classification system used by Slovenian Research Agency, the research problem areas classified in interdisciplinary studies are more linked to traditional humanistic topics (e.g., ethnographic and cultural origins of national identity in Slovenia) than to leading edge research areas such as nano-, bio-, info-, and cognitive sciences (ARRS, 2013). The result, in the Slovenian case, is the research problem areas included in the category "interdisciplinary studies" are very undervalued from the perspective of researchers and in R&D policy discourse.

The official system of scientific classification used at the Slovenian Research Agency reflects the history of state regulation of science in Slovenia: Its scientific classification has the role of an important R&D policy instrument. Classifications of science, as part of an organized R&D policy effort, usually define "the rules of the game" in national scientific systems. Issues of which type of scientific activity deserves less or more financial support in the state budget, or which type of science is best suited to different policy purposes, can hardly be solved intelligibly without classifying types of science. The research activities of scientists do not take place in a social vacuum, and various R&D policy instruments (the use of classification systems, bibliometric indicators to measure R&D output, etc.) govern the access of scientists to research funds, which affects their reputations in communities of professional colleagues.

We differentiate three basic periods for the scientific classification in Slovenia. In the first period, before 1991, when the organizational structure of science in Slovenia was subjected to the common legislative rules of the former Yugoslavia, the official differentiation of the national "scientific landscape" encompassed many peculiarities. At that time, the scientific system in Slovenia was contained by the framework of its national borders and ideologies. The disciplines were characterized by isolationism and parochialism, which had consequences for the system of scientific classification (Mali, 2011).

In the second period, after Slovenia's independence and changes in the political regime in 1991, R&D policy actors in Slovenia showed an increasing interest in adapting its former classification system of science to European Union (EU) and The Organisation for Economic Co-operation and Development (OECD) standards. In the first decade after 1991, governmental institutions made many efforts to adapt the organizational structure of Slovenia's scientific system to the recommendations submitted by the OECD in the *Frascati Manual* (Bole-Kosmač & Kramberger, 2002). The harmonizing with recommendations in the *Frascati Manual* was not fully successful for two reasons. First, the Fields of Scientific Classification (FOS) in the *Frascati Manual* represent a general compromise between different national systems (based on a very general taxonomy of first-level [main scientific fields] and second-level categories [scientific disciplines]).[9] Therefore, it was not very useful in providing guidelines for Slovenia as a transitional country that needed a more radical transformation of its scientific classification system. Second, increased international harmonization has been hindered by the lack of interest inside Slovenia's scientific system. To preserve the status quo without any kind of change serves the interests of influential lobbying groups in science and politics. Slovenia is not only a small country, it is a mini-country (Thorsteinsdóttir, 2000, p. 434). Small country size does not need to lead to a high degree of transparency in R&D policy. On the contrary, with limited formal mechanisms for coordination, there is always a risk that the system is poorly equipped to reduce the influence of informal lobbying groups and to ensure more transparency and flexibility in R&D policy regulation.

In the third period, after the establishment of the Slovenian Research Agency in 2004, the efforts to make any kind of modifications in classification systems mostly dried up. It seems R&D policy actors continued to accept the supremacy of their outdated views on the classification system of science. However, the creation of the Slovenian Research Agency as the new form of intermediary institutions did have many positive effects on R&D evaluation procedures. Even so, the classification system of the Slovenian Research Agency after Slovenia joined the EU is not entirely in accordance with the Common European Research Classification Scheme (CERIF, 1991).[10] Currently, after more than 20 years of various initiatives to modernize the classification system of science in Slovenia, it seems little has changed at the institutional level.

In this article, we do not make a detailed, comprehensive review of existing official classification systems for science, nor do we provide an extended evaluation of these

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systems. However, we do lay the foundations for examining the value of the cognitive criteria used in them. Because both cognitive and social boundaries and interrelations between scientific disciplines evolve over time, all static systems of scientific classifications remain arbitrary at any given point in time. Given the evolution of cognitive and social structures of science, we expect that any useful classification system must be flexible enough to change. Expressed differently, these classification systems need to be sensitive to significant changes in the cognitive and social structures of disciplines. As shown in Figure 2, one characteristic tendency for the production and dissemination of knowledge in various fields of modern science is intensifying scientific collaboration. One indicator is the growth of coauthored publications. At a minimum, systems of scientific classification must be flexible enough that new levels of scientific collaboration can be detected. If so, the interrelationships among scientific disciplines found in our clustering results (see later) will have important heuristic value.

Because our analyses are restricted to the Slovenian scientific system, the results cannot be generalized directly to the international scientific arena at large. Even so, it presents a good case for extending the resulting knowledge about the dynamics of disciplinary structures in a small scientific community to the broader domain of all science.

In the next section, we describe the data used in this study and continue with an abbreviated description of a recently developed procedure for clustering symbolic data. This procedure was used extensively, and the results are presented later in the Results section. We conclude by discussing some of the implications of our findings.

Data

Our clustering analysis was performed on the bibliographic data of all Slovenian researchers and the disciplines to which they belong. The data set was obtained from the Current Research Information System (SICRIS), which includes information on all current and former researchers registered at the Slovenian Research Agency (henceforth labeled by ARRS) and at the Cooperative On-Line Bibliographic System & Services (COBISS), which is the officially maintained database of all publications available in Slovenian libraries.

From this system, we collected complete scientific bibliographies of all Slovenian researchers who ever had a research identification number (ARRS ID) provided by the Slovenian Research Agency. Our data set is limited to publications published between the years 1986 and 2010. The total number of researchers with an ARRS ID who published in this period is 18,426. These researchers collaborated with another 94,062 authors who are not registered at ARRS. Together, they published 256,415 publications that are, by the evaluation criteria of ARRS, treated as scientific productions. These data were organized into five 5-year intervals, spanning 1986–2010.

We have information regarding the main scientific discipline for the majority (15,322) of researchers registered at ARRS. The data about discipline memberships were provided by the researchers themselves when they applied for an identification number.[11] In the classification system used by ARRS, 72 scientific disciplines are classified into the seven scientific fields shown in Table 1.[12]

Our bibliometric analysis was performed on the 66 research disciplines listed in Figure 4 and in Appendix A. For each discipline over the 5-year intervals we considered, the number of researchers who published in a period was at least 10. Using this threshold, four disciplines were excluded: technology-driven physics, communications technology, sport, and ethnic studies. In addition, two additional disciplines from the interdisciplinary field (the nature and civilizational-cultural image of Slovenian territory and people through time [NCKS] research program and interdisciplinary research) were excluded for reasons explained earlier and shown in Figure 2. When included in the analyses, these six disciplines were highly unstable.

The clustering procedure was applied to the structure of collaboration measured with the following four categories:

- Single-authored publications
- Publications coauthored with researchers within the discipline and within Slovenia
- Publications coauthored with researchers from other disciplines also in Slovenia
- Publications coauthored with authors outside ARRS[13]

Table 2 provides a summary of the contribution weights for authors collaborating on a scientific production. Categories were defined using the weighted numbers of publications of researchers where the weights are proportional to each coauthor's contribution, defined according to the number of coauthors of each scientific work and the corresponding discipline of each author. At the level of a single publication, the weight from a coauthored publication of each coauthor is $\frac{1}{a}$, where a equals the number of coauthors. This weight, for each coauthor, is additionally multiplied by the relative frequency according to his collaboration with others, whether the other coauthors come from the same discipline, other disciplines, or are from outside (when they are not registered at ARRS). The denominator of a weight equals a^2. The weights of coauthors for whom the discipline is not available (and so, are not registered in the Slovenian Research Agency) are attributed to the category "outside of the research agency." By definition, the sum of all weights for each publication equals 1. Single-authored publications form a special case where the author weight from the first category equals 1 and all other contribution weights are 0.

Four categories of collaboration in a discipline were computed as the sum of all (weighted) contributions of the authors who belong to a specific discipline in each 5-year period, divided by the weighted number of all publications from this discipline in the time period, and multiplied by 100.

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TABLE 2. An author's contribution weights for a publication with five coauthors.

Authors of publication		Contribution weights		
Author	Discipline of an author	Within the discipline	Between disciplines	Outside research agency
1	Sociology	$\frac{2}{25}$	$\frac{1}{25}$	$\frac{2}{25}$
2	Sociology	$\frac{2}{25}$	$\frac{1}{25}$	$\frac{2}{25}$
3	Mathematics	$\frac{1}{25}$	$\frac{2}{25}$	$\frac{2}{25}$
4	Outside ARRS	0	0	$\frac{5}{25}$
5	Outside ARRS	0	0	$\frac{5}{25}$

Clustering of Symbolic Data Procedure

We cluster scientific disciplines according to five 5-year period collaboration structures described by five discrete distributions with four categories. Therefore, we do not have the classical clustering case with five variables with numerical values, but have discrete distributions that are not continuous. Such data are an example of *symbolic* data. Recent developments of multivariate techniques dealing with symbolic data include Billard and Diday (2006). A clustering procedure to deal precisely with our type of symbolic data has been developed (Korenjak-Černe, Kejžar, & Batagelj, 2010; Korenjak-Černe, Batagelj, & Japelj Pavešić, 2011) and has been termed a modal multivalued symbolic data clustering procedure. Several clustering procedures for symbolic data have been adapted and implemented in R (R Development Core Team, 2012) within the package Clamix (Batagelj & Kejžar, 2011). Ward's hierarchical clustering procedure (Ward, 1963), which we used in this article, also has been adapted.

