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Do collaborations enhance the high-quality output of scientific institutions? Evidence from the Italian Research Assessment Exercise

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ABSTRACT

In this paper, we analyze the effects of research collaborations on the scientific output of academic institutions, drawing on data from the first official Italian research assessment exercise. We measure the scientific performance of a research unit as the number of publications that received an excellent grade in the evaluation process. Different aspects of scientific collaboration are taken into account, such as the degree of openness of a research team towards other institutions and/or countries, the frequency of co-authorships, and the average size of co-authoring teams. Using econometric models for count data, we find that greater and more frequent knowledge exchange resulting from collaboration with external or foreign colleagues increase researchers' productivity.

1. Introduction

In recent years, scientific productivity of universities has become one of the most important issues for economic policy, as witnessed by the growing number of studies by economists and other social scientists. It has also become increasingly clear that dealing with governance and organizational issues is essential in enhancing the efficiency of universities (Aghion et al., 2010). Central to this issue is the increasing trend in scientific collaborations observed both between individuals and organizations since the 1980s in all fields of research (Durden and Perri, 1995; Beaver, 2001; Goyal et al., 2006). Sharp increases have been observed in co-authorships (Slaughter and Leslie, 1997; Ziman, 2000; Gibbons et al., 1994; Adams et al., 2005; Wagner and Leydesdorff, 2005; Wuchty et al., 2007; Bammer, 2008), as well as in less formal modes of academic co-operation, such as visiting periods and participation to conferences which have the same effect of boosting knowledge exchange and social interaction among researchers and universities (Katz and Martin, 1997; Kalaitzidakis et al., 2004; Adams et al., 2005; Freeman, 2010).

This phenomenon is correlated to factors such as technical progress in communications (Rosenblat and Mobius, 2004) and increasing specialization (Jones, 2009), but it is also due to a policy orientation which favourably views research collaborations. Indeed, believing that the scientific productivity of universities can be enhanced by collaborations, most governments have launched initiatives, such as bringing researchers together in large new centres of excellence and financing research projects carried out by international networks of universities (Katz and Martin, 1997; Kalaitzidakis et al., 2004; Adams et al., 2005). However, the evidence on the impact of collaborations on the productivity of universities and departments is mixed, and it is not clear which collaboration type is most effective.

This also leads to other questions concerning what kind of collaborations should be supported. Should governments and universities encourage researchers mobility and exchanges *across* research institutes, or should they favour the establishment of large agglomerations of research units so as to raise the probability of developing better matching *within* departments? Should policymakers encourage large or small co-authorship teams? Should policy makers provide finance for visiting periods and invitations from and towards foreign universities? In answering these questions, the empirical literature offers little guidance.

The aim of our paper is to understand whether collaboration between individual scientists boosts the quality of scientific production of research units and, if so, which form of collaboration is the most effective. Our unit of analysis is a department, defined on the basis of its institution and research field. We ask whether different characteristics of collaboration, such as the average size of co-authorship teams, the frequency of co-authorship, and the

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openness of a co-authorship team towards researchers from other institutions and/or countries, may have different effects on the production of high-quality research.

We estimate a model of scientific production by using mainly data drawn from the Italian Research Assessment Exercise (RAE) for the period 2001–2003, which was the first official evaluation of academic research performance in Italy. In our paper, high-quality research is measured as the number of publications that were ranked excellent by panels of experts within the RAE. This indicator draws on competent peer review by scholars who, along with their own subjective judgments, used the available bibliometric information – i.e. citations, impact factor, number of pages, etc. (see Clerides et al., 2011, for a discussion of peer review and metric-based indicators).

In our model of scientific production, the number of excellent publications produced by each department is a function of four indicators of intellectual collaboration. First, the share of co-authored publications, in order to capture the extent of formal collaborations that involve the department members. Second, the number of authors per publication, that is, the average size of collaborating teams involving department members and their co-authors. Third, the share of non-affiliated authors, a measure of the openness of department members to formal collaboration with researchers from other universities. Fourth and last, the turnover of international visiting scholars, to account for the openness to *informal* knowledge exchange with foreign academic institutions. Our estimates are based on a Poisson model, a negative binomial model – that allows for data overdispersion – and an exponential Poisson model estimated with instrumental variables – two-stage residual inclusion (2SRI) method – to take endogeneity problems into account.

The results from our empirical analysis lend support to the view that, in order to improve the quality of its publications, a scientific organization has to encourage interactions with scientists from other institutions and countries. In fact, we find that co-authorships with external researchers and visiting periods have positive effects on a research unit's number of excellent publications. Thus, we find that openness to both formal and informal collaborations and knowledge exchange across academic institutions can really enhance the high-quality productivity of scientific departments. These results are confirmed with increased magnitude and significance when we control for the endogeneity of scientific collaborations and for differences between science and social science fields. Moreover, and consistently, we obtain the opposite results when we re-estimate our econometric models on publications that received lower grades. Finally, we find a negative correlation between the size of a scientific team and the number of excellent publications, while the total amount of collaborations has a positive but not statistically significant effect. Taken as a whole, these results suggest that while the total amount of collaborations per se have no effects on the production of high quality science, what matters is the composition of the collaborating teams.

We contribute to the relevant literature in at least two ways. First, we re-assess the evidence on the relationship between intellectual collaboration and the productivity of academic organizations. Although the literature has considered both quantity-based and quality-based indicators of academic productivity, recently the balance has tipped in favour of the hypothesis that, if at all, collaborations affect mainly the quality of scientific production, justifying our focus on quality (Hollis, 2001; Laband and Tollison, 2000, 2003; Rosenblat and Mobius, 2004). Second, and as already mentioned, we aim to ascertain which policy instruments are more appropriate to stimulate the scientific production of academic institutions, i.e. encouraging research mobility across universities vs. favouring matching within institutions to be achieved, for instance, through large agglomerations of researchers. On this issue, few empirical papers are available (Kalaitzidakis et al., 2004; Ramos et al., 2007; He et al., 2009).

The paper is structured as follows. Section 2 reviews the main empirical and theoretical findings on scientific collaboration. Section 3 presents an empirical model of scientific production and describes the data and the empirical strategy. The results are discussed in Section 4, while Section 5 concludes.

2. Intellectual collaboration and scientific output: a literature review

The empirical literature on intellectual collaboration offers a number of insights that are useful to frame our analysis. Conceptually, works on the relationship between collaboration and scientific productivity can be classified along two dimensions: (i) qualitative vs. quantitative indicators of scientific performance, (ii) individuals vs. institutions as the unit of analysis.

Concerning the former dimension, the existing literature shows that collaboration between scientists is effective in boosting the quality of research outputs, while the effect on the sheer quantity of publications can even be negative. Section 2.1 is devoted to exploring this tension between publication quality and quantity, and backs up our choice to focus on an indicator of publication quality. As regards the unit of analysis, recent empirical research has increasingly paid attention to the scientific performance of departments, seen as a more appropriate unit of analysis than individuals if knowledge is best transmitted through face-to-face communication and gives rise to external effects (see Section 2.2).

