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Heterogeneity of collaboration and its relationship with research impact in a biomedical field

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Abstract This paper analyses existing trends in the collaborative structure of the Pharmacology and Pharmacy field in Spain and explores its relationship with research impact. The evolution in terms of size of the research community, the typology of collaborative links (national, international) and the scope of the collaboration (size of links, type of partners) are studied by means of different measures based on co-authorship. Growing heterogeneity of collaboration and impact of research are observed over the years. Average journal impact (MNJS) and citation score (MNCS) normalised to world average tend to grow with the number of authors, the number of institutions and collaboration type. Both national and international collaboration show MNJS values above the country's average, but only internationally co-authored publications attain citation rates above the world's average. This holds at country and institutional sector levels, although not all institutional sectors obtain the same benefit from collaboration. Multilateral collaboration with high-level R&D countries yields the highest values of research impact, although the impact of collaboration with low-level R&D countries has been optimised over the years. Although scientific collaboration is frequently based on individual initiative, policy actions are required to promote the more heterogeneous types of collaboration.

Keywords Scientific collaboration · Research impact · Bilateral and multilateral collaboration · Spain · Biomedicine · Co-authorship

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Introduction

Science is increasingly becoming a collaborative endeavour. Collaboration allows scientists to share knowledge, expertise and techniques, cope with interdisciplinary research topics, and get involved in sophisticated research projects (Katz and Martin 1997). It is responsible for the creation of a knowledge flow which interconnects scientists, institutions and countries, contributes to determine the cognitive and social structure of scientific fields (Corley et al. 2006), and has a great influence on the output of research (Sonnenwald 2007).

From a bibliometric standpoint, collaboration is usually analysed through co-authorship in scientific publications. Many bibliometric studies have analysed the effect of collaboration on the productivity and/or impact of publications at the micro level (scientists) (He 2009), the meso level (institutions, disciplines) (Abramo et al. 2009; Franceschet and Costantini 2010; Gazni and Didegah 2011) and the macro level (countries) (Narin et al. 1991; Glänzel 2001). The idea that collaboration is linked to high scientific productivity of scientists has been pointed out by some authors (Lee and Bozeman 2005), whilst the positive influence of collaboration—especially international collaboration—on research impact has been discussed by others (Glänzel 2001).

Collaboration shows a growing trend in intensity, range of aims and heterogeneity (Jha and Welch 2010). The term "heterogeneous collaboration" is used in the literature to refer to collaboration which concerns a variety of participants or purposes (Hackett 2005). Partner diversity contributes to boost the benefits of collaboration since it brings about a higher variety of points of view leading to higher creativity (Reagans and Zuckerman 2001) and innovation (Talke et al. 2011), and in the long term, to step up the advance of knowledge. Collaboration amongst different institutions is supposed to involve a higher degree of heterogeneity when compared to in-house collaboration and has been associated with higher impact and quality of research (Franceschet and Costantini 2010).

The study of collaboration practises and their relationship with research impact is a matter of great concern for policy makers and scientists themselves. Under the assumption that collaboration enhances the quality of scientific research and even improves its efficiency and effectiveness (Adams et al. 2005; The Royal Society 2011) national and supranational policies have been implemented to foster collaboration. However, the study of collaboration should be contextualised by country and by field since differences between countries and fields have been described in collaborative practises as well as in their tendency to gain from collaboration (Glänzel 2001; Glänzel and Lange 2002). This study is focused on the Pharmacology and Pharmacy field in Spain which is a biomedical research area of strategic interest in the country given the existence of a relatively high share of scientific output by private companies.

Objectives

The main objective of this paper is to study the evolution over time of the collaborative structure of the Pharmacology field in Spain and to explore its relationship with research impact. This paper (a) analyses the evolution in terms of size of the research community, the typology of collaborative links (national, international) and the scope of the collaboration (size of links, type of partners) by means of measures based on co-authorship and (b) explores the relationship between collaboration and research impact.[1]

[1] A preliminary version of this paper has been presented to the Science and Technology Indicators Conference, Montreal, Canada, September 5–8, 2012 (Bordons et al. 2012a).

The following questions are addressed: are there any changes in collaborative practises over time? Does collaboration contribute to increase the productivity of scientists in the field? Does the impact of research tend to increase with the heterogeneity of collaboration?

The study of heterogeneity in collaboration is addressed in this paper considering different related measures. Heterogeneity is assumed to increase as we move up the collaboration-type ladder (from no collaboration to national collaboration and to international collaboration) and with the size of links (number of authors, number of institutions, number of countries). The relationship between heterogeneity of collaboration and research impact is then explored in this framework. The influence of type of partner (by institutional sector, by R&D intensity of countries) on the impact of collaborative research is also analysed.

Methodology

The scientific output of Spanish authors in journals included in the Pharmacology and Pharmacy subfield of the Web of Science database is analysed over two 3-year periods: 1998–2000 and 2006–2008. Only articles and reviews are studied. The analysis focuses on the size of the research community, collaboration features and research impact. Social network analysis is used to identify changes over time in the co-authorship networks in the field.

1. *Size of the research community* It is measured by the number of authors, institutions and papers in the field. Author names are normalised and linked to their institutional address according to an algorithm previously described in the literature (Costas and Bordons 2007). Accordingly, two different measures are used: number of author occurrences (authorships) and number of different authors. For example, ten author occurrences may correspond to only two different authors with five publications each.
2. *Collaboration* Different aspects of collaboration are studied:
   (a) Collaboration type. Publications are classified as belonging to one of the following three groups of papers: non collaborative papers (a single institution), national collaboration papers (at least two Spanish institutions), and international collaboration papers (at least one foreign address). Publications including both national and international collaboration are included in the international type.
   (b) Collaboration scope, which refers to the size and the type of partners involved.

The scope of national links is studied using the following indicators:

- Size of links: it considers the number of partners included in the collaboration. Heterogeneity is assumed to grow as the number of partners involved increases.
- Type of partner by institutional sector. The following institutional sectors are considered: university (UNIV), health sector (HOSP), companies, the Spanish National Research Council (CSIC),[2] non-profit organizations (NPO) and public research centres (including public administration) (PRC). We distinguish between single-sector and cross-sector publications. Cross-sector links may be considered as an indication of a higher degree of heterogeneity in the collaboration since institutional differences in missions, organisation and operation may exist.

[2] Although the CSIC belongs to the sector of public research centres, it has been considered separately under the assumption that collaboration between different CSIC centres involves less diversity than that between CSIC's and other public research centres.

The scope of international links is analysed using the following indicators:

- Size of links: collaboration between two (bilateral) or more countries (multilateral) is studied. Higher heterogeneity is assumed for multilateral collaboration.
- Type of partner by R&D intensity: countries are classified in two classes according to their level of commitment with research and development activities as measured by their gross domestic expenditures in R&D as a percentage of their gross domestic product (%GERD/GDP) (source: World Bank 2012). Those with a %GERD/GDP equal to or higher than the Spanish value are considered as high-level RD countries, whilst the remaining countries are deemed low-level RD countries. Data on R&D expenditure by country refer to 1999. The same reference was used throughout the period to make inter-period comparisons possible. If both a low and a high-level RD country are included in a given publication, then it is deemed to belong in the high-level RD class.

(c) Co-authorship networks. The structural network properties were analysed through the study of links between authors by means of PAJEK software (http://pajek.imfm.si/), which allows us to study the evolution of cohesiveness in networks over time.