Similarity

Most clustering algorithms are based on some kind of distance or (dis)similarity measure between pairs of units. For symbolic data, this measure is the most important transition between the traditional clustering approaches to the clustering of symbolic data. Each variable V_i ($i = 1, \ldots, M$) is described by a distribution (vector) x_i of its values. Assume that T is a representative of the cluster C and is also described by M distributions. The dissimilarity between a unit X from the cluster C and its representative T equals

$$d(X,T) = \sum_i \alpha_i \cdot d(x_i, t_i), \quad \alpha_i \geq 0, \quad \sum_i \alpha_i = 1,$$

where x_i and t_i are relative distributions of the unit, X, and the representative, T, respectively, for the variable V_i with k_i categories, and

$$d(x_i, t_i) = w_{xi} \cdot \|x_i - t_i\|^2 = w_{xi} \sum_{j=1}^{k_i} (x_{ij}, - t_{ij})^2,$$

where $w_{xi} > 0$ is a weight of variable V_i for the unit X. The weight α_i can be used to tune the importance of each variable V_i, its default value is $\frac{1}{M}$, and the weight w_{xi} adds additional information to the distribution (e.g., total number of publications in selected discipline).

Hierarchical Clustering Procedure

The hierarchical clustering procedure starts with each unit as a separate cluster and proceeds with step-by-step merging of the two closest clusters. After each fusion, the distances between the new (fused) cluster and the remaining clusters is determined. These distances can be defined in many different ways with each defining a different clustering method. One is Ward's method (Ward, 1963). The transition to clustering of symbolic data requires a generalization of Ward's definition of the dissimilarity between a fused cluster and other clusters. Korenjak-Černe et al. (2010) provided the generalization of Ward's dissimilarity by the dissimilarity between representatives U and V of the clusters C_u and C_v in the following way:

$$D(C_u, C_v) = \sum_i \alpha_i \frac{A_i \cdot B_i}{A_i + B_i} \|u_i - v_i\|^2 = \sum_i \alpha_i \frac{A_i \cdot B_i}{A_i + B_i} \sum_{j=1}^{k_i} (u_i - v_i)^2,$$

where $A_i = \sum_{X \in C_u} w_{xi}$ and $B_i = \sum_{X \in C_v} w_{xi}$; and $u_i = \frac{1}{A_i} \sum_{X \in C_u} w_{xi} \cdot x_i$ and $v_i = \frac{1}{B_i} \sum_{X \in C_v} w_{xi} \cdot x_i$. This is termed the adapted Ward's method.

Clustering of Scientific Disciplines according to Coauthorship Structures in Time

In this study, the symbolic data are described by the distributions of coauthorship in five time periods. Therefore, each of the 66 disciplines is represented by five discrete distributions with four categories. The scientific disciplines

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are clustered according to squared Euclidean distance using the adapted Ward's hierarchical clustering procedure. The resulting clusters of disciplines represent disciplines with similar distributions of collaboration in time.

Results

Figure 2 displays the different trajectories for the average level of collaboration in six scientific fields. Both the social sciences and humanities had noticeably lower levels of coauthored publications than the first four fields listed in Table 1. Figure 3 goes further by depicting the distributions of collaboration types outlined earlier in the Data section. A simple visual comparison of the patterns of coauthorship distributions among fields in Figure 3 reveals the coauthorship structures in natural sciences and mathematics, engineering sciences and technology, and medical sciences are very similar. The coauthorship structure of these fields changes slightly over time and is relatively high for the category of the level of coauthorship with authors from the *same* discipline. There was a slight decrease in the trend of coauthorship with researchers from other disciplines and an increase in the level of coauthorship with foreign researchers who are not members of the Slovenian Research Agency. Biotechnical sciences are different from the three technical fields because of the distribution of coauthorship in the earliest period (1986–1990) that we study. In this period, the level of single-authored publications in the biotechnical sciences is still higher than in the natural sciences and mathematics, engineering sciences and technologies, and medical sciences. However, the later distributions for the biotechnical sciences quickly take the shape of the other natural, technical, and medical fields.

Although the proportions of single-authored publications of the social sciences and humanities remain higher than all collaborative types through all five presented time periods, the decrease of these proportions is evident. We note that when we excluded single-authored publications, the distribution of coauthorship in social sciences resembled the distribution from the first group of fields (natural sciences and mathematics, engineering sciences and technologies, and medical sciences). In the humanities, the proportion of single-authored publications exceeds the proportion of the sum of all kinds of collaborative publications and identifies the humanities as the least collaborative field.

Clustering of Scientific Disciplines

The clustering of 66 scientific disciplines is presented in the dendrogram in Figure 4. It shows, unsurprisingly, that there are two major groups of disciplines.[14] They are labeled as Cluster 1 and Cluster 2. The first contains disciplines that belong to natural sciences, engineering sciences and technologies, medical sciences, and biotechnical sciences. Cluster 2 has the social sciences and the humanities. Both clusters are very close to the obvious division of scientific fields. However, four disciplines do not fit this simple classification. Mathematics, as a natural science discipline, and landscape design, as a biotechnical discipline, were clustered into Cluster 2 with the social sciences and humanities, whereas, in contrast, administrative and organizational sciences, officially one of the social sciences, and geography, as a humanity discipline, are located in Cluster 1 (see Table 3).

Figure 5 shows that, consistent with Figure 3, the number of single-authored productions is much lower in Cluster 1 than in Cluster 2. However, in both of these clusters, this level drops across the five periods into which 1986–2010 was divided. The level of coauthorship within disciplines is much higher in Cluster 1 than in Cluster 2. For Cluster 1, this level increases over the first three periods and remains high thereafter. This level increases across all five periods for the disciplines in Cluster 2. Even so, for 2006–2010, it does not reach the level shown for Cluster 1 in 1986–1990. Cluster 2 also has lower levels of coauthored papers with researchers in other disciplines within ARRS and with coauthored papers with others outside this research agency. The levels of these two types of collaboration do increase slightly during the period 1986–2010 but never reach the levels for Cluster 1 in 1986–1900. These levels for Cluster 1 fluctuate but finish at higher levels in 2006–2010, especially for coauthored publications with other researchers outside ARRS.

The disciplinary inconsistencies identified within the partition of Figure 4 suggest that some refinement of the partition is merited to obtain more insight into disciplinary changes over time with regard to the different volumes and patterns of coauthored publications.

Refined Clustering of Disciplines

For a more detailed description of the clusters of disciplines, we used the dendrogram in Figure 4 to split Cluster 1 into three subclusters and Cluster 2 into two subclusters. Examining the resulting five subclusters provides more insight into temporal changes with regard to temporal changes in disciplinary coauthorship. We label the three subclusters of Cluster 1 as Cluster 1.1, Cluster 1.2, and Cluster 1.3. The first subcluster consists of three disciplines from the natural sciences and one from the medical sciences. Cluster 1.2 is the largest subcluster and consists basically of disciplines belonging to all scientific fields other than social sciences and humanities. Cluster 1.3 consists of the broadest spectrum of disciplines, from the natural to the humanities.

The second primary cluster is split into two subclusters labeled as Cluster 2.4 and Cluster 2.5. Cluster 2.4 consists only from the disciplines from the social sciences and humanities. Cluster 2.5 is similar to Cluster 2.4 but with two additional disciplines from the natural sciences and one from the biotechnical sciences (see Table 3). At first sight, these do not belong to this cluster, but considering their coauthorship structures, they are more similar to the social sciences and the humanities than to most disciplines from the natural sciences. When considering the appearance of

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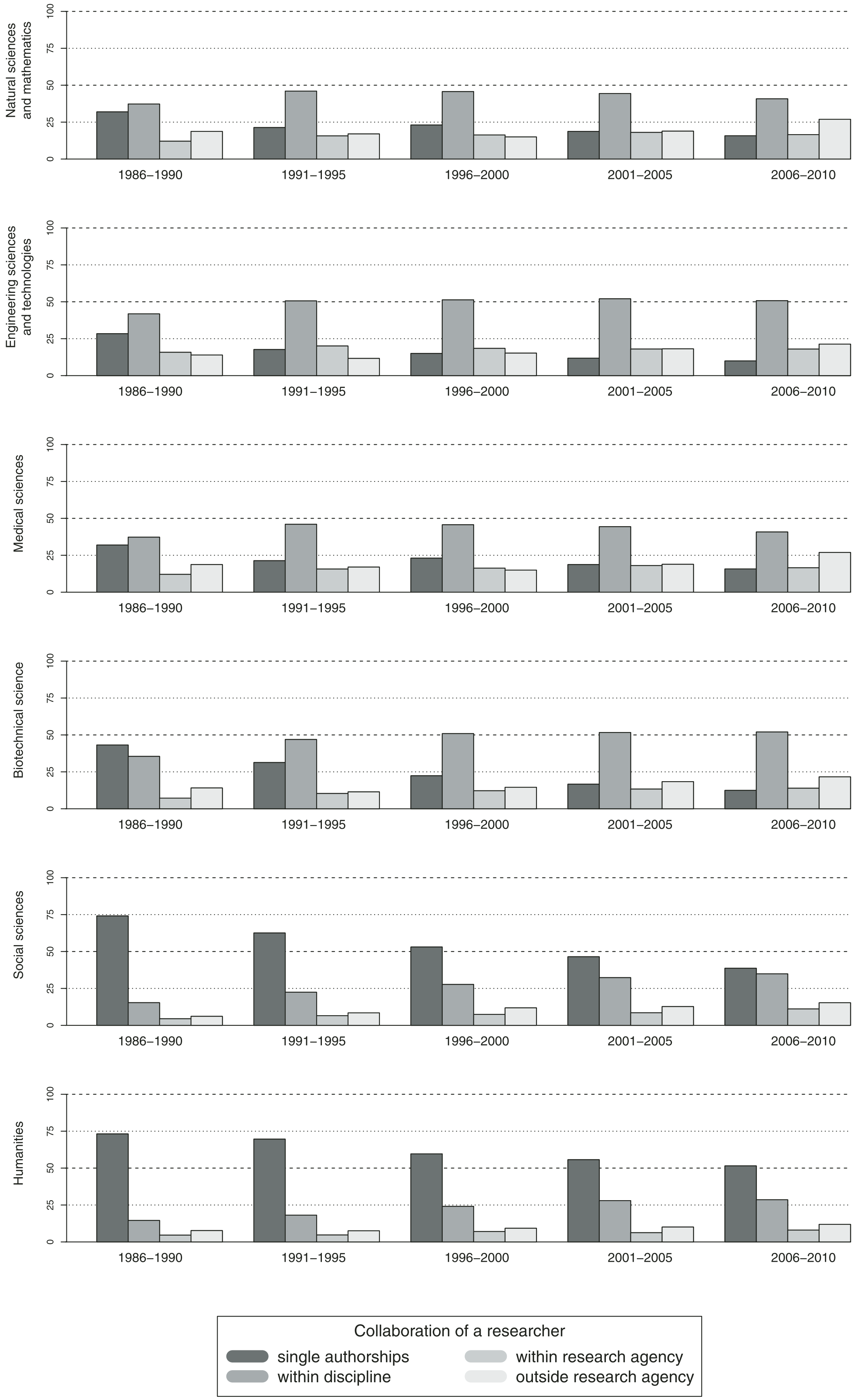