2.1. Effects of intellectual collaboration on the quality and quantity of publications

Early empirical works on the economics of science detected positive correlations between co-authorships and the scientific production of individual researchers, measured by the number of publications. This was the case with de Solla Price and Beaver (1966) on a sample 592 scientists, and with Zuckerman's study (1967) on 41 Nobel laureates, who were shown to be more apt to collaborate than a matched sample of scientists. Durden and Perri (1995) used both total articles and per capita articles to measure academic performance, finding that co-authorship enhances the productivity of individual researchers in economics. Further, using cross-sectional data on individual researchers, Landry et al. (1996) found that higher rates of co-authorship are correlated with higher numbers of published articles in several fields.

However, further work made clear that one should rather expect a positive relationship between co-authorships and the quality of scientific publications, but not necessarily on quantitative measures of scientific productivity. A first insight in this direction came from the results in McDowell and Smith (1992), showing that co-authorship has no significant effect on the total articles normalized by the number of authors. Similar results were obtained by Hollis (2001) on a panel of individual researchers in economics, finding that when scientific production (articles or citations) is divided by the number of authors, co-authorship is negatively correlated to scientific productivity, and suggesting that the gains from co-authorship occur mainly in the form of higher-quality manuscripts. Laband and Tollison (2000), drawing on information from the Journal of Political Economy (JPE) submission and acceptance lists for the period 1982–1986, provide empirical evidence that co-authored scientific papers are more likely to be accepted for publication in JPE – arguably, a top journal in economics – than sole-authored papers. Wuchty et al. (2007) show that the average number of citations received by team-based works exceeds the average citations of "solo" works even in areas, such as arts and humanities, where formal intellectual collaborations are less common, and when the effect of larger networks in the case of multiple authors is taken into account.

Recent works using sources of exogenous variation in co-authorship patterns have demonstrated the existence of a causal effect of co-authorships on scientific productivity. In Azoulay et al. (2010), exogenous variation is provided by the premature death of "superstar" co-authors; the expulsion of co-authors for ethnic or political reasons from Nazi Germany is instead used as an instrument of co-authorship by Waldinger (2012). Both works reveal that the loss of talented co-authors is detrimental for both the quality and quantity of scientific publications. Adding to the above picture, the work by Laband and Tollison (2000) estimated the value of collegial commentary and informal collaboration on published papers in economics by using detailed data on the 251 feature articles published in the Review of Economics and Statistics during the period 1976–80. Laband and Tollison found that informal collaborations are very valuable, since they increase dramatically the quality of published articles, particularly when they occur during a researcher's training period. Hence, informal interactions are at least as important as formal co-authorships in fostering scientific quality.

To explain the impact of collaboration on scientific quality, Hollis (2001) observes that "easy papers", which are more likely to be published in low-tier journals, are mainly produced by single researchers. This highlights the existence of a quality-quantity trade-off in research. Rosenblat and Mobius (2004) view this phenomenon from a different perspective: they argue that the reduction in communication costs has enhanced collaboration between distant agents, but at the same time it has reduced collaboration between individuals with different characteristics, since it enables researchers to be more selective in choosing their partners. The expected effect could be an increase in the quality of matching and in the collaboration of highly talented researchers, but at the same time a reduction in the quality of collaboration and in the productivity of less talented individuals. As a consequence, there can be a "polarization" effect among researchers, raising the production of high-quality articles, while reducing the low- and medium-quality articles. Hence the net effect on the sheer quantity of scientific publications (of an individual researcher or of a group) could be negative.

Earlier evidence of polarization was shown by Pravdic and Oluic-Vukovic (1986), who analyzed collaborative patterns in chemistry at both individual and group level. Polarization dynamics as well as agglomeration dynamics are revealed by the evidence in Agrawal and Goldfarb (2008), who showed that the introduction of Bitnet in US universities during the 1980s, and the ensuing fall in communication costs, mainly benefited the publication performance of middle-tier universities collaborating with top-tier universities localized in the same geographical area. Apparently, although telematic communication would allow matching with very distant scholars, it proves complementary with communication modes rooted in spatial proximity, such as face-to-face interaction. However, the results obtained by Kim et al. (2009) and Ding et al. (2010), based on longer samples, indicate that innovation in information and communication technologies worked as an equalizing force, allowing scientists holding marginal positions in academic networks to partially fill the gap with the more visible scholars.

2.2. *Effects of intellectual collaboration on the scientific output of academic institutions*

Most works in the economics of science focus on the effects of scientific collaboration on the publication performance of the individual researcher. However, interactions among scientists give rise to spillovers, as shown by the evidence on the "departmental effect" (Allison and Long, 1990; Carayol and Matt, 2006) and discussed by Carillo and Papagni (2013) and Carillo et al. (2008). To the extent that such spillovers are localized, the department or research institution might be the most suitable unit of analysis. Collaboration among institutions has been growing over time, as testified by the evidence in Mowery (1992), Powell (1996), Adams and Griliches (2000), Sutter and Kocher (2004) and Adams et al. (2005), who also investigate the underlying determinants of this trend.

To date, the effect of intellectual collaboration on the scientific performance of academic institutions has been largely neglected in the literature. In this context, our work is close to Ramos et al. (2007) who, based on a sample of Spanish economics and business departments, found that international collaborations have a positive and significant effect, while cross-institution within countries co-authorships as such have no significant effect on the scientific production of departments. Adams et al. (2005) used panel data on scientific papers written in 110 top U.S. research universities in the period 1981–1999, finding that collaboration among institutions, especially international collaboration, increases an institution's quality of research, but reduces its quantity. They conclude, in line with the evidence summarized in Section 2.1, that "a trade off of fewer papers in return for larger overall scientific influence may be taking place" (p. 261). The results by Kalaitzidakis et al. (2004) show that the productivity of European economics departments, measured in terms of publications, is significantly enhanced only by a particular type of collaboration, that with North American universities. This paper is highly interesting for our purposes, since it is based on an indicator of international collaboration that is very close to one of our indicators, namely visiting periods and training undertaken by European economists in North America. However, they analyze only international collaborations, while we also take care of collaborations within the same institution. Finally, He et al. (2009) used a longitudinal data set of biomedical scientists affiliated to New Zealand universities, and showed that both collaborations within a university and international collaborations are positively related to article quality.

3. An empirical model of scientific production

What chiefly emerges from the above literature review is that collaboration results in a better quality of publications, but not necessarily in more publications. From a policy maker's point of view, it is important to ascertain what types of collaborations are more effective at boosting the quality of academic publications. Building upon the research agenda suggested by the literature review, we perform an econometric analysis of the relationship between research quality, measured at the level of research units, and the extent and types of collaborations between researchers. The conceptual framework for this analysis is provided by an empirical model of scientific production, presented herein.