3. *Research impact.* For the study of research impact, two citation-based indicators normalised to the average world value are used following the methodology described by the CWTS in Leiden (Waltman et al. 2011). The use of citations as an indicator of research impact in the scientific community is widespread in the literature, although we should stay aware of its advantages and limitations (Moed 2005).

The field-normalised average journal impact (MNJS) is the mean citation rate of the journals in which Spanish scientists have published compared with the mean citation score of all papers published in the field. If MNJS is above 1, scientists are publishing in journals with a relatively high impact (high international visibility). The mean normalised citation score (MNCS) compares the average number of citations to the oeuvre of Spanish scientists with the field mean citation scores. Self-citations are excluded from these calculations. These indicators are calculated for two periods: 1998–2000 and 2006–2008. Citations with a 3-year citation window are used in the analysis. Accordingly, citations received in 1998, 1999 and 2000 are considered for papers published in 1998.

The number of references is included as a proxy for the comprehensiveness of the research (McVeigh and Mann 2009; González-Albo and Bordons 2011; Costas et al. 2012) which contributes to the quality of publications and may attract a higher number of citations (Haslam et al. 2008).

For the study of the applied/basic orientation of research we use the research level of publications, based on a classification of journals in four categories ranging from most-applied journals (level 1) to the most-basic journals (level 4). This was initially described by CHI (Noma 1986) and later updated by ipIQ.

Differences in impact by collaborative type are analysed by means of statistical tests for non-parametric variables (Kruskal–Wallis and Mann-Whitney tests). The influence of network size and type of collaboration on the impact of research is studied through multiple regression analysis for categorical variables (SPSS, version 19).

Results

The scientific output of Spanish authors in Pharmacology and Pharmacy journals totalled 1,971 publications for 1998–2000 and 2,858 for 2006–2008. These publications were

Table 1 Trends in scientific output, research community size and collaboration features in the field

	1998–2000	2006–2008	Growth (%)
(a) Scientific output			
No. publications (total count)	1,971	2,858	45
No. publications (fractional count)	1,689.59	2,334.95	38
(b) Research community			
Individuals			
No. author occurrences (authorships)	9,867	16,125	63
No. different authors (AUCEN[a])	5,896	10,099	71
Institutions			
No. total institutions (occurrences)	4,168	7,898	89
No. Spanish institutions	3,116 (75 %)	5,491 (70 %)	76
No. foreign institutions	1,052 (25 %)	2,407 (30 %)	128
Teams			
Authors/pub. (average)	5.01	5.64	13
Institutions/pub. (average)	2.11	2.76	31
(c) Collaboration pattern (institutions)			
No. non-collab. Pub. (intramural)	847 (43 %)	919 (32 %)	9
No. national collab. Pub.	621 (31 %)	1,027 (36 %)	65
No. international collab. Pub.	503 (25 %)	912 (32 %)	81
(d) National collaboration scope[b]			
No. pub. by number of partners			
Two partners	408 (56 %)	531 (40 %)	23
More than two partners	319 (44 %)	807 (60 %)	134
No. pub. by sectors involved			
Single-sector national collab.	338 (46 %)	516 (39 %)	53
Cross-sector national collab.	389 (54 %)	822 (61 %)	111
(e) International collaboration scope			
No. pub. by number of partners			
Bilateral international collab.	392 (78 %)	622 (68 %)	59
Multilateral international collab.	111 (22 %)	290 (32 %)	161
No. pub. by RD intensity of partners[c]			
%R&D/GDP $<$ Spain	87 (17 %)	166 (18 %)	91
%R&D/GDP $\geq$ Spain	413 (83 %)	734 (82 %)	78

[a] Unique authors are identified and linked to their institutional address (AUCEN file)

[b] Papers which present national and international collaboration simultaneously are included here

[c] %GERD/GDP not available for a few countries (ten publications excluded from related analyses)

studied to analyse changes in the number, diversity and scope of collaborative links and explore the relationship between collaboration and different aspects of research performance (productivity, impact).

Trends in collaboration type and scope

During the period under analysis the size of the scientific community has increased as measured both by the number of authors (increase of 63 %) and by the number of active

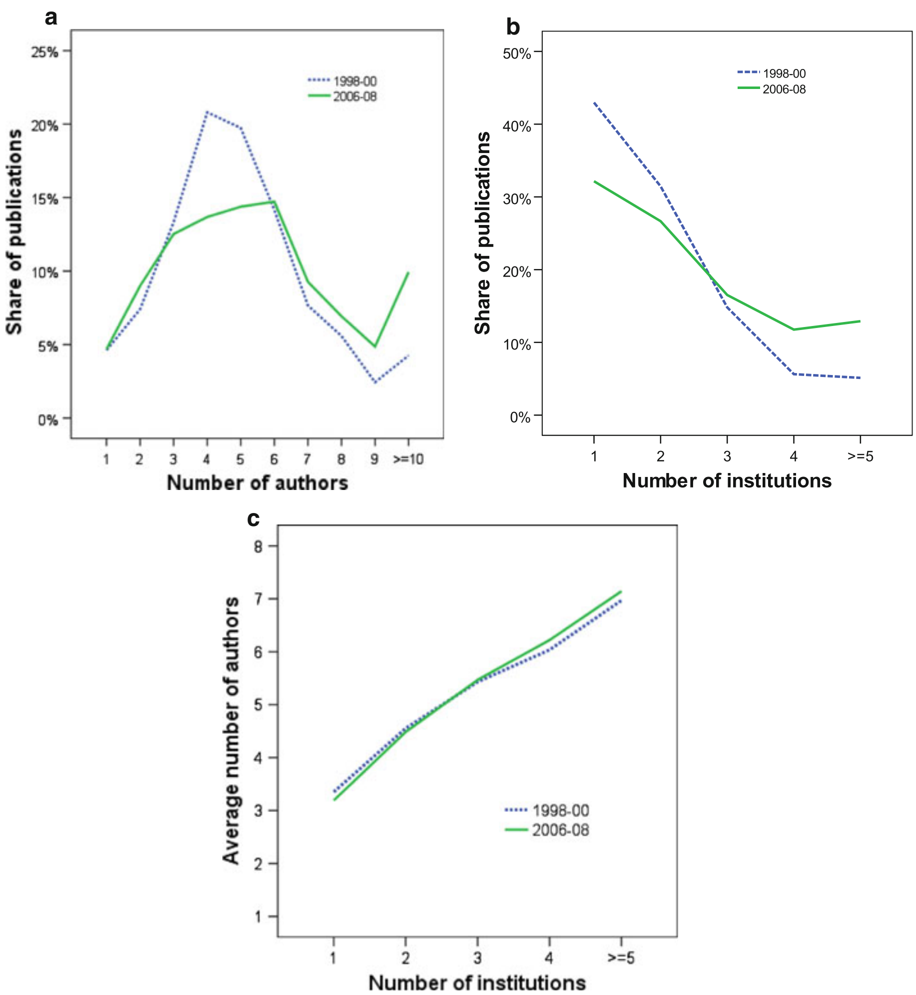

Fig. 1 Changes over time in **a** the distribution of publications by number of authors per publication; **b** the distribution of publications by number of institutions per publication; **c** number of authors by number of institutions

institutions (increase of 89 %), both growing faster than the number of publications (45 %) (Table 1a, b). Research becomes more collaborative, as shown by the increase in the average number of authors per publication, which points to larger research teams, as well as to the upward trend in the number of institutions per publication, an indication of growing extra-mural and institutional collaboration.