FIG. 3. Average distributions of coauthorship in five time periods for each of six research fields defined by ARRS classification.

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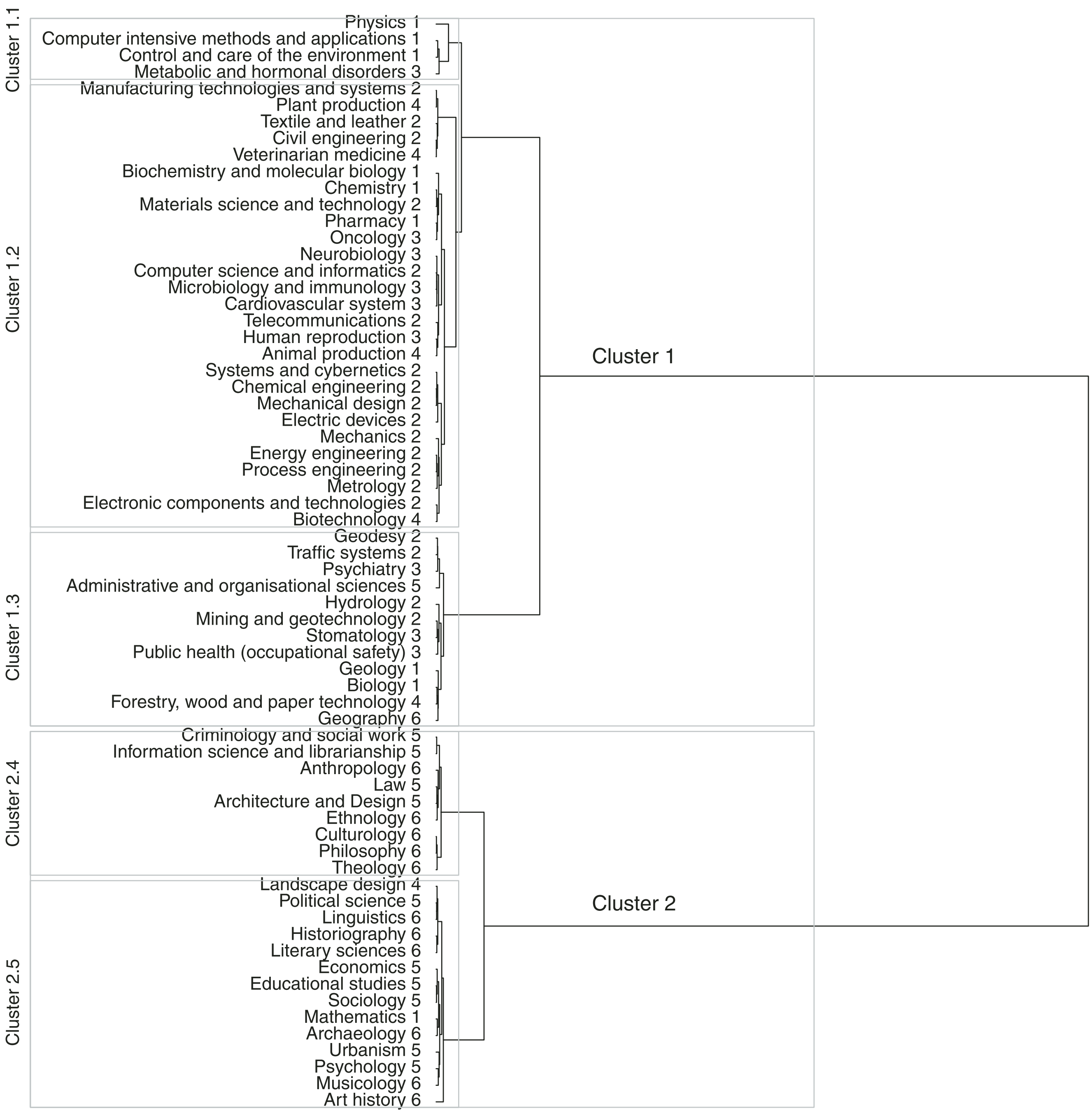

FIG. 4. Dendrogram for the hierarchical clustering of scientific disciplines.

TABLE 3. Classification of disciplines according to the ARRS classification of disciplines and the obtained clustering into two clusters.

Scientific field	Obtained clusters: Cluster 1: "Hard" disciplines	Cluster 2: "Soft" disciplines	Outliers
1 Natural sciences and mathematics	8	1	Mathematics
2 Engineering sciences and technologies	19	0	
3 Medical sciences	9	0	
4 Biotechnical sciences	5	1	Landscape design
5 Social sciences	1	10	Administrative and organizational sciences
6 Humanities	1	11	Geography

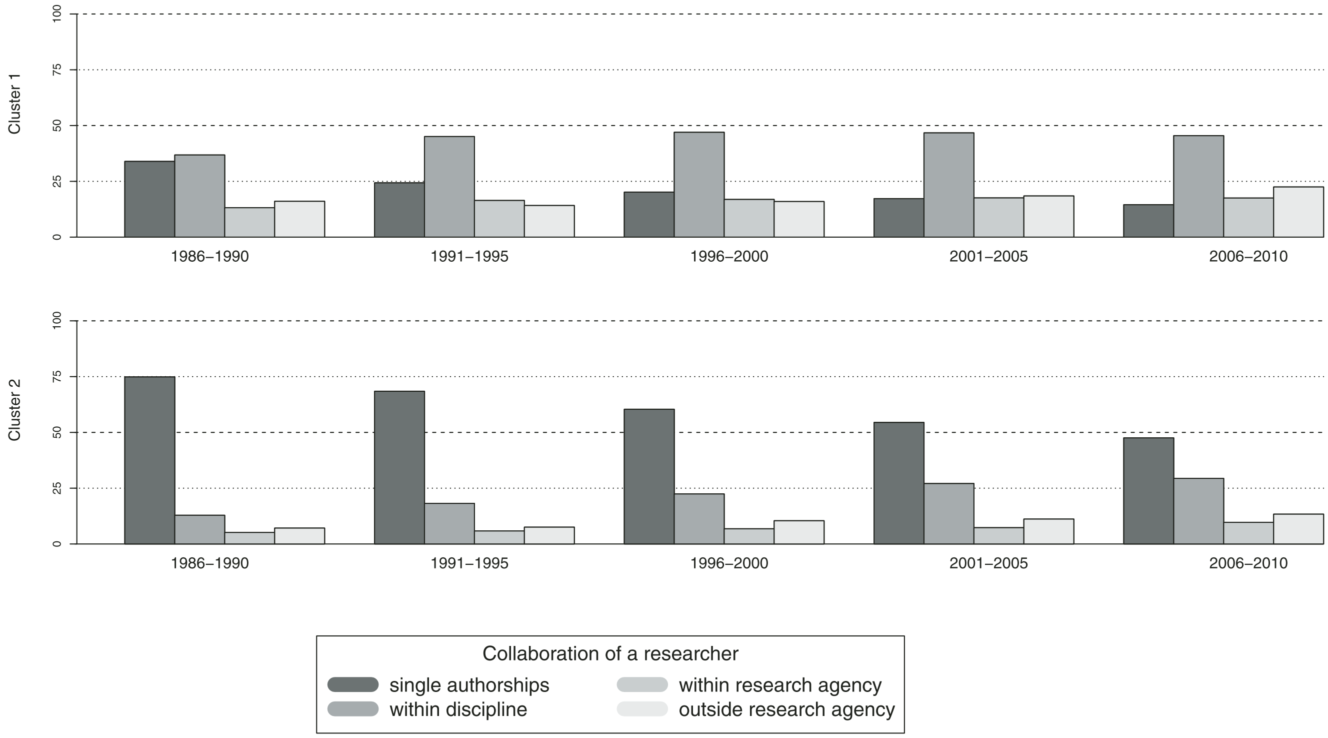

FIG. 5. Average distributions of coauthorship in five time periods for the two main clusters.

disciplines from different subclusters, we note that some disciplines from the first scientific area *natural sciences and mathematics* appear in *all* subclusters other than Cluster 2.4.