Let $y^q_{i,k}$ be the number of publications of quality q by institution $i = 1, \ldots, I(k)$ that operates in field $k = 1, \ldots, 20$, where $I(k)$ is the number of institutions active in field k. Research units are identified by pairs (i, k). We assume that publications are the outcome of a production process in which researchers' effort, $R_{i,k}$, and knowledge, $A_{i,k}$, are translated into research outputs through a production function $F^q(.)$:

$$y^q_{i,k} = F^q(A_{i,k}R_{i,k})$$

The labour-augmenting knowledge factor $A_{i,k}$ is, in turn, a function of intellectual collaborations $(c_{i,k})$, research unit-specific characteristics $(r_{i,k})$, characteristics (z_i) specific to the institution or university to which the research unit belongs, and field-specific effects

(f_k), i.e. features that characterize the technology or organization of the specific research field within which the research unit is active:

$$A_{i,k} = A(c_{i,k}, r_{i,k}, z_i, f_k)$$

Our empirical analysis aims to estimate the marginal effect of c on y^q, controlling for sources of heterogeneity across research units, research institutions and academic fields. In the following subsections, we illustrate our empirical definitions of research units (Section 3.1), scientific output measures (Section 3.2), indicators of scientific collaboration (Section 3.3) and control variables (Section 3.4).

3.1. Defining research units

In defining research units and in measuring research inputs and outputs, we rely on data from the 2001–2003 Italian RAE, which is the first government evaluation of research outputs from Italian universities and research organizations. The assessment was performed between February and December 2005 under the responsibility of a Steering Committee for Research Assessment (CIVR). In a nutshell, the assessment process worked as follows. Each research institution was invited by the CIVR to submit a number of research products, among those published during the 2001–2003 period, to panels of experts nominated by the CIVR for each field. As a rule, each participating institution had to submit a number of research products equal to half the number of full-time equivalent (FTE) researchers. This rule means that, if $R_{i,k}$ is measured as the number of tenured researchers affiliated to institution i in field k, the number of publications to be submitted by i in k was $0.5R_{i,k}$. Hence only a subset of the overall scientific production of academic units was evaluated, namely the works chosen by academic institutes. In turn, each panel appointed two anonymous referees for each publication, and the referees were asked to rate the products according to four grades: excellent, good, acceptable and limited. The referees were invited to express a motivated evaluation of each publication, also taking account of metric-based indicators, such as citation statistics and journal impact factors.

The CIVR dataset provides information on 1086 research units in Italy, hosted by 102 research institutions (universities and non-university research centres) and working in 20 research fields. The fields covered by the dataset include 14 main fields and 6 special fields. Units defined according to the CIVR dataset include all researchers affiliated to the same university or research institute, who belong to scientific sectors as defined by the Ministry of Education, University and Research.

3.2. Quality of scientific output

Our dependent variable y^q is the number of high-quality publications of research units, measured by the number of publications awarded the grade "excellent" in the research assessment exercise. This is a measure of research output coming from a process of referee evaluation, while most works in the economics of science make use of metric-based indicators, such as citation counts, the impact factor and the *h*-index. The advantages of our choice can be easily argued by referring to the extensive literature on the subject. Indeed, the shortcomings of citations as a measure of research quality and innovativeness are well documented (Medoff, 2003; Weingart, 2005; Oswald, 2007; Clerides et al., 2011; Coupe et al., 2010). Referee-based evaluation of scientific productivity, which also lies at the core of the British RAE, can overcome most of those shortcomings because, while referees usually take account of citation counts and journals' impact factor, they use further qualitative information to build their evaluation. Furthermore, referee-based indicators fare better than metric-based indicators in assessing quality in those fields, such as Literature, Law, or History, where monographs are important outlets for research dissemination.

One problem with the Italian RAE is that the mechanism adopted to select the publications to be submitted does not guarantee the full statistical representativeness of output data. However, this problem seems serious in the case of low quality grades, but the count numbers of excellent publications can be considered representative of the whole production of high-quality articles and books. Indeed, rational unit managers would only submit to the committee the best scientific products which, in their view, were more likely to be awarded excellent grades. In this respect, it is worth noting that one of the declared aims of the CIVR assessment exercise was to provide the Ministry of Education, University and Research with merit-based criteria for the allocation of a share of the budgets of public research organizations. This would create incentives for the research units to take the assessment seriously. Accordingly, if publications not submitted to the assessment are of lower than excellent grade, then our dependent variable is the correct measure of high-quality publications. We do not possess information on such publications un-submitted to CIVR, but we use in our estimates only the data of those organizations that in a given field have a number of publications classified in at least one of the grades lower than excellent greater than zero. This should mean no excellent publication has been left un-submitted to CIVR.

3.3. Scientific collaboration indicators

In studying the impact of collaboration on research quality, we seek to capture four essential dimensions of scientific collaboration that may affect the quality of the publications: the *size* of each collaborating team, the extent of formal co-authorships, i.e. the *incidence* of co-authorships involving unit members, the *composition* of the formal co-authorships – within the same institution, between researchers from different institutions – and the *informal* inter-institution collaborations. Consistent with these aims, we have selected four proxies of intellectual collaboration, measured at the research unit level (2001–2003 averages): the average number of authors per submitted publication; the share of co-authored publications (i.e. products featuring at least two authors); the ratio between non-affiliated ("external") and affiliated ("internal") authors; and the turnover of international visiting scholars. In the empirical model previously described, such indicators are included in vector $c_{i,k}$. Let us describe these variables in greater detail.

The first indicator is given by the number of authors per publication submitted by a unit. In this way we capture the average size of each collaborating team. While we do not have strong expectations on the effect of this variable on scientific excellence, the existing literature underlines the existence of diminishing returns with respect to the size of the collaboration team, and shows that the relationship between team size and scientific excellence varies across fields.

The second indicator is equal to the percentage of products submitted by a research unit that feature at least two authors. By means of this variable we capture the extent of co-authorship over the research activity of a department. A similar indicator was used by Sutter and Kocher (2004), while Laband and Piette (1995), Mixon (1997) and Medoff (2003) used simple dummies to capture whether publications were co-authored by more than two or three scholars.