During the whole study period, the average number of authors per publication has increased from 5 to almost 6 (Table 1b). The greatest changes have been identified in publications with 4–5 authors, which altogether, include almost 40 % of the total production in the first period and account for less than 30 % in the second one, in which the percentage of publications with more than 6 authors shows un upward trend, especially for publications with 10 authors or more, up from 5 to 10 %. For the first 3-year period (Fig. 1a), the most frequent number of authors per publication is 4, whilst 6 authors is the

Table 2 Main features of the Pharmacology and Pharmacy network in two 3-year periods

Pharmacology (total authors)	1998–2000	2006–2008
No. publications	1,971	2,858
No. authors (nodes)	5,896	10,099
No. edges (links)	21,292	44,706
No. connected nodes	5,843 (99.10 %)	10,038 (99.40 %)
Density	0.0012252	0.0008768
No. connected components	518	696
No. authors in the main component (%)	2,002 (33.96 %)	5,400 (53.47 %)
Average degree centrality	7.22	8.85
SD degree (standard deviation)	5.63	7.39
Average distance	11.36	8.71
Diameter (longest distance)	28	24
Clustering coefficient (average)	0.88	0.88
Size *k*-core	27	34

predominating figure for the second period. Concerning institutions, the share of publications with 1 institution falls from 43 to 32 %, whilst the percentage of publications with 4 institutions or more is up from 11 % in the first period to 25 % in the second one (Fig. 1b).

Interestingly, the average number of authors per publication remains stable over time if we control for the number of institutions (Fig. 1c). This suggests that the intra-mural size of teams does not change over time whilst the rise observed in the number of authors per publication is mainly due to an increase in the number of institutions participating in publications.

The number of internationally co-authored publications grows faster than that of nationally co-authored papers (65 vs. 81 %, Table 1c). Moreover, the scope of both national and international collaboration also widens over the period. A rise in heterogeneity is observed for national collaboration, since multi-institutional and cross-sector collaboration increase above average (134 and 111 %, respectively; vs. 45 % for the total field, Table 1d).[3] With respect to international collaboration, it was present in 25 % of the publications in the first period but rises to 32 % in the second. Moreover, international collaboration amongst three or more partners (multilateral) grows faster than that between two partners (bilateral), which actually shows a decline in percentage (from 78 % in the first period to 68 % in the second period) (Table 1e). Finally, it is interesting to note that collaboration with high-level RD countries remains quite stable over the years (around 82 % of internationally co-authored papers) although it includes a growing share of papers written in collaboration between low and high-level RD countries (from 5 to 12 %) (Table 1e). Overall, these findings suggest that collaborative research has been conducted in larger and more heterogeneous networks in our second reference period.

[3] Special mention should be made of the rise in the share of co-authored papers between university and hospitals, which increases from 13 to 23 % of university papers over time.

Co-authorship network analysis

The main features of the network of authors in the field are shown in Table 2. During the period under analysis 99 % of all authors were connected to at least another author in each of the study periods and the size of the network expanded from 5,843 to 10,038 connected authors. Interestingly, a rise in network connections over time can be observed by means of different measures which are explained below.

Density, which represents the percentage of all possible connections amongst individuals, shrank slightly over the years, but this measure is not useful to analyse the evolution of network cohesiveness because it depends on the size of the network (density tends to diminish in larger networks because the number of possible links grows with the number of vertices). The average degree is a better measure of overall cohesion, because it does not depend on network size. The average degree centrality increases from 7.2 to 8.9. It measures the total number of authors with which a scientist wrote publications. It reflects the average compactness of the network of authors. The SD informs us about the variability of this measure, which is higher in the second period.

The longest distance amongst members in the network shows us the diameter of the network which falls from 28 to 24. Likewise, the average distance amongst authors falls from 11.4 to 8.7. This means that, in rough figures, any researcher is connected to any other researcher in the network through eight other intermediate researchers in the second period. A decline has been observed from one period to another suggesting that the network is becoming more densely connected.

With regard to the degree of integration we can analyse the components, which are groups of actors that are connected within their group but disconnected with other groups. We observe that the number of components rises from 518 to 696, and the main component connects 34 % of the authors in the first period vs. 53 % in the second one, reflecting a more cohesive network in the most recent period.

The k-core is a maximal sub-network in which each vertex has at least a k degree within the sub-network. We can see that the core of the network increases from 27 in the first period to 34 in the second, which again suggests a more interconnected network in the second period under study.

The tendency of authors to form local clusters with other colleagues is measured through the clustering coefficient, which ranges from 0 to 1. This indicator remains stable for the two periods (0.8).

Research performance

(a) Does collaboration contribute to increase the productivity of scientists?

The number of publications shows a rate of increase below the one observed for the number of authorships (45 vs. 63 %) (Table 1a, b), and the average productivity of scientists (defined as the number of authorships per unique researcher) falls from 1.67 to 1.60 articles per author. Therefore, the growth in production observed in the field is not due to an increase in the productivity of scientists, but to an important surge in the number of active scientists. The general distribution of authors by productivity level is quite similar for both periods. Around 70 % of authors appear only once during each period, whilst only 1 % has published 10 or more publications. A striking finding is the higher range of productivity values observed for the top 5 % of authors with the highest productivity in the second period (1–65 vs. 1–22 in the first period), which suggest a productivity boost for the elite of most productive authors.

(b) Does collaboration contribute to increase the impact of research?

The scientific papers of Spanish authors in Pharmacology and Pharmacy tends to be published in "better" journals (9 % increase in MNJS) and to receive a higher number of citations (13 % increase in MNCS) in the second period. However, both MNJS and MNCS values remain slightly below world average (Table 3). The rising trend in the average number of references per publication is consistent with the publication in higher impact factor journals, since a higher referencing density (average number of references per publication) has been described in this respect (Costas et al. 2012). Interestingly, the second period shows a bias in favour of clinical research when compared to the first period. The percentage of publications published in basic journals (levels 3 and 4) falls from 79 to 68 %.

The influence of the number of authors, the number of institutions and the type of collaboration on the impact of publications is analysed. Figure 2 shows that single-authored publications obtain the lowest impact figures since these papers are published in journals with the lowest MNJS values and receive the lowest number of citations (lower MNCS). As the number of authors goes up, MNJS values also tend to do so and the highest values correspond to papers with at least eight authors. The same trend is observed with respect to citations, but publications with at least 8 authors present a higher increase in the rate of citations (almost 25 % above average). In addition, Fig. 3 reveals an upward trend in impact as the number of involved institutions grows. Comparing the two periods, publications tend to present higher impact values in the second period irrespective of the number of authors (Fig. 2) or institutions (Fig. 3). It is interesting to note that this pattern of impact growth in step with the number of authors and institutions is also observed when nationally and internationally co-authored papers are analysed separately (Appendix).