Figure 6 displays the average distributions of collaboration for each obtained subcluster for five measured time periods. The clusters are ordered by the decreasing percentage of single-authored publications. This decrease is also a general trend, one that can be observed in all five subclusters through all five periods. The increase in the percentage of coauthored publications is the highest for coauthorship with researchers from the same research discipline. For coauthorship with the researchers from the other disciplines and the authors who are not registered at the Slovenian Research Agency, the increases are the smallest.

More specifically, each of five clusters shows a distinct distribution pattern. We consider first Clusters 2.4 and 2.5 before moving on to consider Clusters 1.3, 1.1, and 1.2 in that order.

- Cluster 2.4 has by far the highest percentage of single-authored publications as shown in the top panel of Figure 6. Although collaboration has increased slightly since 1986, still more than 60% of all publications in the disciplines from this subcluster are published by single authors.
  The disciplines in this subcluster are traditionally monograph-oriented disciplines from the humanities including ethnology, anthropology, culturology, philosophy, and theology, together with specific disciplines from social sciences such as criminology and social work, information science and librarianship, architecture and design, and law.
- Coauthorship gains in importance across every period in Cluster 2.5, whereas the number of single-authored publications declines. Indeed, after 2000, the total volume of coauthored publications exceeds the volume of single-authored publications. Even so, the percentage of single-authored publications remains largest among the four categories, as shown in the second panel of Figure 6. Yet the temporal shifts are systematic and clear. These are trends that are likely to continue. This subcluster contains the remaining disciplines from the humanities and the majority of disciplines from social sciences. According to the traditional disciplinary classification into scientific fields, there are two seemingly misplaced disciplines: landscape design from the biotechnical sciences plus mathematics from the natural sciences.
- Cluster 1.3 had a decrease in single-authored publications from 1986 (more than 50%) to 2010 (less than 25%). Despite starting at levels less than those for Clusters 2.4 and 2.5, this decline was the largest among the subclusters. The shape of the distribution in the last time period (2006–2010) is very similar to the distributional shape of Cluster 1 (see Figure 5). The membership of this subcluster is very broad ranging from natural science disciplines (biology and geology), to the technical and the biotechnical sciences (geodesy, forestry, mining and geotechnology, traffic systems, and hydrology), the medical sciences (psychiatry, public health, and stomatology), administrative and organizational sciences that belong to the social sciences, and geography from the humanities.
- Cluster 1.1 has the most uniform distribution of coauthorship types. There was a very low level of single-authored publications, whereas collaboration within the discipline was

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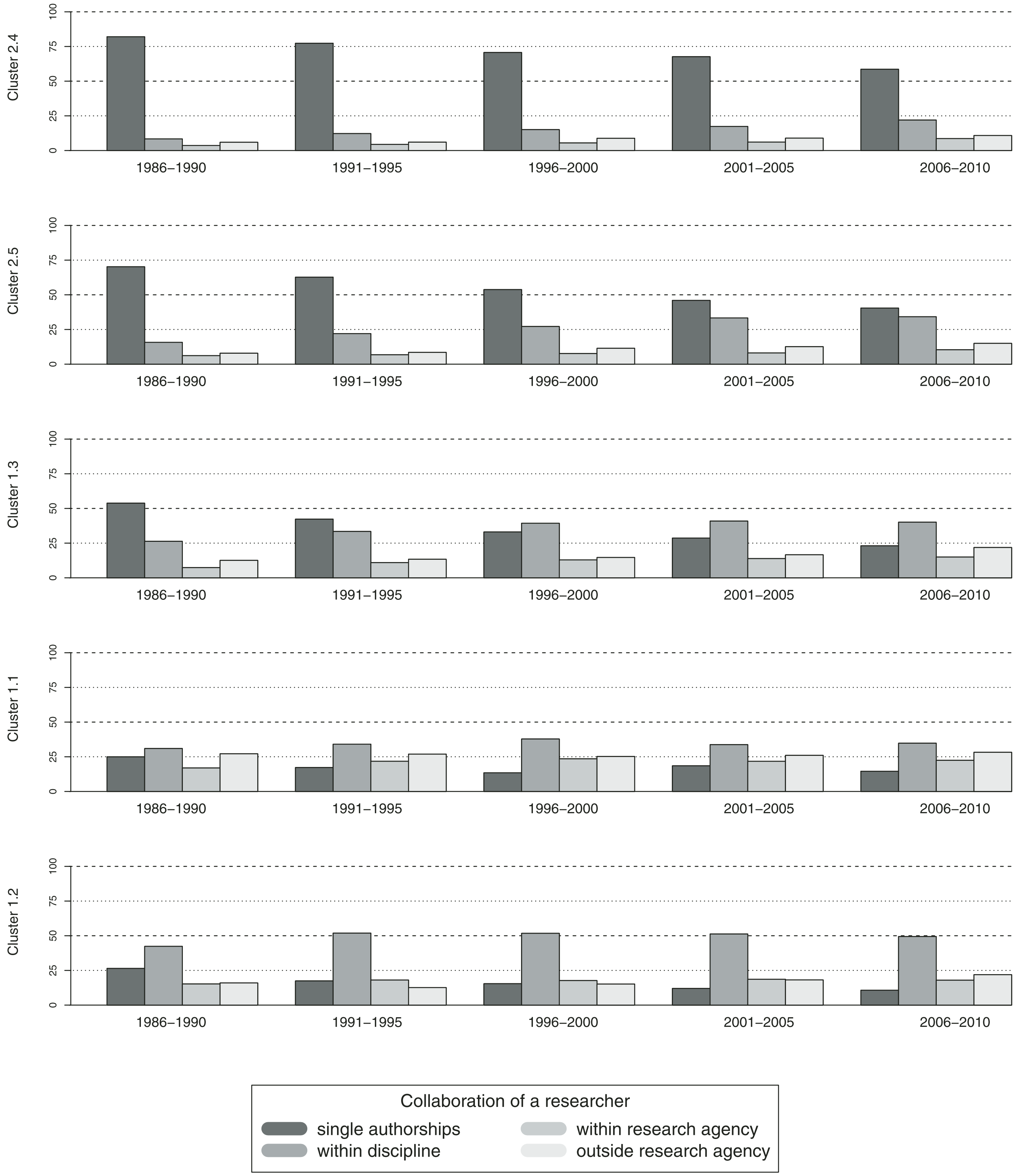

FIG. 6. Average distributions of coauthorship in five time periods for each obtained cluster.

the highest in all periods. We note that this subcluster is the only one in which the proportion of single-authored publications did *not* decline through all five periods. It did drop through the first three periods but increased in the fourth period (2001–2005) as shown the fourth panel of Figure 6. It then dropped in the last period but remained at a level above that in the third period. This anomaly merits further attention. The disciplines in this subcluster are physics, computer intensive methods, and control and care of the environment (all from the natural sciences), and metabolic and hormonal disorders from the medical sciences.

- Cluster 1.2 is by far is the largest subcluster. It contains a large set of disciplines from the natural, technical, biotechnical, and medical sciences. The distributional shape of this subcluster changes the least over time. Its most visible characteristic is a very high level of coauthorship with researchers from the same discipline. This cluster best corresponds with the notion of laboratory sciences discussed by Kronegger et al. (2011), even though it does not contain physics. Among laboratory sciences, small, informally organized collaborations are more common.

Even though each of the subclusters has a different pattern across the four collaboration categories that we consider, there are some common trends as noted earlier. However, there are sufficient differences in these profiles to suggest that there is no single trend over time for the evolution of the collaboration structures of science.

Clusterings according to the Distributions of Coauthorship for Each Period

The clustering procedure of symbolic data used for the analysis allows the clustering of several variables at the same time, which was used to cluster distributions of coauthorship measured in five time periods together (joint clustering). To check the stability of clustering and movement of separate disciplines between clusters over time, additional clustering of disciplines was performed on distributions of coauthorship measured in separate time periods (separate clusterings). As before, the disciplines are clustered into two and into five distinct clusters.[15]

The classification graphs in Figures 7 and 8 are defined by nodes representing obtained clusters of disciplines. In the graph, each node is represented by the average collaboration distributions of the disciplines in the cluster. The arcs in the two figures represent the number of disciplines that change cluster membership in two sequential time periods.