The intensity of external co-authorships is measured by the ratio between the number of authors that are not affiliated to the unit, and the number of affiliated authors of all the publications submitted by the unit. Formally, let $n_{i,k}$ be the number of authors of the publications submitted to the CIVR by unit (i, k). Since these publications can be co-authored with researchers who are not affiliated to unit (i, k), one can write $n_{i,k} = n^{\text{in}}_{i,k} + n^{\text{out}}_{i,k}$ where $n^{\text{in}}_{i,k}$ is the number of affiliated authors per unit (i, k) and $n^{\text{out}}_{i,k}$ is the number of non-affiliated authors. Our indicator of formal external collaborations therefore reads $n^{\text{out}}_{i,k}/n^{\text{in}}_{i,k}$. This variable sheds light on quite an important aspect of academic collaboration: its composition. Indeed, it measures whether the collaborations are more or less outward oriented. This is likely relevant, since the effectiveness of social interactions in academic work may depend on whether co-authorships involve systematic face-to-face contacts or long-distance communication. "Internal" collaborations allow savings in communication and coordination costs, which increase sharply with distance due to knowledge tacitness, especially in a period when Internet-based communication software was less widespread than today. Yet outward-oriented researchers are more likely to find the best-matching co-authors, and the associated benefits may offset the communication and coordination costs, yielding an increase in scientific quality – providing a powerful motivation for "external" collaborations.

The fourth and last indicator of inter-institution collaborations is given by the turnover of international visiting scholars (i.e. the sum of incoming and outgoing). This variable measures the number of affiliated researchers who have visited foreign research units, as well as that of foreign researchers hosted by Italian institutions, for at least three months during the period covered by the research assessment (2001–2003). This is a measure of openness to the international exchange of knowledge, motivated by collaborations that may also be informal, and that are characterized by face-to-face interaction. As such, this variable aims to capture the effects of international spillovers on scientific knowledge.

3.4. Control variables

Our control variables include the characteristics of the research unit, characteristics specific to the university to which the research unit belongs, and field-specific effects.

3.4.1. Research unit-specific controls

Unit-specific characteristics (vector $r_{i,k}$) include the average age of unit members and the number of PhD students and post-doctoral fellows per FTE researcher. The average age of unit members accounts for variations in the marginal productivity of researchers and in their involvement in administrative and organizational responsibilities linked to their age and experience. At the research unit level, the researchers' average age depends on the relative weight of different generations of scientists, and the age distribution of a research unit can significantly affect the organization of its research activity. Experienced researchers might compensate their declining scientific contributions by training youngsters and collecting funds, so that productivity at the research unit level is not reduced (see Bonaccorsi and Daraio, 2003 on this point). PhD students and post-docs can alternatively enhance the marginal product of researchers by offering research assistance, or diminish it if they increase the teaching load upon researchers.

3.5. Institution- and field-specific controls

The institution-specific characteristics that affect the quality of a unit's publications (z_i in the empirical model) are approximated by the number of administrative staff members per researcher, as well as by the "age" of an academic institution, i.e. the years elapsed from its establishment up to 2004.

While the availability of more staff members may boost the productivity of researchers by providing skilled bureaucratic and technical assistance (e.g. in the maintenance of experimental laboratories, in drafting research project proposals), it could also be correlated with heavier teaching loads that reduce the time devoted to research by unit members. The variable *age of institution* may in principle capture the degree of reputation and prestige of academic institutions, presumably higher among universities and research institutes with a longer tradition. However, many of the universities established in Italy during the 1980s and 1990s were spin-offs of large universities created to tap the increasing demand for academic degrees from smaller cities, in a spirit of spatial decentralization of the supply of university education. Typically, older professors with higher position rents would retain their chairs in the old universities, located in the big cities, whereas the new universities would host younger and, on average, more scientifically active colleagues. The age of the institution could thus even correlate negatively with the quality of scientific publications.

Concerning field-specific controls, we acknowledge that fields differ in academic production processes, in competitiveness, and in international openness. Hence, we use field-specific dummy variables and include them in the matrix f_k. Since the very effects of intellectual collaboration may differ across fields, we also perform the empirical analysis separately for two macro-fields: Science and Social Science. Science includes 11 fields: Mathematics, Physics, Chemistry, Geology, Biology, Medicine, Agriculture, Engineering, Electronics, Computing, Nano technologies, Aerospace. Social Science includes five fields: Literature and Arts; History, Philosophy and Psychology; Law; Economics and Statistics; Political and Social Sciences.

The input and output variables described above are organized in a cross-section of research units. Summary statistics for the selected variables are reported in Table 1 for the whole sample and for the two above-mentioned macro-fields.

4. Econometric methods and results

4.1. The econometric approach

In the econometric analysis of scientific productivity, the Poisson regression model is the reference tool whenever the research output is a count variable, as in our case and in previous papers (e.g. Zucker et al., 2006; Bauwens et al., 2011). Hereby we follow this approach. However, the Poisson model assumes that the mean and the variance of the dependent variable are equal, an assumption that does not find support in our dataset: the standard deviation of the publication counts is larger than its mean (see Table 1). Such overdispersion can be handled by means of a negative binomial regression model. We therefore model the conditional expected value of $y^q_{i,k}$ (previously defined) as follows:

$$\mu_{i,k} = E(y^q_{i,k}|X_{i,k}) = \exp(X'_{i,k}\beta_q)$$

and its variance as $\mu_{i,k} + \alpha\mu^2_{i,k}$. In this formulation, $X_{i,k}$ is a matrix of explanatory variables and β_q is the vector of parameters. The negative binomial regression model holds when $\alpha \neq 0$; the Poisson model is a special case when $\alpha = 0$. The model is estimated by maximum likelihood and the hypothesis of no overdispersion ($\alpha = 0$) is subject to testing (see Cameron and Trivedi, 2005; Winkelmann, 2008). The negative binomial estimates of the parameters' standard errors are robust to heteroskedasticity.

In the cross-section data that we use, the causal interpretation of the estimated parameters can be questioned by endogeneity issues, for at least two reasons. First, there are two omitted variables, such as the scientists' reputation and teaching loads, that affect both scientific productivity and collaborations, in particular formal and informal collaborations with external researchers. Indeed, researchers with higher reputation are better off collaborating with similarly well-regarded colleagues, and most often they find these co-authors in other institutions, home or abroad.

Table 1
Summary statistics.