Publications where two or more institutions are involved are published in journals with higher MNJS values than those produced by a single institution, whilst international collaboration provides an extra drive compared to national collaboration, although differences are statistically significant only in the second period. As for the analysis of citations, the lowest MNCS values also correspond to publications produced by a single institution, whilst publications in international collaboration show higher MNCS values than those with only national partners (Table 4). The higher impact of internationally co-authored publications is strongly determined by multilateral collaboration, since this type of collaboration obtains higher MNCS and MNJS values than bilateral collaboration for both

Table 3 Trends in research performance

	1998–2000 Av (SD)	2006–2008 Av (SD)
No. citations/publication	3.75 (5.55)	6.15 (8.22)
No. citations/publication (sc)	2.59 (4.60)	4.68 (6.97)
MNJS	0.88 (0.61)	0.96 (0.59)
MNCS	0.80 (1.29)	0.91 (1.21)
No. references/publication	31.75 (28.54)	48.31 (45.25)
Level	2.90 (0.67)	2.74 (0.72)

Average data (SD)

Significant differences between first and second period for all variables ($p < 0.001$)

sc self-citations removed

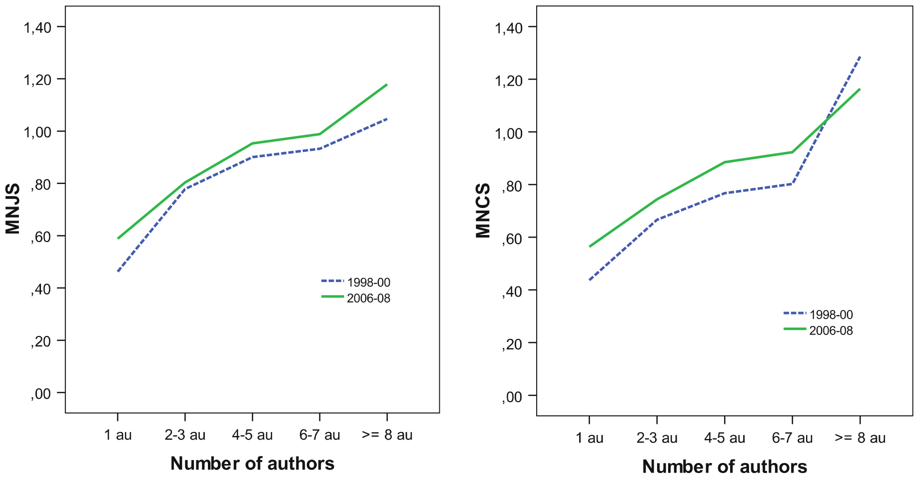

Fig. 2 Average MNJS (*left*) and MNCS (*right*) by co-authorship rate for the two periods under study

periods ($p < 0.01$). Besides, multilateral papers show a lower basic research level than bilateral ones for both periods ($p < 0.01$).[4]

(c) Is the level of development of the partners of research systems an influential factor on the impact of final research?

Our data suggest that this is indeed the case. Collaboration with high-level RD countries seems to be the most beneficial for Spanish partners in terms of impact (Table 4). Figure 4 enables us to compare MNJS and MNCS values by collaboration type for the two reference periods. As far as MNJS values are concerned (graph on the left), it is worthwhile mentioning that collaboration with low-level RD countries attains the lowest values in the first period, but the gap with the remaining collaborative types is reduced in the second one, where its values are similar to those obtained by national collaboration and slightly outperform the impact of publications without collaboration. If field-normalised citations are considered (graph on the right), the same trend is observed. The citation rates of publications co-authored with more intensive RD countries is around 20 % above world average for both periods. It seems that the extra drive derived from collaboration with high-level RD partners compared to the rest of publications is higher in MNCS than in MNJS values. On the other hand, it is noteworthy that publications in collaboration with high-level RD countries are over-represented amongst most cited publications, since one-third of most cited papers are from high-level RD countries although they only account for 20 % of total publications.

Publications co-authored with high-level RD countries tend to be published in more visible journals, receive on average a higher number of citations and are more likely to be amongst most cited papers.

(d) Do all institutional sectors benefit from collaboration?

[4] Average research level: 2.74 for multilateral versus 2.95 for bilateral collaboration in the first period; 2.57 for multilateral versus 2.82 for bilateral collaboration in the second period.

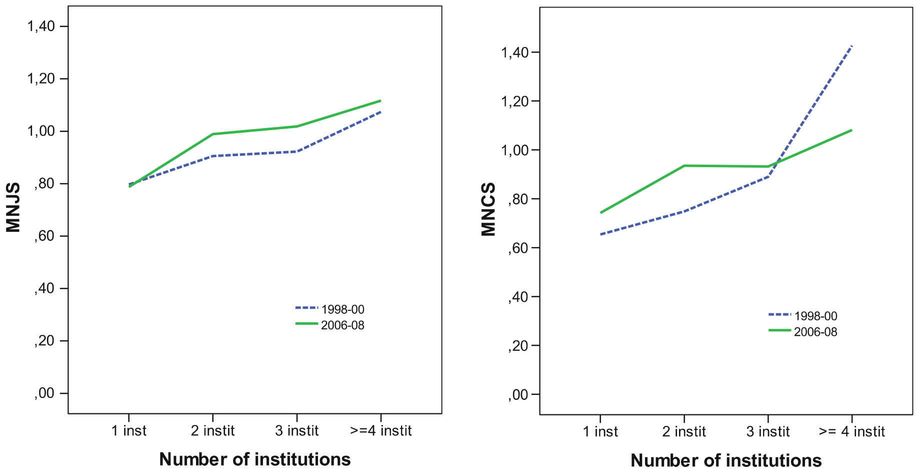

Fig. 3 Average MNJS (*left*) and MNCS (*right*) by number of institutions for the two periods under study

Table 4 Descriptive statistics for MNJS and MNCS by collaborative types and by period

	MNJS			MNCS		
	1998–2000 Av (SD)	2006–2008 Av (SD)	Increase	1998–2000 Av (SD)	2006–2008 Av (SD)	Increase
1. No collab.	0.80 (0.57)	0.79 (0.54)	0.99	0.65 (1.05)	0.74 (1.04)	1.14
2. National collab.	0.94 (0.62)	0.99 (0.49)	1.05	0.79 (1.27)	0.87 (1.00)	1.10
3. International collab.	0.95 (0.65)	1.10 (0.70)	1.16	1.07 (1.59)	1.12 (1.51)	1.05
3.1. Low RD countries	0.64 (0.47)	0.93 (0.49)	1.50	0.48 (0.62)	0.85 (0.84)	1.83
3.2. High RD countries	1.01 (0.66)	1.14 (0.73)	1.05	1.20 (1.70)	1.19 (1.62)	1.03
Total	0.88 (0.61)	0.96 (0.59)	1.09	0.80 (1.29)	0.91 (1.21)	1.13

3-collaborative types (1, 2, 3): significant differences in MNJS and MNCS by collaborative types ($p < 0.001$). Significant differences between all collaborative types except for MNJS of national versus international publications in the first period

4-collaborative types (1, 2, 3.1, 3.2): significant differences in MNJS and MNCS by collaborative types. MNJS: significant differences between all collaborative types, except national versus international coll. with high-level RD countries (in first period). MNCS: significant differences between all collaborative types, except national versus international coll. with low-level RD countries (both periods)

The analysis by institutional sector shows that the impact of research tends to grow as the heterogeneity of collaboration rises (from single-institution publications to nationally co-authored ones and from national to international collaboration) for most sectors. Data for the 2006–2008 period shown in Fig. 5 reveal that almost all sectors tend to present MNJS and MNCS values above 1 for internationally co-authored publications. National collaboration leads to MNJS values above world average in a few sectors, but only international collaboration is associated with MNCS value above world average.