The results of the clustering into two clusters are relatively stable through time; in all time periods, there is a (small) group of disciplines that "move" between the first cluster and the second cluster. In all time periods, the core of this "transitional" group consists practically from the same disciplines: biology, geology, mining and geotechnology, stomatology, public health, and forestry. In addition to this core of disciplines, the inconstancy is shown also by psychiatry, and administrative and organizational sciences. From the period 2001–2005 to the period 2006–2010, two disciplines from natural sciences and mathematics (biology and geology), two disciplines from engineering sciences and technologies (mechanic and mining and geotechnology), three disciplines from scientific field medicine (stomatology, public health, and psychiatry), one discipline from biotechnology (forestry), and one from social sciences (administrative and organizational sciences) moved

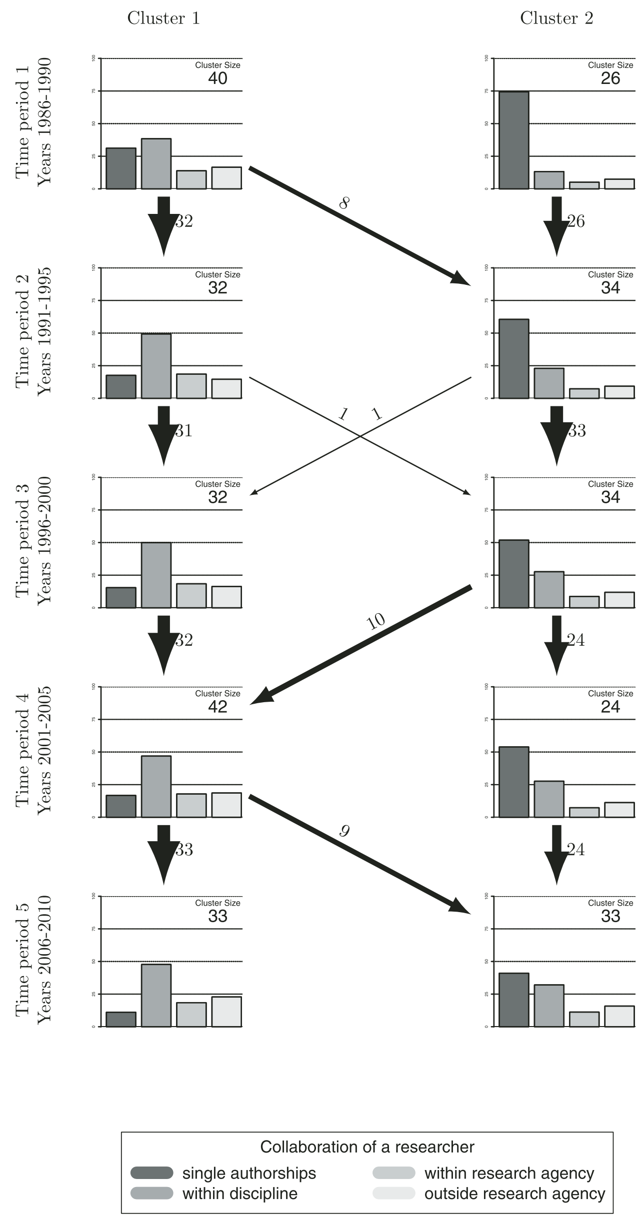

FIG. 7. Transitions of disciplines among clusters through separate clusterings in time.

from Cluster 1 to Cluster 2. Quite an interesting regularity is seen in the dynamics of "movable" disciplines between Clusters 1 and 2. It could be explained by internal characteristics of these disciplines, as well as by external factors having an impact on the dynamics of disciplines. The relationship between internal and external factors that have an impact on the dynamics of scientific disciplines can be observed from various perspectives. In our case, the dynamics of the core group of movable disciplines can be described in terms of their internal (epistemological) characteristics, whereas at the same time, external (macro) factors constitute a framework of scientific dynamics. The scientific dynamics is based on historical contingencies regarding the interaction between

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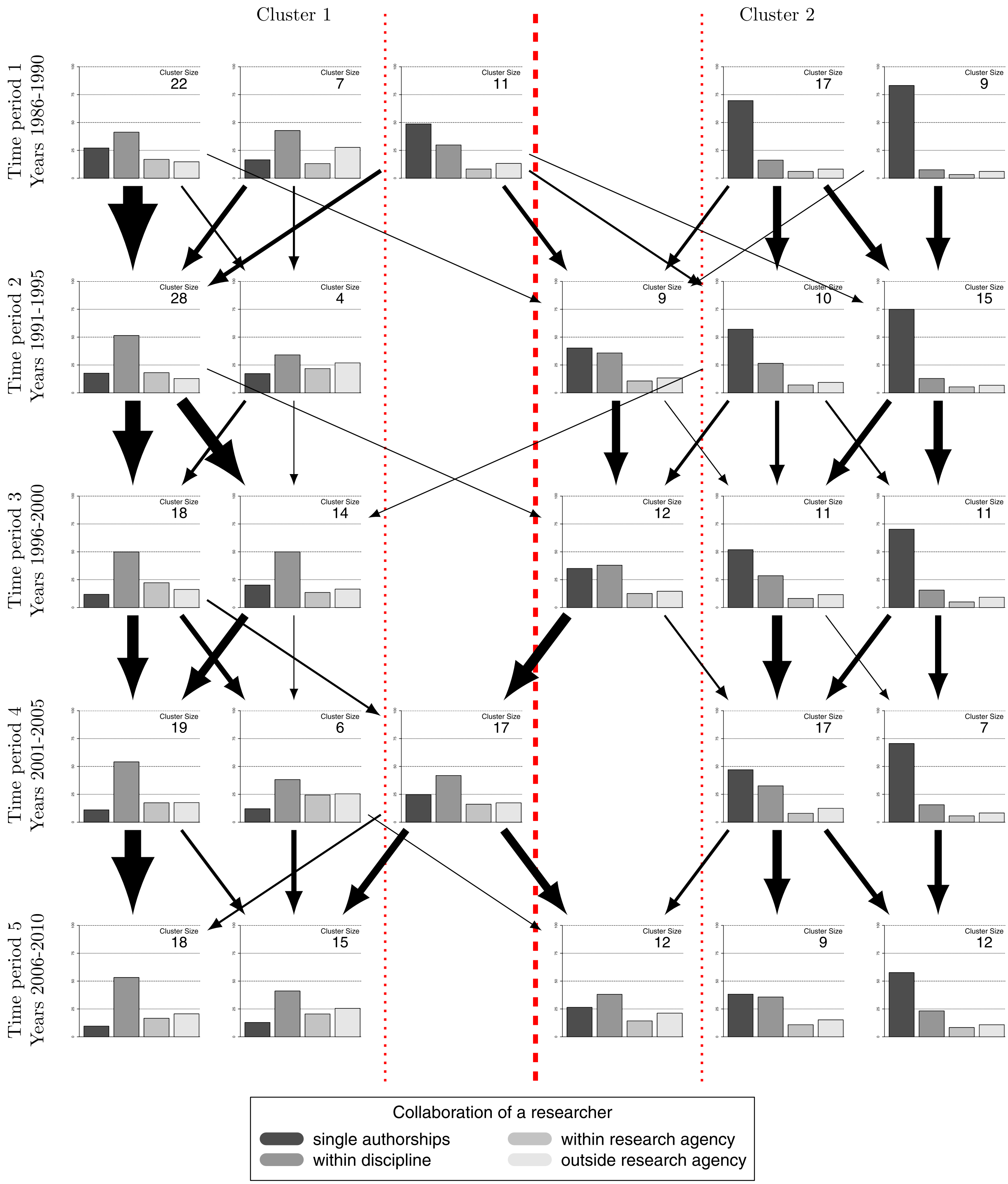

FIG. 8. Transitions of disciplines among clusters through separate clusterings in time. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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inside-outside disciplinary logic and changing forces. The diagrams in Figure 7 and in Figure 8 clearly show the instability of both obtained clusters after Slovenia's independence in 1991 and after joining the EU in 2005, when the "transitional cluster" of disciplines moved from the first cluster to the second and back again.

The separate clustering into five clusters is less stable and clear than the clustering into two clusters. As shown in Figure 8 and in Table A1 (see Appendix A), the number of subclusters, parts of two clusters identified in separate clusterings into two clusters, change through time. With few exceptions, it is hard to think about clusters existing across the *entire* period with regard to collaboration patterns.

To test whether the instability empirically obtained clusters through time is the result of the relatively small number of publications published in these disciplines, the table with the number of publications (according to the contribution index presented in Table 2) is provided in Appendix B (see Table B1). As noted earlier, the smallest disciplines were excluded from the analysis (technology-driven physics, communications technology, sport, ethnic studies, NCKS research program, and interdisciplinary research). The number of publications within the unstable scientific disciplines is small across the studied time periods. However, it is not always the smallest size.

Conclusions

The first obvious partition of scientific disciplines according to the structure of coauthorship shown in Figure 4 had two large clusters of disciplines. This provided the foundation for a preliminary description of the changes in this aspect of collaboration structures from 1986 to 2010 for 66 scientific disciplines in Slovene science. A more useful clustering of these scientific disciplines, again according to the structure of coauthorship, was obtained from Figure 4 by further partitioning the two main clusters. The resulting five subclusters of the scientific disciplines provide a more detailed description of temporal changes.

The finer grained partition clearly separates the majority of the disciplines from the natural, technical, biotechnical, and medical fields into three subclusters (Clusters 1.1, 1.2, and 1.3) and most of the disciplines from the social sciences and humanities into another two subclusters (Clusters 2.4 and 2.5). The most diverse subcluster (Cluster 1.3) merits further attention because of the diversity of disciplines within it. We label it as a "transitional cluster" and placed it in the middle panel of Figure 6 because its distributional shapes lie between those of the two panels above it and the two panels below it in Figure 6. Figure 8 shows that in separate clusterings in time, the "transitional cluster" twice belongs to the main Cluster 1 (first and fourth time period) and at three time periods to the main Cluster 2. The details of this subcluster suggest that the classification system of the Slovenian Research Agency is based on a limited number of historically defined epistemological criteria that require continual revision. One consequence of this seeming epistemological rigidity in the existing classification system is that two scientific disciplines can be classified as very distant by some criteria and very close by other criteria. It is important to include both sets of criteria, especially those that permit a flexible characterization of the modern production of scientific knowledge. The various forms of cooperation among researchers leading to common coauthorship patterns are crucial indicators of the new type of scientific knowledge production. The structure of scientific disciplines (as well as the relations between disciplines) have been in a state of flux: new disciplines emerge, established disciplines shrink and fade away or they grow and recombine with others. When such classification systems neglect the changing environment, new factors may appear with the potential to lead us away from observing the production of new scientific knowledge. To use only one classification system of science as an exhaustive and fixed set of sciences, such as the periodic table in chemistry with an exhaustive set of possible chemical elements, is acceptable only in ideal-typical models for explaining science. In reality, open systems of production of scientific knowledge are emerging. Only classification system of science based on open systems of production of scientific knowledge can enhance the productivity of the scientific enterprise. As science evolves, its classification system must change as well.

