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Research Groups: How big should they be?

Isabelle Cook, Sam Grange, Adam Eyre-Walker

We have investigated the relationship between research group size and productivity in the life sciences in the United Kingdom using data from 398 principle investigators (PIs). We show that the number of publications increases linearly with group size, but that the slope is modest relative to the intercept, and that the relationship explains little of the variance in productivity. A comparison of the slope and intercept suggests that PIs contribute on average 5-times more productivity than an average group member and using multiple regression we estimate that post-doctoral researchers are approximately 3–times more productive than PhD students. We also find that the impact factor and the number of citations are both non-linearly related to group size such that there is a maximum. However, the relationships explain little of the variance and the curvatures are shallow so the impact factor and the number of citations do not greatly depend upon group size. The intercept is large relative to curvature suggesting that the PI is largely responsible for the impact factor and the number of citations from their group. Surprisingly we find this non-linear relationship for post-docs, but for PhD students we observe a slight but significant decrease in the impact factor. The results have important implications for the funding of research. Given a set number of Pis there is no evidence of diminishing returns in terms of the number of papers published and only a very weak cost to very large groups in terms of where those papers are published and the number of citations they receive. However, the results do suggest that it might be more productive to invest in new permanent members of faculty rather than additional post-docs and PhD students.

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Research Groups: How big should they be?

Isabelle Cook
Sam Grange
Adam Eyre-Walker*

School of Life Sciences
University of Sussex
Brighton
BN1 7FR
United Kingdom

*Corresponding author: a.c.eyre-walker@sussex.ac.uk

Introduction

How large should a research group be? Should resources be concentrated into a small number of research groups or should funding be more evenly distributed? This question has been investigated in a number of different countries at a variety of different levels of organisation. Most analyses of individual research groups, rather than departments or universities, have found that the number of research papers per group member, is either unrelated (Cohen 1981; Johnston et al. 1995; Seglen & Aksnes 2000) or that it declines with group size (Brandt & Schubert 2013; Carayol & Matt 2004; Diaz-Frances et al. 1995). Reports that there is an optimal group size (Qurashi 1984; Qurashi 1993; Stankiewicz 1979) appear to have limited statistical support (see for example Cohen's (Cohen 1984) criticism of Qurashi (Qurashi 1984)), as do reports that productivity increases exponentially with research group size (Wallmark et al. 1973) (see criticism by (Cohen 1981)).

The question of research group size and the allied question of funding has been brought back into focus with a recent analysis of National Institute of Health (NIH) data. Jeremy Berg, a former director at the NIH, found that both the number of papers and the median impact factor (IF) of papers increased with NIH funding per lab until a maximum was attained at approximately $750,000 per year, after which both the number of publications and the median IF declined (see https://loop.nigms.nih.gov/2010/09/measuring-the-scientific-output-and-impact-of-nigms-grants/, reported by (Wadman 2010)). This has led to a policy by which grants from well-funded labs are subject to additional review by the NIH (Berg 2012). However, Berg presents no statistical evidence in support of the maximum. A truer reflection of the data might be that funding explains very little of the variance in publication rate or where those papers get published. A recent analysis of the Canadian funding of science comes to a very similar conclusion (Fortin & Currie 2013). Various measures of productivity and impact, including the number of publications and the number of citations, are positively corelated to the level of funding, but the relationship is very weak, both in terms of the slope of the relationship and the variance explained. Furthermore they show that an increase or decrease in funding, over the period they considered, had no significant effect on measures of productivity and impact (Fortin & Currie 2013).

Here we consider the current relationship between research group size and productivity in the Biological Sciences in the United Kingdon. We consider the number of papers pubished by a research group, the journals in which those papers appear and the number of citations they receive as a function of group size. We define a group here as a principle investigator (PI) and their associated post-doctotal researchers, henceforth post-docs, PhD students, technicians and other research staff (usually pre-doctoral research assistants).

Materials and Methods

Group size

We emailed all principle investigators (PIs) in biological science departments in universities that had made a return to sub-panel 14 (Biological Sciences) of the 2008 edition of the Research Assessment Exercise. Email addresses were harvested from departmental web-sites. Emails were sent in two phases, in October 2012 and in October 2013 by IC and SG respectively. Contactees were asked to provide the number of post-docs, PhD students, technicians and other staff working in their group. If individuals were part-time or shared between faculty we asked that they be counted as a fraction of a full time equivalent. Contactees were also asked whether they had been at the same institution over the preceeding 5 years, and only individuals that fullfilled this criterion were included in subsequent analysis; this was to make it possible to identify the publications produced by each PI. Copies of the emails sent to PIs are included as supplementary information.

Publication data

The publications published by a PI were obtained by searching the ISI Web of Science database by employing their author search facility using last name, first initial and institutional address, restricting the search to papers published in the life sciences. To check the data, we listed the initials or first names associated with each paper returned by the initial search – for example a search of Jones, C at Dundee might return publications from Jones, Chris and Jones, Cate. Publication files containing multiple authors were manually curated. We also checked all publication files that had papers with more than 20 authors since the address field in the initial search is not diectly associated with the author – for example, a search of Jones, C at Dundee might return a paper by Jones, C at Cambridge, who co-authored a paper with someone at Dundee. Such mistakes are more likely for papers with many authors. The publication data was downloaded by AEW in July and August 2014, however only papers published between and including 2008 to 2012 were considered for scientists contacted in 2012, and between and including 2009 to 2013 for scientists contacted in 2013. For each publication we divided the number of citations by the number of years since publication. We also counted the number of authors for each paper and obtained the impact factor of the journal in was published using impact factors from 2013.