Which sector benefits most from international collaboration? Focusing on the 2006–2008 period, internationally co-authored publications of companies get impact values at least 30 % higher than average company publications (both MNJS and MNCS

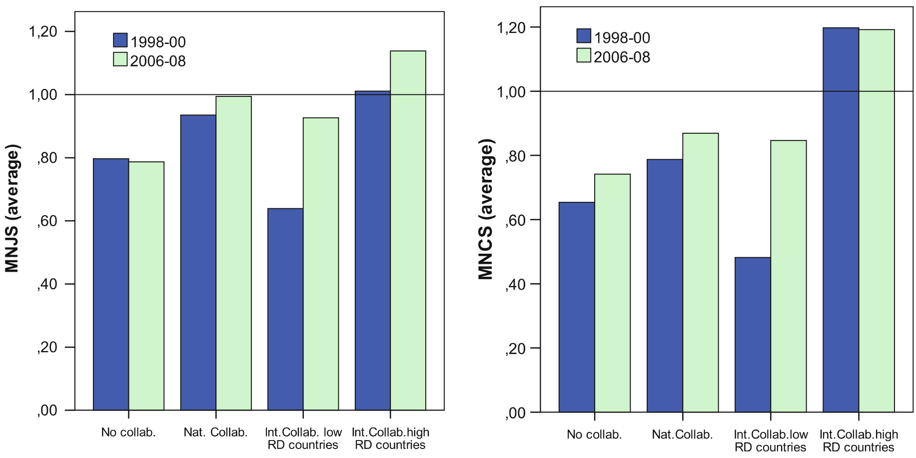

Fig. 4 Average MNJS (*left*) and MNCS (*right*) by four collaboration types for the two reference periods

values); and the same applies to hospital publications (in this case only MNCS values) (Fig. 5).

Considering the set of nationally co-authored publications, those involving partners from different institutional sectors show higher MNJS ($p < 0.001$) and MNCS values ($p < 0.05$) than those with partners from the same sector. This is observed for the first period, whilst no differences appear for the second. Since cross-sector collaboration also involves, on average, a higher number of institutions, the analysis is also conducted controlling for the last variable. In this case, the differences are reduced to publications written by two institutions in the first period, where higher impact (MNJS and MNCS) is observed for cross-sector partnership ($p < 0.01$).

(e) Influence of network size and type of collaboration on the impact of publications.

Categorical regression analysis is used to explore the influence of different variables on the impact of research. This method is preferred to the conventional regression analysis because of the skewed distribution of the variables and the fact that we have some nominal variables (collaboration type). Categorical regression may introduce numerical, nominal and ordinal variables which are effectively transformed into interval variables (using SPSS). Multiple regression analysis is applied to the transformed variables. The number of institutions was removed from the analysis due to collinearity problems.

MNJS and MNCS are the dependent variables in two different analyses (Tables 5,6, 7, 8). For each variable, two different models are developed and applied to both reference periods. Independent variables include the number of authors, the type of collaboration (four categories, international collaboration is disaggregated by partner RD intensity), and the number of references.

Analysis I: MNJS as the dependent variable (Table 5, 6). For the two periods the three variables mentioned above are significant and show a positive influence over MNJS (positive beta coefficients). In the first period, the most influential variable is the number of references (highest beta value), followed by the number of authors and the type of collaboration. As observed in Table 6, the system quantifies the "collaboration type" categorical variable into a numerical one, which shows a rising trend from "International collaboration with low-level RD countries" (lowest value), through "No collaboration"

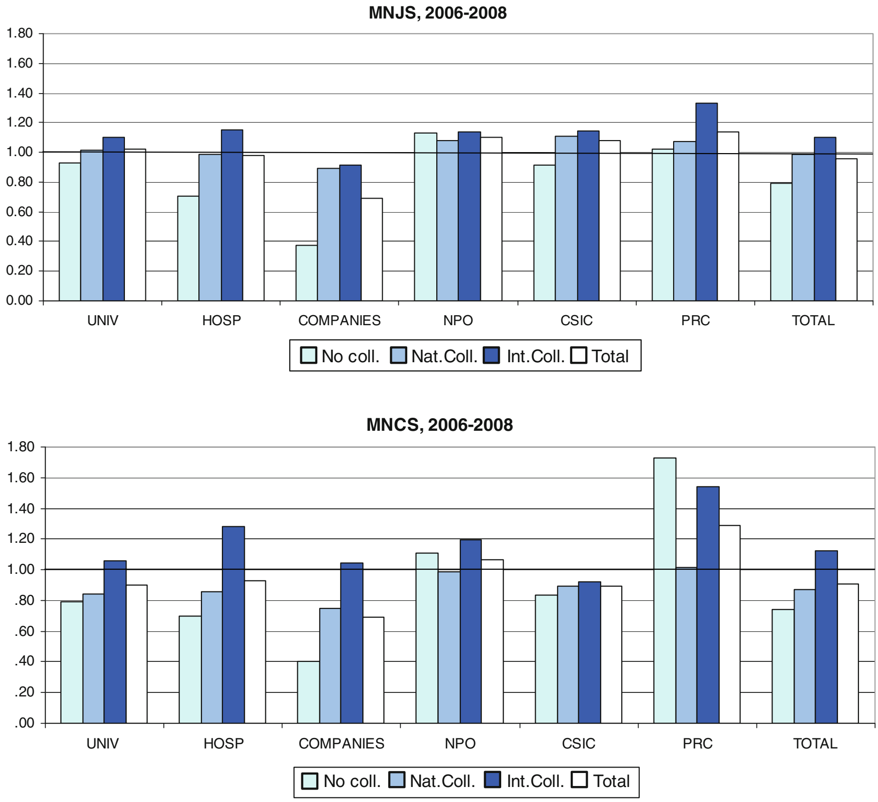

Fig. 5 MNJS and MNCS by institutional sector and collaboration type (2006–2008). The number of publications by institutional sector is as follows: University = 1,567; Hospitals = 1,060; Companies = 413; Non-profit organizations (NPO) = 340; CSIC = 296; Public research centres (PRC) = 133 articles

and "National collaboration", to "International collaboration with higher-level RD countries" (highest value). It is interesting to point out that "No collaboration" and "National collaboration" return very similar values, whilst "Int. Col. with low-level RD countries" is well below such values and "Int. Col. with high RD countries" largely exceeds them. Accordingly, the lowest MNJS corresponds to collaboration with low-level RD partners, whilst the highest is found for high-level RD investing partners. With regard to the second period, the number of authors is the most influential variable. Here the type of collaboration is transformed into a numerical variable showing a rising trend from "No collaboration" (lowest value) to "International collaboration with high-level RD countries" (highest value) (Table 6). A striking finding is that low-level RD countries are not associated with lowest MNJS values any longer.

Analysis II: MNCS as the dependent variable (Tables 7, 8). The most influential variable is MNJS, which means that publications in high impact factor journals are more likely to receive high citation rates. The number of references per publication is the second most influential variable for both periods. The type of collaboration is more influential than the number of authors for the first period, whilst both variables show very similar beta coefficients for the second period.