The awareness of the dynamic production of scientific knowledge is especially important for R&D policy decision-makers who use the classification system as an instrument for R&D evaluation procedures and for the distribution of public R&D resources. Traditional concepts for the production of scientific knowledge are no longer sufficient, especially with the recent increased pressure on R&D policy actors in Slovenia to encourage applied science. Applied research attempts to establish knowledge for use in implementing policies for practical outcomes. Moving into applied research and creating new forms of knowledge production requires the use ofadditional evaluative criteria. For example, new interdisciplinary and transdisciplinary areas of scientific knowledge are precisely the type of knowledge that must be regulated (and assessed) from outside the realm of traditional academic scientific classifications in an arena where external social, economic, and policy factors play much more important roles (e.g., Bergmann and Schramm, 2008; Mali et al., 2010).

Recognizing that a system of scientific classification, one that is not closed, is by itself insufficient, R&D policy actors also need to promote careful and democratic dialogue among affected actors to contribute to the improvement of scientific classification. R&D policy actors need to use systems of scientific classification wisely. Bibliometricians have established that some disciplines from the fields of social sciences and humanities can be very similar to disciplines from the natural, technical, and medical sciences, whereas other disciplines have characteristics that push them far away from the traditional publication profile of the natural-technical group of scientific disciplines. In the case that we arrange scientific disciplines only in regard to criteria "monograph-oriented versus article-oriented" disciplines, we will rarely encounter two homogeneous groups of disciplines belonging to the social sciences and humanities, and disciplines belonging to the natural-technical sciences (e.g., Nederhof, 2006; Van Leeuwen, 2006). Our bibliometric analysis of coauthorship networks in science leads to a similar conclusion despite the upheavals of war and national independence. For example, the presence of mathematics and landscape design from the natural sciences in a subcluster with social science disciplines provides supporting evidence. These empirical results reinforce a view that change in the collaboration structures of scientific disciplines will have more impact on the formal organization of scientific knowledge in Slovenia. They suggest also universal patterns of knowledge creation not restricted to the conditions of single nations.

The results of our bibliometric analysis have shown a high level of dynamism in science as practiced in Slovenia. The ordering of the clusters in Figure 6 revealed systematic patterns regarding the structural dynamics of scientific collaboration. Putting to one side the temporal dimension, the graphical distributions can be stacked one on top of another in the order presented in Figure 6. Visually, the transitions show a gradual evolution of publishing collaboration in science from an early stage of mainly single-authored publications toward a uniformly distributed coauthorship structure. One cluster in this ordering is the bottom one in Figure 6 with the strongest collaborations within disciplines. This cluster consists of scientific disciplines where the research is mainly performed in laboratories with several coresearchers. One direct consequence is that researchers in these collaborative projects publish papers together with colleagues within the same scientific discipline.

This line of thought can be taken one step further. Single-authored productions must be within the discipline of the authors producing them. The disciplines in Clusters 1.1 and 1.2 show higher levels of within-discipline coauthorship, and the disciplines in Cluster 2.5 are moving in this direction. This suggests, at least for Slovenia, a reason for less work taking place within interdisciplinary studies. It seems that the institutional organization of modern science, especially within universities, still places constraints on cross-disciplinary collaboration. Budget flows are organized by disciplines and this reduces incentives for researchers to collaborate across disciplinary boundaries. We suspect that these constraints and disincentives are not unique to Slovenia and represent an important R&D policy issue that merits serious attention in other national and transnational contexts.

Acknowledgments

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Endnotes

1. In the context of epistemology and methodology of social sciences, Weber (1988) had already elaborated the basic difference between nomothetic sciences (*Gesetzeswissenschaften*) and idiographic sciences (*Ereigniswissenschaften*). Weber's basic focus was on how to break the (epistemological) barriers between both types of sciences (Mali, 2006).

2. Recently, commitment to various methodologies (artificially) still divide scientists. In a very general sense, *Methodenstreit* is the symbolic expression of a rather old-fashioned disagreement between quantitative (usually based on a critical rationalistic epistemology) and qualitative methods (relying more on an interpretative epistemology).

3. In the sociology of science, there are many theoretical and empirical insights into how the professional socialization in the context of scientific disciplinarity takes place (e.g., Fuchs, 1992; Kuhn, 1962). In traditional explanations within the sociology of science, teaching and research in the context of disciplinarity are craft activities, learned by experience through on-the-job training in academic apprenticeships or work within a "guild system." Academic apprenticeship is thought to distinguish scientific activity from other professional activities such as work in mass production industries and bureaucratic institutions. The expectations concerning the scientific activity (including the production of novelty), which is supposed to have a high level of task uncertainty and individual freedom, makes it impossible that social and cognitive organization of science, through its whole history, would have the same characteristics as the bureaucratic and industrial system of work planning and control (Ravetz, 1971).

4. Modern scientific influence is exerted by peer review through collegial control in the context of scientific disciplines. The focal points of the organization of peer review systems are the "collegiums" of scholars focused within their academic scientific disciplines (see Hornbostel, 1997; Whitley & Gläser, 2007). We note that the traditional academic peer review systems, in recent decades, have been supplemented by various external evaluation systems. In some contexts, these external systems may replace the peer review system when policy directives are considered (Hemlin & Rasmussen, 2006).

5. De Haan (1997) suggested six indicators to measure collaboration between researchers in the field of social sciences and humanities: coauthorship, shared editorship of publications, shared supervision in PhD projects, writing research proposals together, participation in formal research programs, and shared organization of scientific conferences. We primarily deal with coauthorship as one form of collaboration practices in science (Kronegger, Ferligoj, & Doreian, 2011; Kronegger, Mali, Ferligoj, & Doreian, 2012; Mali, Kronegger, & Ferligoj, 2010). We use such data, in large part, because of their availability even though about half of scientific collaboration efforts are invisible in formal communication channels because they need not result in coauthored publications nor are they acknowledged in scientific texts (Cronin, 2001; De Haan, 1997; Laudel, 2002). Yet publications are part of the visible *institutionalized* structure of science, whereas informal communications are not.

6. The source of the data presented in Figures 1 and 2 is presented in the Data section.

7. There is a basic difference between these bibliometric networks. If science citation networks are the best bibliometric indicators to depict the whole (cognitive) structure of scientific knowledge, then coauthorship networks are the best bibliometric indicators for depicting the various patterns of (cognitive and social) collaborations in the academic scientific disciplines (Newman, 2001).

8. Although clustering and classification are, in essence, synonyms, we use the former for establishing our partitions, whereas an official classification of scientific disciplines was our point of departure.

9. The 2002 *Frascati Manual* included an FOS classification. After several reviews, a Revised FOS classification was published in 2007 that consisted of the following first-level categories (main scientific fields):

natural sciences, engineering and technology, medical and health sciences, agricultural sciences, social sciences, and humanities (OECD, 2007).

10. CERIF is recognized by the European Commission as an important item for surveying the R&D potential EU members. The information obtained on the basis of the CERIF usually helps the formulation of the R&D policy at the national level (Joerg, 2010). Unfortunately, the heterogeneity in the organization of national "R&D landscapes" often discourages efforts to reach a unique EU classification of science.

11. Changes of research discipline later in career are rare and were not monitored within this analysis. The data on researchers' affiliations to research disciplines therefore resemble the situation from autumn 2012 when data were captured.

12. These 72 scientific disciplines in the classification system used by ARRS are further divided into 297 research problem areas. In the expert literature, research problem areas are usually defined as scientific subdisciplines or scientific specialties. Research problem areas or (better) scientific specialties are described as the local intellectual areas where knowledge claims are disputed and articulated (Chubin, 1976; Niiniluoto, 1995). Ziman argued "one of the principal responsibilities of a recognized research scientist is to be sufficiently familiar with the literature of his or her specialty to assess the novelty and/or plausibility of a research report or project proposal in that field" (Ziman, 2000, p. 189).

13. Authors from outside of ARRS are sometimes labeled as "foreign authors."

14. The numbers printed beside discipline names are identification numbers of scientific fields listed in Table 1.

15. The complete list of clustered disciplines, classification of Slovenian research agency, and clustering results are presented in Appendix A.

References

Abbasi, A., Altmann, J., & Hossain, L. (2011). Identifying the effects of co-authorship networks on the performance of scholars: A correlation and regression analysis of performance measures and social network analysis measures. Journal of Informetrics, 5(4), 594–607.

ARRS. (2013). Raziskovalne vede, podroja in podpodroja (klasifikacija ARRS). Retrieved from http://www.arrs.gov.si/sl/gradivo/sifranti/sif-vpp.asp

Babchuk, N., Keith, B., & Peters, G. (1999). Collaboration in sociology and other scientific disciplines. The American Sociologist 30, 5–21.

Batagelj, V., & Kejžar, N. (2011). clamixClustering Symbolic Objects. Retrieved from https://r-forge.r-project.org/projects/clamix

Beaver, D., & Rosen, R. (1979). Studies in scientific collaboration—Part III. Professionalization and the natural history of modern scientific co-authorship. Scientometrics, 1(3), 231–245.

Becher, T., & Trowler, P. (2001). Academic tribes and territories (2nd ed.). Buckingham, UK: Open University Press/SRHE.

Bergmann, M., & Schramm, E. (Eds.) (2008). Transdisziplinaere Forschung. Frankfurt, Germany: Campus Verlag.