	Obs.	Mean	Std.Dev.	Min	Max
No. of excellent publications	931	6.19	16.55	0	367
No. of researchers (FTE)	931	39.37	75.19	0.3	1319.3
No. of PhD and post-docs	931	1.21	1.75	0	24.3
Age of institution	928	264.19	298.3	4	916
No. of administrative staff per researcher	931	1.14	0.82	0	8
Average age of unit members	758	44.59	3.33	29.5	55
% of co-authored publications	931	0.68	0.38	0	1
No. of authors per publication	931	5.43	16.69	1	325.75
External authors ratio	931	0.62	1.41	0	32.33
International visiting	931	2.21	6.25	0	107.1
Science					
No. of excellent publications	641	6.71	19.3	0	367
No. of researchers (FTE)	641	41.73	87.53	0.5	1319.3
No. of PhD and post-docs	641	1.15	1.7	0	23.9
Age of institution	641	267.13	298.99	5	916
No. of administrative staff per researcher	641	1.10	0.74	0	8
Average age of unit members	513	43.97	3.22	29.5	55
% of co-authored publications	641	0.89	0.21	0	1
No. of authors per publication	641	7.21	19.85	1	325.75
External authors ratio	641	0.83	1.65	0	32.33
International visiting	641	2.54	7.35	0	107.1
Social Science					
No. of excellent publications	290	5.03	7.39	0	58
No. of researchers (FTE)	290	34.16	34.48	0.3	198.2
No. of PhD and post-docs	290	1.35	1.85	0	24.3
Age of institution	287	257.61	297.15	4	916
No. of administrative staff per researcher	290	1.23	0.96	0.19	8
Average age of unit members	245	45.88	3.2	34.5	54
% of co-authored publications	290	0.23	0.27	0	1
No. of authors per publication	290	1.48	0.64	1	4.14
External authors ratio	290	0.15	0.29	0	3
International visiting	290	1.47	2.31	0	13.4

	No. of excellent publications	No. of researchers (FTE)	Average age of unit members	Age of institution	No. of PhD and post-docs	No. of administrative staff per researcher	% of co-authored publications	No. of authors per publication	External authors ratio	International visiting
Correlation matrix										
No. of excellent publications	1									
No. of researchers (FTE)	0.6604	1								
Average age of unit members	0.2641	0.2834	1							
Age of institution	0.2712	0.2918	0.3229	1						
No. of PhD and post-docs	0.1856	0.3703	0.1184	0.0428	1					
No. of administrative staff per researcher	−0.0919	−0.1188	−0.0884	−0.1392	−0.0516	1				
% of co-authored publications	0.0394	−0.0618	−0.2606	0.0614	−0.0702	−0.0595	1			
No. of authors per publication	0.1975	0.0454	−0.0766	0.0731	−0.0134	−0.0421	0.7567	1		
External authors ratio	0.0295	−0.1725	−0.1709	−0.0457	−0.0761	0.0214	0.5724	0.6807	1	
International visiting	0.0766	0.0958	−0.0335	0.0243	0.2239	−0.1692	0.0805	0.1191	0.0763	1

Of course, a good reputation is typically gained by demonstrating the capacity to produce high quality science. Hence the omission of the scientists' reputation would bring about a correlation between collaboration indicators and the error term, leading to inconsistent estimates. We have a similar problem with teaching loads. For scientists with heavier teaching loads, external collaborations and visiting periods are more costly in terms of time, and a greater teaching effort translates into less time for achieving a high scientific quality. Such endogeneity problems are relevant especially for the composition of collaborations, i.e. external vs. internal, and for informal collaborations with foreign universities. A unit with low reputation and heavy teaching loads may forcedly resort to internal collaborations in the attempt to keep a high volume of scientific production. In other words, marginal changes in reputation and in teaching loads induce a sort of substitution between external and internal collaborations, without necessarily affecting the total number of collaborations entertained by a unit.

Second, the number of international visiting scholars is likely affected by simultaneity and measurement errors. Indeed, scientific quality and visiting scholars in our database both refer to the 2001–2003 period. This simultaneity problem is partly mitigated by the fact that visiting periods enjoyed in 2001–2003 are rooted in past relationships with foreign institutions. Concerning measurement errors, the *International visiting* variable is a composite indicator providing information both on stays abroad based on consolidated long-term relationships between universities, and on visits based on short-lived or recently established relationships. We believe that stays abroad can fully deliver their benefits on the academic productivity of a unit only if they are based on consolidated, long-term contacts. Recently-established relationships may still be unable to effectively stimulate productivity; short-lived visits are probably unable to exert any positive impact. We therefore see visiting periods based on one-off or recent relationships as noise disturbing what we consider the truly interesting signal: visiting periods based on durable international relationships. If such measurement errors are not controlled for, the estimated marginal effect of visiting scholars on high-quality publications is likely to reflect a mix between highly effective informal intellectual exchanges (based on long-term contacts) and weaker informal collaborations (recent relationships, short-lived visits).

In order to avoid these biases, we look for instrumental variables able to capture the exogenous variation in the collaboration indicators suspected of endogeneity. A first group of instrumental variables relate to the international mobility of students, namely the logarithm of the number of students in international mobility, its square, and the logarithm of the funds for students' international mobility (both measured in 1999; source: MIUR). These variables are lagged with respect to the period of interest (2001–2003) so as to avoid simultaneity. The underlying idea is that agreements for student exchanges are more likely to be proposed and designed by scientists who are more involved in long-term international collaborations. Indeed, researchers with weak CVs and low foreign language skills are unlikely to bear the bargaining costs of striking such agreements. At the same time, there is no reason to expect a direct effect on the quality of publications, since the students participating in international exchange programmes are not involved in the research activities carried out by the departments, and the funds allocated for the international mobility of students are not used for scientific purposes.

The second group of instrumental variables builds on the insight that geographical distance can act as a source of exogenous variation in external collaborations. Italy is characterized by very little academic job mobility, due to the lack of a proper academic job market; most researchers take jobs in their regions of origin. Thus, the geographical distribution of talented researchers is approximately random. Yet spatial proximity among researchers can powerfully stimulate external collaboration, whereas the costs of beginning and maintaining external collaborations increase with the distance from current and potential co-authors. We follow a similar insight to that of Card (1993), who used college proximity as an instrument for the education outcomes in estimating the returns to schooling.

Italy is a long thin peninsula stretching about 1300 km from North to South. Whereas Northern cities in the Po Valley are rather close to each other, the population in the Centre and Southern regions is mostly located along the coastlines, and the two large islands, Sardinia and Sicily, are quite remotely placed to the South-West. Hence, the latitude and longitude of cities and towns where universities have their headquarters are natural choices as instruments, since they exogenously capture the weight of transportation costs without exercising an autonomous effect on publication quality. We take their natural logarithms.

Clearly, living in a well-connected and densely populated part of Italy need not stimulate external collaborations if colleagues from the same field are located far away. We thus use a further instrumental variable that combines geographical and social distance, namely the relative number of same-field researchers within 100 km. We compute this as follows: for university i in field k, it is the number of researchers affiliated to universities located within a crow-fly distance of 100 km from university i and operating in field k, divided by the number of researchers affiliated to university i in field k. The minimum of this variable is equal to 1, occurring when researchers in a given university/field have no close neighbours, whereas higher values indicate that it is more likely for researchers to find colleagues in the same field at a reasonably small distance. We use the crow-fly distance instead of the road distance, since the latter may be affected by the per-capita regional income and thus may not be exogenous (e.g. richer regions are endowed with better transport infrastructures and more research funds).