Table 5 Categorical regression analysis to explain MNJS

MNJS	Standardised coefficients		F	Sig.
	Beta	Bootstrap (1,000) estimate of std. error		
1998–2000				
No. references	0.277	0.024	132.137	0.000
No. authors	0.164	0.028	35.250	0.000
Coll_type	0.101	0.027	13.535	0.000
Corrected $R^2 = 0.132$				
2006–2008				
No. references	0.136	0.023	35.044	0.000
No. authors	0.235	0.022	114.048	0.000
Coll_type	0.143	0.021	47.081	0.000
Corrected $R^2 = 0.114$				

Table 6 Transformation of the "collaboration type" variable (*coll_type*) in the categorical regression analysis shown in Table 5

Category	Frequency	Quantification
1998–2000		
Int. collab. high RD countries	413	1.352
National collaboration	620	0.071
No collaboration	842	−0.348
Int. collab. low RD countries	87	−3.559
2006–2008		
Int. collab. high RD countries	732	1.192
National collaboration	1,025	0.350
Int. collab. low RD countries	166	−0.014
No collaboration	908	−1.354

Both analyses indicate that there is a positive correlation between impact and some indicators of collaboration such as the number of authors and the type of collaboration. The number of authors is more influential than the collaboration type for explaining MNJS, whilst the opposite trend is observed for MNCS. In spite of the existing correlation, we cannot draw inferences about causality due to the low values of R^2.

Figure 6 shows the MNJS and MNCS variables by collaboration type and number of authors for the two periods. The greatest impact corresponds to collaboration with high-level RD countries in all four graphs. In general terms, we can see a slightly upward trend of impact as the number of authors grows, especially for publications written by a single institution or by several domestic ones. Attention should be paid to the fact that the greatest impact (either for MNJS or MNCS) is obtained for publications with eight or more authors. In fact, for publications with a single institution or several domestic ones, impact above world average is only obtained if the number of authors is eight or more. Internationally co-authored publications tend to show the highest impact values in all cases, but this impact is similar to that of the other collaborative types in terms of MNJS whilst it is well above that in the case of MNCS. This is consistent with the stronger influence of the

Table 7 Categorical regression analysis to explain MNCS

MNCS	Standardised coefficients		*F*	Sig.
	Beta	Bootstrap (1,000) estimate of std. error		
1998–2000				
No. references	0.112	0.021	28.708	0.000
No. authors	0.082	0.033	5.994	0.003
Coll_type	0.101	0.022	21.532	0.000
MNJS	0.447	0.021	440.734	0.000
Corrected $R^2 = 0.261$				
2006–2008				
No. references	0.106	0.016	42.097	0.000
No. authors	0.045	0.021	4.641	0.003
Coll_type	0.051	0.028	3.247	0.011
MNJS	0.422	0.016	676.396	0.000
Corrected $R^2 = 0.204$				

Table 8 Transformation of the "collaboration type" variable (*coll_type*) in the categorical regression analysis shown in Table 7

Category	Frequency	Quantification
1998–2000		
Int. collab. high RD countries	413	1.899
No collaboration	842	−0.305
Int. collab. low RD countries	87	−0.718
National collaboration	620	−0.750
2006–2008		
Int. collab. high RD countries	732	1.366
Int. collab. low RD countries	166	1.336
No collaboration	908	−0.150
National collaboration	1,025	−1.059

collaborative type on MNCS values compared to MNJS values shown in the categorical regression analysis.

Discussion

Our data show the growing role of collaboration in the Pharmacology and Pharmacy field in Spain as evidenced by the upward trend in the number of authors, institutions and countries per paper. This is consistent with the trends described for world science in general (Gazni et al. 2012) and for Spanish science in particular (Gómez et al. 2010). In Gazni's study on world scientific publications in WoS during 2000–2009, Pharmacology and Toxicology is ranked 6th out of 22 areas according to the multi-authored publication rate, 12th by its multi-institutional rate and 19th by its international publication rate. An

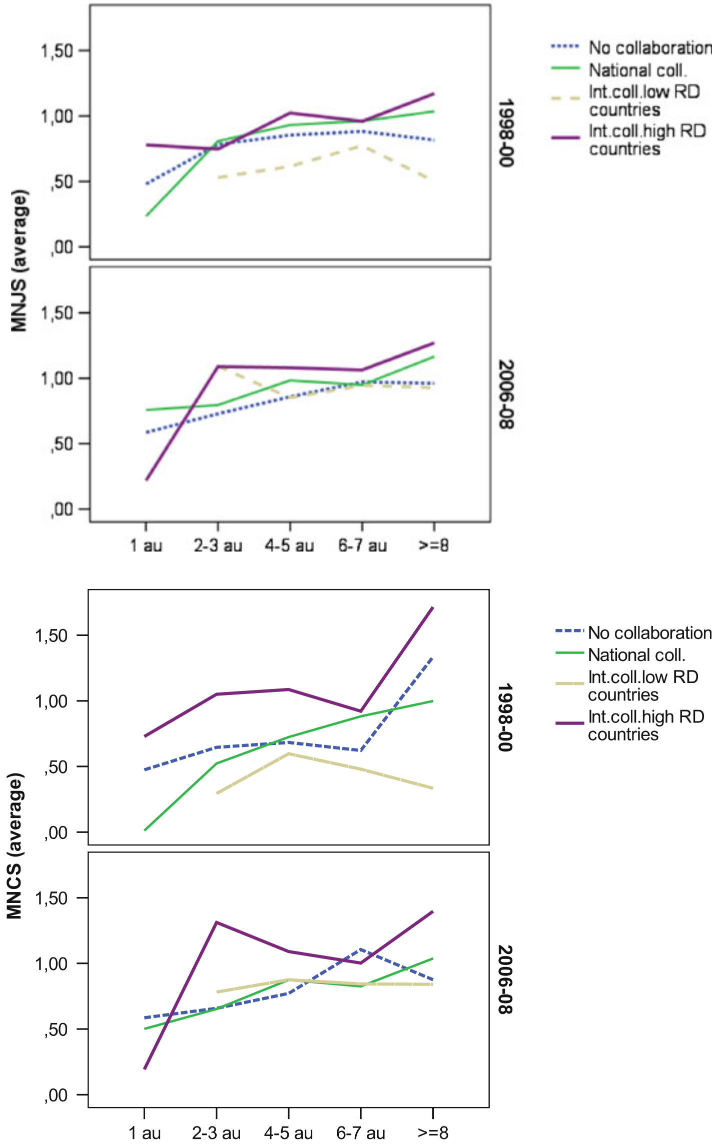

Fig. 6 Impact by number of authors, type of collaboration and period. 26 single-authored publications (0.5 % of total papers) present more than one institutional address. These records were kept in the collaborative categories under the assumption that they were more heterogeneous than single-authored single-address papers since their authors may benefit from a wider range of scientific influences at their different institutional addresses

upward trend in collaboration over the years was observed in all cases. These data illustrate that research in this area is conducted by research teams (high rate of multi-authored publications) with a remarkable level of national collaboration and a smaller role of international links. Our data concerning Spanish research show higher rates of collaboration than those described by Gazni for the world output (around 15 % points higher), but it is well established that inter-country differences do exist due to different factors such as country size, rate of scientific development, and political or economic reasons (Glänzel and Schubert 2004). The growth rate of collaborative papers in the Pharmacology and Pharmacy field in Spain is similar to the growth rate described for Biomedicine in the country (an increase of 71 vs. 74 % in collaborative publications, respectively), but below the overall country average (an increase of 91 %) since the highest increase has been described for traditionally low collaborative fields within the Social Sciences and Humanities (an increase of around 200 %) (Bordons et al. 2012b).