Billard, L., & Diday, E. (2006). Symbolic Data Analysis. Conceptual Statistics and Data Mining. New York, NY, USA: Wiley.

Bole-Kosmač, D., & Kramberger, A. (2002). Informacijski sistem slovenske znanosti v 90. letih: Klasifikacija raziskovalnih področij. In S. Sorčan (Ed.), Raziskovalna dejavnost na Slovenskem v 90. letih dvajsetega stoletja (pp. 199–219). Ljubljana: Slovenska akademija znanosti in umetnosti.

Börner, K., Boyack, K. W., Milojević, S., & Morris, S. (2012). An introduction to modeling science: Basic model types, key definitions, and a general framework for the comparison of process models of science dynamics. In A. Scharnhorst, K. Börner, & P. Besselaar (Eds.), Models of Science Dynamics. Vol. 69 of Understanding Complex Systems (pp. 3–22). Berlin/Heidelberg, Germany: Springer.

Börner, K., Dall'Asta, L., Ke, W., & Vespignani, A. (2005). Studying the emerging global brain: Analysing and visualizing the impact of co-authorship teams. Complexity, 10(4), 57–67.

Börner, K., Klavans, R., Patek, M., Zoss, A. M., Biberstine, J. R., Light, R. P., Larivière, V., & Boyack, K. W. (2012). Design and update of a classification system: The UCSD map of science. PLoS ONE, 7(7), e39464+.

CERIF. (1991). Commission Recommendation concerning the harmonisation within the community of research and technological development databases (6 may 1991). Official Journal L, 189, 1–34.

Chubin, D. (1976). The conceptualization of scientific specialities. Sociological Quarterly, 17, 448–476.

Creswell, J. (2003). Research sesign: Qualitative, quantitative, and mixed methods approaches. Thousand Oaks, CA, USA: SAGE Publications.

Cronin, B. (2001). Hyperauthorship: A postmodern perversion or evidence of a structural shift in scholarly communication practices? Journal of the American Society for Information Science and Technology, 52(7), 558–569.

De Haan, J. (1997). Authorship patterns in Dutch sociology. Scientometrics, 39(2), 197–208.

Fara, P. (2009). Science: A four thousand year history. New York, NY, USA: Oxford University Press.

Fuchs, S. (1992). The Professional Quest for Truth: A Social Theory of Science and Knowledge. Albany, NY, USA: State University of New York Press.

Fuller, S. (1997). Science. Concepts in the Social Sciences. Buckhingam, United Kingdom: Open University Press.

Glänzel, W., Schubert, A., & Hans-Jürgen, C. (1999). A bibliometric analysis of international scientific cooperation of the European Union (1985–1995). Scientometrics, 45, 185–202.

Hagstrom, W. (1965). The Scientific Community. New York, NY, USA: Basic Books.

Hemlin, S., & Rasmussen, S. (2006). The shift in academic quality control. Science, Technology & Human Values, 31(2), 173–198.

Hornbostel, S. (1997). Bewertungen in der Wissenschaft. Wissenschaftsindikatoren. Opladen, Germany: Westdeutscher Verlag.

Joerg, B. (2010). CERIF: The Common European Research Information Format Model. Data Science Journal, 9(24), 24–31.

Katz, J. S., & Hicks, D. (1997). How much is collaboration worth? A calibrated bibliometric model. Scientometrics, 40(3), 541–554.

Korenjak-Černe, S., Kejžar, N., & Batagelj, V. (2010). Clustering of population pyramids presented as histogram symbolic data. In Joint Meeting GfKl – CLADAG 2010, Florence, 8–10 September 2010. Program and abstracts (pp. 161–162). Florence, Italy: Department of Statistics of the University of Florence.

Korenjak-Černe, S., Batagelj, V., & Japelj Pavešić, B. (2011). Clustering large data sets described with discrete distributions and its application on TIMSS data set. Statistical Analysis and Data Mining, 4, 199–215.

Kronegger, L., Ferligoj, A., & Doreian, P. (2011). On the dynamics of national scientific systems. Quality & Quantity, 45(5), 989–1015.

Kronegger, L., Mali, F., Ferligoj, A., & Doreian, P. (2012). Collaboration structures in Slovenian scientific communities. Scientometrics, 90(2), 631–647.

Kuhn, T.S. (1962). The Structure of Scientific Revolutions (3rd ed.). Chicago, IL, USA: University of Chicago Press.

Larivière, V., Gingras, Y., & Archambault, É. (2006). Canadian collaboration networks: A comparative analysis of the natural sciences, social sciences and the humanities. Scientometrics, 68, 519–533.

Laudel, G. (2002). What do we measure by co-authorship? Research Evaluation, 11(1), 3–15.

Mali, F. (2006). Epistemologija družbenih ved. Razlaga in razumevanje [in Slovene]. Ljubljana: Fakulteta za družbene vede.

Mali, F. (2010). Turning science transdisciplinary: Is it possible for the new concept of cross-disciplinary cooperations to enter Slovenian science and policy? In L. Kajfež-Bogataj, K.H. Müller, I. Svetlik, & N. Toš (Eds.), Modern RISC-Societies: Towards a New Paradigm for Societal Evolution (pp. 461–474). Vol. 14 of Complexity Design Society. Vienna, Austria: Echoraum.

Mali, F. (2011). Policy issues of the international productivity and visibility of the social sciences in Central and Eastern European countries. Sociologija i Prostor (Sociology and Space), 48(3), 415–435.

Mali, F., Kronegger, L., & Ferligoj, A. (2010). Co-authorship trends and collaboration patterns in the Slovenian sociological community. Corvinus Journal of Sociology and Social Policy (CJSSP), 1(2), 29–50.

Manzon, M. (2011). Comparative Education. Vol. 29 of CERC Studies in Comparative Education. Dordrecht, Netherlands: Springer.

Mulkay, M. (1975). Three models of scientific development. Sociological Review, 23(3), 509–526.

Nederhof, A. (2006). Bibliometric monitoring of research performance in the Social Sciences and Humanities: A review. Scientometrics, 66(1), 81–100.

Newman, M.E.J. (2001). The structure of scientific collaboration networks. Proceedings of the National Academy of Sciences of the United States of America, 98(2), 404–409.

Niiniluoto, I. (1995). The Emergence of Scientific Specialities: Six models. Poznan Studies in Philosophy of the Sciences and Humanities, 44, 211–223.

OECD. (2007). Revised field of science and technology (FOS) classification in the Frascati Manual. Technical report. Retrieved from: http://www.oecd.org/science/inno/38235147.pdf

Price, D.S. (1965). Networks of Scientific Papers. Science, 149, 510–515.

R Development Core Team. (2012). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Ravetz, J. (1971). Scientific Knowledge and Its Social Problems. Oxford, United Kingdom: Clarendon Press.

Stichweh, R. (1994). Wissenschaft Universität, Professionen. Soziologische Analysen. Frankfurt, Germany: Suhrkamp Verlag.

Storer, N., & Parsons, T. (1968). The discipline as a differentiating force. In E. Montgomery (Ed.), The Foundations of Access to Knowledge: A Symposium. Frontiers of Librarianship (pp. 101–121). Division of Summer Sessions. Syracuse, USA: Syracuse University Press.

Szostak, R. (2004). Preface. In Classifying Science: Phenomena, Data, Theory, Method, Practice. Netherlands: Springer.

Thorsteinsdóttir, H. (2000). Public-sector research in small countries: Does size matter? Science and Public Policy, 27(6), 433–442.

Van Leeuwen, T. (2006). The application of bibilometric analyses in the evaluation of social science research. Who benefits from it, and why it is still feasible. Scientometrics, 66(1), 133–154.

Ward, J. (1963). Hierarchical grouping to optimize as objective function. Journal of the American Statistical Association, 58, 236–244.

Weber, M. (1988). Gesammelte Aufsèatze zurWissenschaftslehre. Gesammelte Aufsätze. Tübingen, Germany: J.C.B. Mohr (Paul Siebeck) Verlag.

Whitley, R. (1984). The Intellectual and Social Organization of the Sciences. Oxford, United Kingdom: Clarendon Press.

Whitley, R., & Gläser, J. (Eds.) (2007). The Changing Governance of the Sciences (Vol. 26). Dordrecht, the Netherlands: Springer.

Ziman, J. (1994). Prometheus Bound. Science in Dynamic Steady State. Cambridge, United Kingdom: Cambridge University Press.

Ziman, J. (2000). Real Science. What It Is, and What It Means. Cambridge, United Kingdom: Cambridge University Press.

Appendix A

TABLE A1. Clustering results.