As suggested by Wooldridge (2002) and Terza et al. (2008), we use the two-stage residual inclusion method (2SRI) to estimate the causal effect of collaboration on the high-quality publications of Italian research units. Following Terza et al. (2008) we assume the regression model:

$$Y = g(x_e\beta_e + x_o\beta_o + x_u\beta_u) + u, \quad (1)$$

where the function g(.) is exponential, x_e denotes a vector of endogenous variables, x_o denotes observable exogenous regressors, x_u denotes the unobservable, β are vectors of coefficients, and u is the random error. The first stage consists of the usual regression of endogenous variables on all instruments, as in 2SLS. In the second stage, we apply non-linear least squares to Eq. (1) with regressors x_e, x_o, and the first-stage residuals. Hence, first-stage residuals approximate for unobservable variables.

Note that a test of the exogeneity of international visiting and of the share of external authors can be conducted by testing the null that the value of the parameter of the first-stage residuals is zero. In the second stage, unbiased estimates of standard errors are obtained by applying bootstrapping techniques.

In summary, we estimate three models for the number of excellent publications: a Poisson model, a Negative Binomial model, and an exponential Poisson estimated with instrumental variables (2SRI) to account for the likely endogeneity of international visiting periods of researchers and the share of external authors. We also perform 2SRI estimates on two sub-samples: Science fields and Social Science fields, in order to detect possible differences between these two macro-areas of research.

It is worth noting that if our empirical model captures the essential features of the scientific production process, then the variables that explain the number of excellent products should be significantly correlated with the lowest-quality products, but with opposite signs. Hence, for the sake of robustness we also present estimates which use the number of acceptable publications as the dependent variable.

4.2. Results

Hereby we illustrate the estimation results. Table 2 reports maximum likelihood estimates of the Poisson and Negative Binomial models of excellent publications, along with goodness-of-fit measures and test statistics for the hypothesis of over-dispersion. The results from the 2SRI estimations are given in Table 3 for both the first and the second stage, and for acceptable publications as well, for comparison. In Table 3 we also report the F statistics introduced by Angrist and Pischke (2009), which is the appropriate test for the null of weak instruments when more than one variable is suspected of endogeneity. The small sample critical values of the Angrist–Pischke F statistic for the case of a 2SRI model have not yet been tabulated. Hence, in line with the existing literature we compare the test values with the critical values of the Cragg-Donald statistic tabulated by Stock and Yogo (2002) for the case of a linear IV model with i.i.d. errors. Finally, the 2SRI estimates based on the Science and Social Science subsamples are the contents of Table 4. To save space, the coefficients of field-specific dummies are omitted.

Table 2
Determinants of the number of excellent scientific publications in Italy (2001–2003). Poisson and negative binomial estimates.

	Poisson		Negative binomial	
	Coeff.	*z*-Value	Coeff.	*z*-Value
No. of researchers	1.038***	24.99	1.041***	24.72
No. of authors per publication	0.011	0.22	0.011	0.22
Share of co-authored publications	0.709**	2.4	0.626*	1.95
External authors ratio	0.392***	3.69	0.399***	3.83
International visiting period	0.003	0.34	0.014	1.16
No. of PhD and post-docs	0.223**	2.43	0.149	1.63
Average age of unit members	−0.100	−0.16	−0.186	−0.31
Age of the institution	0.009	0.44	0.023	1.17
No. of administrative staff per res.	−0.309**	−2.42	−0.349***	−3.08
Constant	−0.604	−0.25	−0.026	−0.01
Field dummies	Yes		Yes	
$\ln\alpha$			−2.564	0.215
α			0.077	0.017
No. of observations	665		665	
Pseudo-R^2	0.640			

Notes: The dependent variable is the absolute number of excellent publications. All the regressors, except for the variable International visiting, are taken as logarithms. The variable average age of unit members refers only to universities. Heteroskedasticity robust *z*-statistics are also reported. Standard errors of α and $\ln\alpha$ are in square brackets.
* 10% level of significance.
** 5% level of significance.
*** 1% level of significance.

Before giving the detailed results, some remarks are in order. Estimation performance indicators show that the whole econometric exercise is able to capture the main features of the productivity of Italian research organizations. The Poisson regression displays values of the pseudo-R^2 statistic of 64%, a rather high value for a cross-sectional study. Most of the estimated parameters display high *z*-value statistics. The likelihood-ratio test after the Negative Binomial estimates suggests rejection of the null of $\alpha = 0$ (i.e. equality of mean and variance of the distribution of the dependent variable), confirming the presence of over-dispersion. The 2SRI regressors also display a high explanatory power. Our suspicions on the endogeneity of *International visiting* and *External authors* are confirmed, since the parameters of the first-stage residuals are significantly different from zero. We were therefore able to correct for the biases induced by omitted variables, measurement error, and simultaneity problems. Finally, the positive effects of collaborations on the number of excellent publications are mirrored in their negative effects on acceptable publications.

Table 3
Determinants of the number of excellent and acceptable scientific publications in Italy (2001–2003). Two-stage residual inclusion estimates. Endogenous variables: external authors, international visiting.

	2nd stage				1st stage			
	Excellent		Acceptable		External authors		Int. visiting	
	Coeff.	*z*-Value	Coeff.	*z*-Value	Coeff.	*z*-Value	Coeff.	*z*-Value
No. of researchers	1.005***	10.89	1.102***	9.08	−0.056***	−4.67	0.278***	4.77
No. of authors per publication	−0.720***	−3.15	0.859***	2.61	0.290***	12.26	0.304***	2.67
Share of co-authored publ.	0.106	0.19	0.661	1.11	0.357***	3.93	−0.213	−0.49
External authors ratio	2.482***	3.24	−3.237***	−3.10				
International visiting	0.384***	4.61	−0.522***	−5.10				
1st S.R., Ext. authors	−2.073***	−2.64	2.457**	2.52				
1st S.R., Int. visiting	−0.410***	−4.86	0.549***	5.09				
No. of PhD and post-docs	0.429***	3.18	−0.029	−0.27	−0.028	−1.15	0.224*	1.88
Avg. age of unit members	−0.057	−0.06	1.572	1.57	−0.227	−1.39	0.018	0.02
Age of the institution	−0.063**	−1.97	0.005	0.20	0.005	0.66	0.032	0.85
No. of administrative staff	0.141	0.81	−0.278	−1.15	−0.013	−0.33	−0.085	−0.45
Constant	−2.521	−0.72	−7.641*	−1.88	−9.119*	−1.80	−15.574	−0.64
No. of visiting students					0.011	0.65	−0.426***	−5.40
Expenditure for visiting stud.					−0.028***	−3.20	0.100**	2.39
No. of visiting students, squared					0.000	0.19	0.049***	4.12
No. of researchers within 100 km					0.000***	4.77	0.000	−0.27
Longitude					0.118**	2.10	−0.812***	−3.01
Latitude					0.552*	1.91	1.686	1.21
Field dummies	Yes		Yes		Yes		Yes	
No. of observations	665		664		665		665	
Adj. R^2	0.900		0.900					
Angrist–Pischke *F*					2.637		16.359	

Notes: The dependent variable is the absolute number of excellent or acceptable publications. All the regressors, except for the variable International visiting, are taken as logarithms. The variable average age of unit members refers only to universities. The instruments are the logarithm of the number of students visiting foreign universities in 1999 plus one, its squared value, the logarithm of funds for students visiting foreign universities in 1999 plus one, the relative number of same-field researchers within 100 km, the longitude and the latitude of the university cities. Heteroskedasticity robust *z*-statistics are also reported.
* 10% level of significance.
** 5% level of significance.
*** 1% level of significance.