The description of co-authorship links by means of a social network analysis provides us with interesting information to analyse changes in the collaborative structure of this field. Specifically, a larger (longer diameter) and more integrated and cohesive network of authors (higher average degree centrality, shorter average distance amongst authors and higher share of authors in the main component) is observed for our second period of reference. In this paper, the share of authors in the main component is lower than in other studies (see e.g. Newman 2001, where the discipline with the smallest main component contained 57 % of authors), but it is probably due to our journal-based delimitation of the field. In any case, the important issue is the growing rate observed for this indicator over the years (from 34 to 53 %) suggesting a fairly general increase of collaboration in the field. Overall, the growing interconnection amongst authors might enhance the transmission of knowledge in the scientific community as well as contribute to carry out research more effectively.

Heterogeneity of collaboration

Collaboration practises evolve towards greater heterogeneity. On the one hand, as the number of contributing authors and institutions grows, so does the likelihood of finding more diverse partners in research activities. On the other hand, not only collaboration involves a greater number of institutions in recent years, but also there is a rise in collaboration across institutional sectors and countries which grows faster than collaboration within a given sector or within the same country and constitutes a potential source of diversity.

The upward trend in the number of authors per publication points to a larger size of research teams. However, if we control for the number of institutions, very small differences in the number of authors per publication are found between the first and the second period under analysis. This means that the rise in extra-mural collaboration is the main cause responsible for the upward trend in the number of authors per publication. Researchers tend to be ever more open to establish links with other teams both from their own country and from abroad, thus probably facilitating access to infrastructures and complementary knowledge to an extent that would not be reached by merely expanding the size of in-house.

Our study reveals an important surge in cross-sector publications and, in particular, joint hospital–university publications. This is especially relevant since, in as far as biomedicine is concerned, it is deemed to be an indicator of the development of translational research, i.e. to translate basic research into medical practise, bridging the gap between basic and clinical research. A bi-directional flow is supposed to exist between basic research settings and clinical ones and such flow may lead to mutual learning, creation of new knowledge and transfer of this knowledge into practise (Lander and Atkinson-Grosjean 2011). These cross-sectoral links may prove crucial in pharmacological research for the development and trial of new drugs and their introduction in the market.

With regard to international links, two different types of partnership are considered: bilateral and multilateral collaboration. Bilateral collaboration is the prevailing type in both reference periods, but multilateral collaboration gains ground over time (from 22 to 32 %). This ascending trend, which has also been identified in other studies dealing with science in Latin American and European countries (Gómez et al. 1999; Glänzel and Lange 2002; Mattsson et al. 2010), points to a trend of increasing involvement in large global research projects (Gorraiz et al. 2012; Basu and Vinu-Kumar 2000). On the other hand, Spanish authors collaborate mainly with high-level RD countries (more than two-third of internationally co-authored publications), but the percentage of publications including both high and low-level RD countries has more than doubled (from 5 to 12 %). Overall, these findings point to the existence of more heterogeneous networks of countries in the last period under study.

Collaboration and scientific productivity

The size of scientific output has expanded by about 45 % from 1998–2000 to 2006–2008, which is a rate very similar to that described for all fields in Spain for the same period. Our data suggest that this upward trend in production is due to a growing number of active authors rather than to an increase of author productivity, since the average productivity of authors declined slightly over time and the number of authors grew faster than the number of publications (63 vs. 45 %). The possibility that complexity of research objectives targeted by researchers has risen over time, thus requiring the involvement of larger and more multidisciplinary teams could be one underlying reason to explain why the surge in collaboration is not associated with a boost in individual productivity. In our study, only the productivity of most productive authors tends to rise, which suggests that this elite of very prolific authors may benefit most from collaboration (Beaver and Rosen 1979), but further research is needed to confirm this statement. Notwithstanding, the fact that only publications in Pharmacology and Pharmacy journals are considered in this study and pharmacologists also publish in journals on other subfields (Bordons and Barrigón 1992) should not be ignored; therefore, the pending question to be solved would be to determine whether growing collaboration has lead to more publications in other subfields and dealing with more complex scientific questions.

Collaboration and impact of research

Over the years, scientific output tends to be published in "better" journals (increase of 9 % in MNJS), presents a higher number of references per publication and receives a higher number of citations/publication normalised to world average (increase of 13 % in MNCS), altogether suggesting an ascending trend in the scientific influence of Spanish pharmacological research.

Is this increment also related with the rise in collaboration? Our data suggest that this is the case, since MNJS and MNCS values tend to grow in step with the number of authors and, to a minor extent, with the number of institutions. In fact, the highest impact is observed for publications with more than seven authors or more than four institutions. A positive relationship between the number of authors, the number of institutions and the research impact of publications has also been observed in other studies (see e.g. Gazni and Didegah 2011). The underlying reason suggested in the literature is the higher quality of research developed in the framework of larger teams which complement each other in their specialisation profile and available skills, and which are able to produce more original, consistent and comprehensive research (Katz and Martin 1997). The fact that higher citation rates may be due to a higher number of self-citations has also been suggested (Glänzel and Thijs 2004). For the purposes of our study, the influence of self-citations is to be discarded since they were removed from the calculation of citation rates. However, it is true that, for publications with a higher number of authors and institutions, the dissemination of research through personal networks may contribute to favour the visibility of papers and their likelihood to be cited (Goldfinch et al. 2003). However, the fact that multi-authored publications not only tend to receive more citations but also to be published in higher impact journals supports the positive influence of collaboration on final research.

If the type of collaboration is taken into account, we observe that publications in national collaboration tend to be published in better journals and receive a higher number of citations than those written by a single institution but lower than internationally co-authored publications. Both national and international collaboration contribute to obtain MNJS values above country average, but only internationally co-authored publications attain citation rates above world average. This is consistent with the results of Thijs and Glänzel (2010) concerning the scientific output of 15 EU countries in 2003, who observed that extra-mural collaboration boosted citation rates and international collaboration added to this effect, especially in the medical fields. Moreover, the higher impact of multilateral papers compared to bilateral ones observed in our study is consistent with the findings of Glänzel and Lange (2002) in a study on worldwide scientific output during 1995–1996 (SCI) where higher observed and expected citation rates were described for multinational biomedical papers. Differences in the aims and organisational factors underlying both types of collaboration may contribute to explain these results. Bilateral collaboration is supposed to reflect national research portfolios and it is more likely to be based on individual initiative (Gorraiz et al. 2012; Basu and Vinu-Kumar 2000), whilst multilateral collaboration comprises research with a more global orientation and may be the result of institutional or international initiatives. As far as pharmacological research in Spain is concerned, bilateral collaboration shows a more basic research level and higher relative involvement of academic scientists (university and CSIC), whilst multilateral collaboration shows a more applied orientation and higher relative activity of hospitals and NPOs (Bordons et al. 2012b). This category of publications probably includes clinical trials, which frequently involve many institutions and countries in a given paper and tend to receive more citations than conventional papers in Biomedicine (see e.g. Kostoff 2007; García-Romero et al. 2009).

It seems that research impact tends to grow with the type of collaboration and the number of authors, but which of these variables is more influential? Our study shows that the number of authors is more influential than the type of collaboration on the MNJS indicator, whilst a stronger influence of the type of collaboration is observed for MNCS. This is partly explained by the high MNCS values of papers in collaboration with high-level RD countries (20 % above world average with small differences by the number of authors), a long way from the impact of the remaining collaborative categories, especially for the first period. As a consequence, establishing links with foreign partners is a useful collaborative strategy to increase the citation rate of publications. However, it is interesting to note that expanding the size of the teams, even at local or national level, is also positively associated with the impact of research, especially in terms of MNJS.