Clustering type	Joint		Separated					Separated				
Period	T1–T5		T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
No. of clusters	2	5			2					5		
1. Natural sciences and mathematics												
Mathematics	2	5	2	2	2	2	2	4	4	4	4	3
Physics	1	1	1	1	1	1	1	1	1	1	1	1
Biology	1	3	1	2	2	1	2	3	4	3	3	3
Chemistry	1	2	1	1	1	1	1	1	2	2	2	2
Biochemistry and molecular biology	1	2	1	1	1	1	1	1	2	2	1	1
Geology	1	3	1	2	2	1	2	2	3	3	3	3
Computer intensive methods and appl.	1	1	1	1	1	1	1	1	1	2	1	1
Control and care of the environment	1	1	1	1	1	1	1	2	1	2	1	1
Pharmacy	1	2	1	1	1	1	1	1	2	1	3	2
2. Engineering sciences and technologies												
Civil engineering	1	2	1	1	1	1	1	2	2	1	2	2
Chemical engineering	1	2	1	1	1	1	1	2	2	2	2	2
Energy engineering	1	2	1	1	1	1	1	2	2	2	2	1
Materials science and technology	1	2	1	1	1	1	1	1	2	2	2	2
Mechanics	1	2	1	1	1	1	2	2	2	2	1	3
Systems and cybernetics	1	2	1	1	1	1	1	2	2	2	2	2
Computer science and informatics	1	2	1	1	1	1	1	2	2	2	2	2
Telecommunications	1	2	1	1	1	1	1	2	2	1	2	2
Electronic components and technologies	1	2	1	1	1	1	1	2	2	2	2	1
Manufacturing technologies and systems	1	2	1	1	1	1	1	3	2	1	2	2
Mechanical design	1	2	1	1	1	1	1	2	2	2	2	2
Electric devices	1	2	1	1	1	1	1	2	2	2	2	2
Process engineering	1	2	1	1	1	1	1	2	2	2	2	2
Textile and leather	1	2	1	1	1	1	1	3	2	1	2	2
Metrology	1	2	1	1	1	1	1	2	2	2	3	1
Mining and geotechnology	1	3	1	2	2	1	2	3	3	3	3	3
Geodesy	1	3	2	2	1	1	1	4	4	1	3	1
Traffic systems	1	3	2	2	2	1	1	4	3	3	3	1
Hydrology	1	3	1	1	2	1	1	3	2	3	3	2
3. Medical sciences												
Microbiology and immunology	1	2	1	1	1	1	1	2	2	1	2	1
Stomatology	1	3	1	2	2	1	2	3	3	3	3	3
Neurobiology	1	2	1	1	1	1	1	2	2	1	3	1
Oncology	1	2	1	1	1	1	1	1	2	1	3	1
Human reproduction	1	2	1	1	1	1	1	2	2	1	2	2
Cardiovascular system	1	2	1	1	1	1	1	2	2	1	3	1
Metabolic and hormonal disorders	1	1	1	1	1	1	1	2	1	2	3	1
Public health (occupational safety)	1	3	1	2	2	1	2	3	3	3	3	3
Psychiatry	1	3	2	2	2	1	2	4	3	3	3	3
4. Biotechnical sciences												
Forestry, wood and paper technology	1	3	1	2	2	1	2	3	3	3	3	3
Animal production	1	2	1	1	1	1	1	2	2	2	2	2
Plant production	1	2	1	1	1	1	1	3	2	1	2	2
Veterinarian medicine	1	2	1	1	1	1	1	2	2	1	2	2
Landscape design	2	5	2	2	2	2	2	4	5	4	4	4
Biotechnology	1	2	1	1	1	1	1	2	2	2	1	1
5. Social sciences												
Educational studies	2	5	2	2	2	2	2	4	4	4	4	4
Economics	2	5	2	2	2	2	2	4	4	4	4	3
Sociology	2	5	2	2	2	2	2	4	4	3	4	4
Administrative and organizational sciences	1	3	2	2	2	1	2	4	3	3	3	3
Law	2	4	2	2	2	2	2	5	5	5	5	5
Political science	2	5	2	2	2	2	2	4	5	4	4	4
Criminology and social work	2	4	2	2	2	2	2	5	5	5	4	5
Urbanism	2	5	1	2	2	2	2	3	5	4	4	3
Psychology	2	5	2	2	2	2	2	4	4	5	4	4
Architecture and design	2	4	2	2	2	2	2	5	5	5	5	5
Information science and librarianship	2	4	2	2	2	2	2	5	5	5	4	4
6. Humanities												
Historiography	2	5	2	2	2	2	2	5	5	4	4	5
Archaeology	2	5	2	2	2	2	2	4	4	5	4	4
Anthropology	2	4	2	2	2	2	2	4	5	4	5	5
Ethnology	2	4	2	2	2	2	2	4	5	5	5	5
Linguistics	2	5	2	2	2	2	2	4	5	4	4	4
Culturology	2	4	2	2	2	2	2	5	5	5	5	5
Literary sciences	2	5	2	2	2	2	2	4	5	5	4	5
Musicology	2	5	2	2	2	2	2	4	4	4	4	5
Art history	2	5	2	2	2	2	2	5	3	4	4	5
Philosophy	2	4	2	2	2	2	2	5	5	5	5	5
Theology	2	4	2	2	2	2	2	5	5	5	5	5
Geography	1	3	1	2	2	2	2	3	4	3	4	4

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Appendix B

TABLE B1. Number of publications (contribution index).

	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010
1. Natural sciences and mathematics					
Mathematics	409.05	487.32	657.30	897.93	1113.79
Physics	576.20	922.92	1436.11	1794.99	2030.45
Biology	232.38	405.95	741.08	846.19	1016.93
Chemistry	484.49	804.16	1557.63	1676.00	1516.13
Biochemistry and molecular biology	132.78	227.23	343.39	326.43	380.35
Geology	134.29	221.34	467.38	605.44	553.23
Computer intensive methods and appl.	20.07	50.33	100.84	167.32	174.09
Control and care of the environment	54.85	96.12	153.50	185.38	242.34
Pharmacy	147.84	223.78	417.31	510.66	497.62
2. Engineering sciences and technologies					
Civil engineering	294.74	538.15	753.11	763.90	969.19
Chemical engineering	153.60	237.74	581.97	622.40	670.52
Energy engineering	179.91	565.16	912.39	1008.67	1259.63
Materials science and technology	192.62	523.58	894.53	882.95	1120.32
Mechanics	131.29	220.34	223.16	188.17	265.99
Systems and cybernetics	288.75	577.79	996.22	995.45	1304.47
Computer science and informatics	367.54	954.24	1436.28	1814.27	1961.33
Telecommunications	77.49	166.82	437.66	555.60	534.31
Electronic components and technologies	92.18	398.67	715.16	751.07	853.83
Manufacturing technologies and systems	249.57	486.17	838.15	1018.08	1011.83
Mechanical design	96.71	279.27	441.42	577.44	647.23
Electric devices	68.45	170.20	241.17	301.73	358.97
Process engineering	111.15	205.83	305.79	367.71	298.49
Textile and leather	109.37	243.02	394.46	412.86	469.94
Metrology	53.03	142.61	289.48	272.72	250.40
Mining and geotechnology	18.70	43.57	64.93	53.72	72.10
Geodesy	23.17	63.19	136.61	192.23	215.38
Traffic systems	41.42	107.91	254.23	315.53	371.00
Hydrology	21.28	58.46	96.35	122.57	178.15
3. Medical sciences					
Technology driven physics	0.00	0.00	0.48	5.68	6.17
Communications technology	0.50	2.42	17.89	44.44	130.98
Microbiology and immunology	186.92	326.67	823.60	697.14	645.77
Stomatology	90.01	93.57	161.58	106.47	135.02
Neurobiology	245.73	467.73	964.79	783.49	779.67
Oncology	172.29	449.26	791.99	631.04	716.88
Human reproduction	124.44	271.78	630.05	638.05	432.60
Cardiovascular system	204.74	368.04	746.08	750.38	527.01
Metabolic and hormonal disorders	39.02	209.00	298.22	229.41	200.53
Public health (occupational safety)	163.04	278.10	671.14	697.44	822.40
Psychiatry	32.43	45.50	170.15	114.98	145.17
4. Biotechnical sciences					
Forestry, wood and paper technology	123.81	358.37	626.89	600.35	723.41
Animal production	91.20	284.96	448.28	453.63	444.41
Plant production	278.54	469.46	851.82	1091.84	1170.35
Veterinarian medicine	112.54	288.47	776.35	505.95	348.80
Landscape design	24.62	36.95	81.34	55.02	55.14
Biotechnology	89.20	228.99	361.06	328.00	397.87
5. Social sciences					
Educational studies	412.33	922.02	1533.33	2077.33	2545.26
Economics	1182.05	1595.82	2165.62	2494.16	3149.44
Sociology	370.49	554.37	834.81	1037.50	1154.11
Administrative and organizational sciences	258.95	345.85	509.71	718.63	927.27
Law	484.85	785.28	1072.52	1587.46	1669.94
Political science	188.54	327.90	626.12	937.53	1150.86
Criminology and social work	98.34	167.20	367.75	429.92	485.98
Urbanism	33.80	81.22	166.87	204.11	227.50
Psychology	109.72	304.03	398.31	561.62	630.29
Sport	6.18	31.73	93.66	152.79	245.08
Ethnic studies	0.00	0.25	5.83	13.67	35.02
Architecture and design	72.90	91.13	185.95	284.90	337.37
Information science and librarianship	11.32	37.38	82.52	171.73	140.24
6. Humanities					
Historiography	455.46	803.60	1424.60	1804.20	1765.25
Archaeology	82.41	134.77	230.16	349.15	488.02
Anthropology	228.14	304.21	419.45	465.62	501.87
Ethnology	123.88	208.12	361.53	400.77	597.79
Linguistics	280.64	576.91	1015.67	1394.36	1748.12
Culturology	194.41	300.46	443.98	520.85	663.18
Literary sciences	183.51	348.71	718.94	868.97	1101.47
Musicology	51.43	136.78	239.99	258.53	279.95
Art history	86.02	303.75	337.00	411.02	533.54
Philosophy	271.67	495.27	743.55	916.35	971.45
Theology	22.00	69.67	151.13	230.72	280.84
Geography	244.79	384.40	570.56	626.99	828.55
7. Interdisciplinary research					
NCKS research program	12.90	20.15	44.71	54.63	72.58
Interdisciplinary research	17.02	29.47	70.33	80.86	180.83

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