Table 4
Determinants of the number of excellent and acceptable scientific publications in Italy (2001–2003), for the Science and Social Science sub-samples. Two-stage residual inclusion estimates. Endogenous variables: external authors, international visiting. The share of co-authored publications is excluded from the set of regressors.

	2nd stage, excellent publications			
	Science		Social Science	
	Coeff.	*z*-Value	Coeff.	*z*-Value
No. of researchers	1.057***	5.27	1.106***	9.36
No. of authors/publication	−0.772*	−1.84	−1.848*	−1.70
External authors ratio	2.396**	2.19	6.680**	2.01
International visiting	0.362***	2.90	0.333**	2.08
1st S.R., Ext. authors	−2.004*	−1.84	−5.496	−1.62
1st S.R., Int. visiting	−0.393***	−3.11	−0.365**	−2.13
Age of unit members	−0.188	−0.13	−2.068	−1.39
Age of the institution	−0.060	−1.41	−0.076	−1.19
No. of PhD and post-doc	0.560***	3.01	0.141	0.58
No. of administrative staff	0.149	0.44	0.113	0.37
Constant	−2.028	−0.38	5.601	1.00
Field dummies	Yes		Yes	
No. of observations	359		214	
Adj. *R*-squared	0.896		0.919	
AP F test, Ext. auth.	2.113		0.898	
AP F test, Int. visiting	8.699		8.882	

Notes: The dependent variable is the absolute number of excellent or acceptable publications. All the regressors, except for the variable International visiting, are taken as logarithms. The variable average age of unit members refers only to universities. The instruments are the logarithm of the number of students visiting foreign universities in 1999 plus one, its squared value, the logarithm of funds for students visiting foreign universities in 1999 plus one, the relative number of same-field researchers within 100 km, the longitude and the latitude of the university cities. Heteroskedasticity robust *z*-statistics are also reported.
* 10% level of significance.
** 5% level of significance.
*** 1% level of significance.

4.2.1. *The effects of scientific collaboration*

A first glance at the results reported in Table 2 shows that two of the collaboration indicators – share of coauthored publications, external authors – positively affect publications quality. The elasticities vary between .563 and .669 for the share of coauthored publications, and between .318 and .415 for external authors. The coefficient of international visiting is positive, but it is significant only in the Negative Binomial estimates. The authors per publication coefficients are not statistically different from zero.

The 2SRI estimates reported in Table 3 correct for the endogeneity of international visiting and external authors. As already mentioned, the suspected endogeneity of these two variables is confirmed by the significant (and negative) coefficients of the first-stage residuals. These results mean that the unobservables reduce the production of high quality research. Hence in this case the negative effect of teaching loads prevails over the positive effect of reputation. Looking at the coefficient estimates, we find a positive and significant causal effect of both external authors and international visiting on the number of excellent publications. The share of co-authored publications no longer has a significant impact, whereas we detect a negative and significant effect of authors per publication. The latter can be seen as evidence of decreasing returns.

In detail, the correction for endogeneity takes the International visiting parameter from 0.014 (Negative Binomial) to 0.384, and the external authors parameter from 0.399 (Negative Binomial) to 2.482. Once again, we find that the collaborations between authors from different institutions increase the quality of scientific research, even when such interactions and contacts are informal, as during visiting periods. Hence, high-quality research greatly benefits from interactions with colleagues affiliated to other academic organizations. Both the composition of formal collaborations and the intensity of informal collaborations drive scientific excellence.

Can we trust these estimates as causal effects? We believe that we can. Indeed, first-stage *F* tests reject the null of weak instruments. The Angrist–Pischke *F* test in the first-stage equation for International visiting is a whopping 16.359, well above the critical values tabulated by Stock and Yogo (2002) for the smallest bias. Less strong are the instruments in the External authors first stage, with an Angrist–Pischke test equal to 2.637. This is, however, not a sign of weak instruments if we accept a 25% LIML size bias.

Interestingly, both the *external authors* and the international visiting variables show negative and significant coefficient estimates when we consider acceptable publications as the dependent variable. Thus, the emerging picture is one in which formal and informal collaborations between authors from different institutions greatly alter the quality distribution of scientific products, because they increase the number of excellent products and, at the same time, reduce the number of products of lesser quality. The main advantages of cooperative research may well be due to the openness to different scientific environments and greater freedom in the choice of collaborators.

Estimates on macro-field subsamples provide further interesting insights. Indeed, Table 4 shows that external collaborations are important for the quality of publications in the fields of Science (coefficient estimate: 2.396) and even more in Social Science (6.680). Visiting periods significantly improve the productivity of researchers in both macro-fields, with similar magnitudes (0.362 in Science, 0.333 in Social Science). The field differences with respect to external co-authorship can be explained by the fact that the practice of co-authorship was already widespread among Italian researchers in Science, while it was quite new and gaining strength in Social Science, with huge positive effects on productivity. The lack of differences concerning the visiting periods, instead, is surprising in light of the peculiarities of fields such as Literature, Arts, and Law, where Italian is the main language, and the enduring backwardness of some parts of the Italian social sciences that are quite closed to the world community.

4.2.2. *Inputs and control variables*

The regression results confirm the importance of human capital inputs. Indeed, the parameters of the number of researchers are always significant and positive, with values close to one. The coefficients associated to the average age of unit members are negative, but not statistically significant in any specification concerning excellent products. The magnitudes in Social Science are larger than in the whole sample and in Science. The fact that the best Social Science units are relatively young may signal that in some disciplines, such as Economics and Statistics, methodological and technical innovations appear quite frequently: since younger fellows move swifter down the learning curve, units with a lower average age are better able to implement such innovations.

The age of the research institution has a positive but not significant coefficient in the Poisson and Negative Binomial models, but the coefficients turn negative and significant when we estimate the 2SRI model. However, significance vanishes when we break down the whole sample into Social Science and Science. These results suggest that older institutions are unable to exploit their larger stock of organizational experience. The PhD students and Post-Doc variable affects the number of excellent publications in a positive and statistically significant way in all whole-sample specifications (Poisson, Negative Binomial, 2SRI). The positive effect is confirmed in the Science subsample, but not in the Social Science one. These estimates thus show that post-graduate students are useful resources for the scientific performance of research units, but only in Science. The effect of the administrative staff is negative and significant in the

Table 5
Determinants of the number of excellent scientific publications ascribed to each academic organization in Italy (2001–2003). OLS and Two-stage residual inclusion estimates. Endogenous variable: International visiting.