The fact that the impact of nationally co-authored papers also tends to grow with the number of authors and the number of institutions is a relevant finding which partially contradicts the results of Goldfinch concerning the scientific output of New Zealand Crown Research Institutes (Goldfinch et al. 2003) where higher levels of co-publications with domestic institutions not only did not result in an increase of citation rates, but reduced them. According to Goldfinch, national collaboration in peripheral countries may improve the quality of research but not its visibility and resulting citation rates due to the limited size of national social networks. In the case of Spanish pharmacological research, increasing the number of authors in domestic papers seems to be positive in terms of both publication journals and citation rates. However, it is interesting to point out that national collaboration shows a stronger positive effect on MNJS values than on MNCS values, which could be partly explained by Goldfinch's thesis on the limited size of national networks. The higher visibility and dissemination amongst the world scientific community of internationally co-authored papers and the presumably global interest of a research topic which is addressed collectively amongst scientists from different countries are factors that—apart from the intrinsic quality of research—may contribute to explain their higher citation rates.

An interesting finding of this study is that a positive relationship of collaboration, and especially of international collaboration, with the impact of publications is observed for all the different institutional sectors within the country. National collaboration leads to MNJS values above world average in a few sectors, but only international collaboration is associated with MNCS values above world average. The greatest benefit of international collaboration is observed for companies, which increase their MNJS and MNCS values by 33 and 55 %, respectively, compared to the average values of impact in the sector. This sector shows the lowest overall impact in both periods, which supports the idea that the "weakest" partners (in terms of impact) are the ones who could benefit the most from collaboration (Bordons et al. 1993; van Leeuwen and Tijssen 2007).

The higher impact of cross-sector collaboration as compared with that developed within a given sector was observed only for two-institution publications and in the first period. This finding supports only partially our hypothesis of growing impact for the more heterogeneous research developed in the framework of cross-sector publications. A possible explanation is that for higher co-institutional levels the number of institutions is a stronger source of diversity than the variety of institutional sectors. However, a more plausible reason is that the identity of the sectors involved other matters, since there are inter-sector differences in impact of research and collaboration with the most influential sectors (in terms of impact) might be especially positive for the less influential ones, as has been observed for companies. The detailed study of all such interconnections is beyond the objectives of this paper but it is an interesting issue for future analysis. A limitation of the cross-sector collaboration indicator is that it does not take into account the activity of a number of corporations or networks of institutions (for e.g., "CIBER",[5] networks of research centres in biomedicine) which are trans-sectoral according to their composition but are included in our study in the NPO sector class on the basis of their non-profit aims.

Spanish authors collaborate mainly with high-level RD countries and this type of collaboration seems to be advantageous for Spain in terms of scientific impact. However, it is interesting to observe that the impact of the collaboration with low-level RD countries tends to grow over time in terms of both impact of publication journals and citation rates, thus indicating that the collaboration with these low-level RD countries has been optimised over the years. It may indicate that Spanish scientists have made a more careful choice of partners during our last reference period, but also that both Spanish and foreign teams are

[5] "Centros de investigación biomédica en red" (CIBER), created by the Spanish government to achieve a critical mass of researchers by fields and beyond institutional boundaries to succeed in obtaining excellence in research.

taking advantage of the learning experience derived from collaboration over the years, thus suggesting a kind of "beneficial investment" effect of prolonged collaboration. Moreover, it should be noted that whilst the share of Spanish publications including only low-level RD countries remains stable throughout the period, the share of multilateral publications written by both low and high-level RD countries shows an upward trend. This can be understood in the context of the increasing globalisation of research (Tijssen et al. 2012), in general terms, and of the growing role of multilateral projects in pharmacological research, in particular, associated to the development of multi-country clinical trials. Moreover, deliberate government policies may support international collaboration as a method to foster regional cohesion and building scientific capacity in the least advanced countries (Mattsson et al. 2010).

All in all, our results show evidence of changes in the collaborative practises of Spanish scientists in the pharmacological field during the period under study which lead to the extended presence and heterogeneity of collaboration and is associated to a rising trend in research impact. A large number of authors and institutions, and the presence of international collaboration, in particular with high-level RD countries, are strategic factors which contribute to optimise the impact of Spanish publications in the field. Although the growing citation rates of collaborative papers might be enhanced by their access to larger social networks and related higher visibility, the fact that they are also published in higher impact factor journals points to a genuine improvement of research quality for collaborative papers. From a science policy perspective, it should be noted that promoting more heterogeneous collaboration (e.g. multilateral, cross-sector) probably needs more external stimulus than just establishing more simple links (e.g. bilateral, intra-sector) which are more easily developed by scientists on their own. The study of the "heterogeneity" of collaboration is addressed in this paper considering the collaboration type and the size of links, and assuming higher heterogeneity as the size of the links expands. The development of specific indicators to also measure "diversity" between partners remains our next objective to extend and deepen the study of the role of heterogeneity in research collaboration.

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Appendix

See Table 9.

Table 9 Descriptive statistics for MNJS and MNCS by collaborative type, number of authors, number of institutions and period

	1998–2000		2006–2008	
	MNJS	MNCS	MNJS	MNCS
National collaboration				
1 author	0.23 (0.11)	0.01 (0.03)	0.76 (0.50)	0.50 (0.56)
2–3 authors	0.81 (0.59)	0.52 (0.64)	0.80 (0.55)	0.65 (0.79)
4–5 authors	0.93 (0.60)	0.72 (1.19)	0.98 (0.47)	0.87 (0.99)
6–7 authors	0.96 (0.65)	0.88 (1.34)	0.95 (0.48)	0.83 (1.00)

Table 9 continued

	1998–2000		2006–2008	
	MNJS	MNCS	MNJS	MNCS
>7 authors	1.04 (0.64)	1.00 (1.59)	1.17 (0.45)	1.04 (1.10)
2 institutions	0.89 (0.61)	0.66 (0.89)	0.96 (0.50)	0.83 (1.04)
3 institutions	1.00 (0.63)	0.84 (1.52)	0.98 (0.48)	0.88 (0.94)
>3 institutions	1.08 (0.65)	1.49 (2.16)	1.07 (0.48)	0.93 (0.97)
International collaboration				
1 author	0.78 (–)	0.73 (–)	0.22 (0.02)	0.19 (0.32)
2–3 authors	0.72 (0.51)	0.94 (1.53)	1.08 (0.66)	1.18 (1.72)
4–5 authors	0.95 (0.64)	0.99 (1.44)	1.03 (0.49)	1.03 (1.47)
6–7 authors	0.93 (0.63)	0.82 (1.13)	1.04 (0.51)	0.97 (1.06)
>7 authors	1.08 (0.72)	1.53 (2.12)	1.22 (0.92)	1.31 (1.76)
2 institutions	0.94 (0.61)	0.92 (1.22)	1.05 (0.57)^{ns}	1.17 (1.65)^{ns}
3 institutions	0.84 (0.62)	0.94 (1.52)	1.06 (0.52)^{ns}	0.98 (1.23)^{ns}
>3 institutions	1.07 (0.71)	1.40 (2.02)	1.15 (0.83)^{ns}	1.17 (1.56)^{ns}

Average values (SD)

Significant differences in MNJS and MNCS by number of authors and number of institutions in all cases ($p < 0.05$) except in those marked with "ns"

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