	OLS		2SRI		Exponential 2SRI	
	Coefficient	z-Value	Coefficient	z-Value	Coefficient	z-Value
No. of researchers	2.52	11.66***	2.09	8.91***	0.84	7.88***
No. of authors per publication	−0.33	−1.32	−0.64	−2.35**	−0.19	−1.74*
Share of co-authored publ.	1.16	1	1.28	1.1	0.28	0.54
International visiting	0.52	2.85***	1.75	4.06***	0.49	3.97***
First-stage residual			−1.31	−3.03***	−0.53	−4.33***
No. of PhD and post-docs	0.28	1.01	−0.05	−0.17	0.38	2.95***
Avg. age of unit members	0.93	0.59	1.98	0.98	0.22	0.22
Age of the institution	0.246	2.85***	0.15	1.39	−0.04	−1.49
No. of administrative staff	0.12	0.22	1.03	1.5	0.27	1.11
Constant	−9.24	−1.42	−15.7	−1.86*	−4.06	−0.98
Field dummies	Yes		Yes		Yes	
No. of observations	757		757		757	
Adj. R-squared	0.57		0.55		0.88	
Kleibergen–Paap Wald rk F statistic			30.91		30.91	

Notes: The dependent variable in OLS and 2SRI estimates is the log of the total number of excellent articles multiplied by n_i/n, where n_i is the number of authors affiliated to a department and n is the total number of authors, while in exponential 2SRI the dependent variable is the same but untransformed in log. All the regressors, but the variable *International visiting*, are taken as logarithms. The variable *average age of unit members* refers only to university faculties. In specifications 2SRI and exponential 2SRI the variable *International visiting* is endogenous and the instruments are the longitude and the latitude of the university cities. Heteroskedasticity robust *t* and *z*-statistics are in parentheses.
* 10% level of significance.
** 5% level of significance.
*** 1% level of significance.

Poisson and Negative Binomial models, but it loses significance and changes sign in 2SRI estimates and in the subsamples.

4.3. An alternative definition of the dependent variable: scientific publications per authors' head

So far in this paper we have attempted to explain the effects of collaboration on total scientific output of high quality, measuring this with the total number of articles rated excellent by CIVR referees. However, a different strategy to measure the quality of co-authored research output ascribes only a share of total output to a single author or an institution. For example, Adams et al. (2005) estimate a model of scientific publications in which the output is measured by the sum of fractions of citations to papers by a university in a given field. Another notable quantitative study is that of Hollis (2001) where the quality of the publications of a single economist is measured as the ratio of the value of a quality index to the number of authors of the publications.

This approach is based on the idea that the output of a research team can be divided into several parts, and that each part can be attributed to an individual researcher. However, while this may hold when a scientific product is measured only in terms of quantity, it may not hold when it is measured also in terms of quality: if scientific output is measured in terms of quality, dividing the output by the number of authors, it is likely to underestimate the contribution of collaboration to scientific production. In the research team a large part of the work also consists in monitoring the work of others, or in training younger researchers. Moreover, the research activities of a team can contain some duplication of functions which, while not ensuring an increase in the amount of scientific publications, guarantee an increase in their quality. If we divide publications by the number of authors, we eliminate by definition the team work that can give rise only to an increase in quality.

Of course, some authors may well adopt a free rider behaviour or there can be such high transaction and coordinating costs as to reduce the productivity of a team also in terms of quality. In this case, if we do not divide by the number of co-authors, we may overestimate the effect of team collaboration. For this reason, although our preferred measure of the quality of publications is the absolute number of excellent articles, we provide a robustness check of our results by using as a dependent variable the total number of excellent articles multiplied by $n^{\text{in}}_{i,k}/n_{i,k}$, where $n^{\text{in}}_{i,k}$ is the number of authors of excellent publications affiliated to one department and $n_{i,k}$ is the total number of authors of the same publications submitted to the CIVR for evaluation, given that in this case the collaboration effects are underestimated.

The independent variables are the same as in the previous regression models, except for the variable *external authors* which does not enter the estimated equations because it is negatively correlated with the dependent variable by definition. The dependent variable is the logarithm of the excellent publications ascribed to a department. We estimate a linear model with OLS and apply the 2SRI to account for the endogeneity of the variable international visiting scholars, in which case we use two instrumental variables: the longitude and the latitude of the university cities. Furthermore, we estimate an exponential model of the number of excellent scientific publications per authors' head similar to that we used for the count number in the previous subsections. In this case too, we apply 2SRI instrumental variables with the same set of regressors and instruments as in linear 2SRI.

Regression results are shown in Table 5. The estimated parameters of the extent of co-authorship in all the estimated models are positive but not statistically significant, while the size of a team shows a negative and significant coefficient. Thus with this definition of the dependent variable we obtain a confirmation of the previous results: the extent of formal collaborations is not significant and still shows a positive sign, while the variable that captures the international mobility of researchers is still significant and with a positive effect on high-quality research. Hence, this feature of social interactions in the scientific community seems to approximate the essence of knowledge exchange and its importance for science. The average age of researchers is, as in the previous case, not statistically significant. The other context variables, such as PhD students, administrative staff and the age of the institution, are not significant.

5. Conclusion

In this paper we investigated the effects of co-authorship and other forms of social interaction on the productivity of scientists. This issue has become crucial in any debate on policies to foster science in advanced countries, since there is currently extensive collaboration in the community of researchers. We approached the issue empirically by estimating econometric models for count data from the first assessment of the research output of 102 Italian universities and research organizations, whether public or private. The data refer to 20 disciplines, and have several positive features, the chief one being that research products are assigned to four different quality categories through a process of peer evaluation, which is more reliable than the common use of metric-based indicators.

The picture that emerges from the results of this econometric exercise on the determinants of high-quality scientific productivity shows the importance of the flows of knowledge that arise from collaborations among researchers from different institutions and/or countries. These are among the most robust determinants of the production of excellent publications. Among the control variables, the presence of PhD and Post-doc students and the age of the institution are the most effective at increasing the production of excellent publications.

The overall set of regression results has strong implications for science policy. It emphasises that knowledge exchange with researchers in the global scientific community is vital for those who aim to achieve the highest quality of research, and has limited or even negative effects on those who do not compete for international prestige in academic research.

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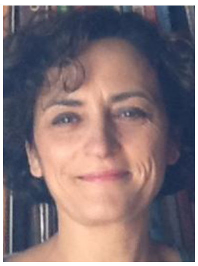

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