Statistics

To test whether the regression coefficients were significantly different to each other in a multiple regression we bootstrapped the data by PI, re-running the multiple regression calculating the difference between the regression coefficients each time. We repeated this 10,000 times. The p-value was the number of differences between regression coefficients that were greater or less than zero, as appropriate (e.g. in testing whether the number of papers is more strongly dependent upon the number of post-docs and PhD students, where the regression coefficient for post-docs is greater than that for PhD students, the p-value was the number of differences between the bootstrap coefficients that were negative).

Data availability

The anonymised dataset is available in supplementary table S1.

Ethical considerations

It was not considered necessary to submit this study for ethical review given the nature of the project – simply requesting research group size information directly from PIs. All participants gave their written consent in the form of an email reply. All data was treated as confidential. Copies of the emails sent to PIs are included as supplementary data.

Results

In order to investigate the relationship between scientific productivity and research group size within the biological sciences in the United Kingdom we contacted all principle investigators

(PI) who were in UK research departments that took part in the 2008 Research Assessment Exercise. In total 2849 academics were contacted personally by email, of which 398 (10%) replied and had been at the same institution over the previous 5 years. We required them to have been present at the same institution so that we could obtain their publication record over that period (see Materials and Methods).

Group size

Most biology research groups in the UK are of modest size, containing less than 10 staff and students (Figure 1). The mean research group size is 6.3 (standard deviation of 4.4) with a range of 0 to 30, excluding the PI. On average a research group contains 3.0 PhD students, 2.1 postdocs, 0.5 techinicians and 0.7 other staff (mostly research associates). The numbers of post-docs, PhD students, technicians and other staff are mildly but significantly positively correlated to each other, with the exception of PhD students and other staff (Table 1).

Number of publications versus group size

The average number of publications published by each group in the previous five years was 22.0 papers (SD = 18.8) but varies considerably between PIs, from 0 to 177. Although the distribution is skewed, all analyses were qualitatively unaffected by using a log or square-root transformation.

The number of publications over the preceding 5 years is significantly correlated to the total group size (here defined as the number of post-docs, PhD students and other researchers – i.e. excluding the PI) ($r = 0.43$, $p<0.001$)(Figure 2). However, group size explains less than 20% of the variance in the number of papers, and at all levels of group size there is substantial variance in the number of papers produced (Figure 2). The relationship between the number of papers produced and group size appears to be linear since a quadratic term in a linear regression is not significant ($p = 0.17$). However it is conspicuous that the intercept (10.44 (SE=1.48)) of the linear regression is high relative to the slope (1.81 (0.19)). In other words, a PI with no group will on average produce 10.4 papers over a 5 year period and each additional team member adds just 1.81 extra publications over that period. Given the non-zero intercept it is not surprising that the number of papers per group member, including the PI, decreases with increasing group size (Figure 3).

A multiple regression suggests that the number of published papers is significantly and positively correlated to the number of PhDs ($p=0.006$), post-docs ($p<0.001$) and other researchers ($p=0.001$), but not the number of technicians ($p=0.46$). Each post-doc is estimated to add 3.50 (SE = 0.41) papers per 5 years whereas PhD students and other researchers add 1.07 (0.37) and 1.66 (0.48) papers respectively. All these estimates are significantly different to each other at the 0.01 level. The intercept in this model is 10.59 (1.48) suggesting that PIs are about 3x more productive than post-docs and almost 10x more productive than PhD students.

In the biological sciences most papers are co-authored, often with a large number of co-authors - the mean number of authors per paper considered here is 9.3. As a consequence the number of papers may not reflect the output of a particular research group but the collaborations the group participates in. We therefore also considered the number of papers in which the PI was first or last author (these are traditionally the places where the lead PI on a project will appear in the biological sciences). On average each PI produced 11.6 (SD = 10.0) first and last author papers, which means that about half of all papers associated with a PI are first and last author papers. However, the proportion of papers that are first author papers varies significantly between PIs (Chi-square = 1455, df = 378, $p < 0.001$). The proportion is not surprisingly significantly negatively correlated to the number of authors on a paper ($r = -0.18$, $p<0.001$), but it is not correlated to group size ($r = -0.019$, $p = 0.70$).

The number of first and last author papers is significantly correlated to group size ($r = 0.44$, $p<0.001$), with an intercept (5.26 (0.79), $p<0.001$) and a slope (0.99 (0.10), $p<0.001$) that are approximately half the values observed for the total number of publications as we would expect given that approximately half of all papers are first and last author papers. The number of first and last author papers is significantly corelated to the number of PhD students ($b = 1.02$ (0.19), $p<0.001$), post-docs ($b = 1.77$ (0.22), $p < 0.001$) and other members ($b = 0.61$ (0.26), $p = 0.017$), but not the number of technicians ($b = -1.01$ (0.57), $p = 0.075$). All of these estimates are significantly different to each other at the 0.01 level. The intercept in this model is 4.83 (0.78).

Impact versus group size

Do large research groups produce not only more papers, but also papers which appear in journals with higher IFs and which gain more citations? Since the distributions of the IF and the number of citations per year are highly skewed we took the log of the IF and the number of citations per year, and then calculated the mean of these log values for each PI. Qualitatively similar results are obtained using the raw values.

We find that mean log IF is significantly correlated to group size ($r = 0.12$, $p=0.022$) but the correlation is very weak; group size only explains 2% of the variance. However, in contrast to the number of papers, we find that including a squared term in the regression is significant ($p = 0.006$) and this substantially improves the fit of the model ($r = 0.18$, $p= 0.002$), suggesting there is an optimal group size in terms of the IF (Figure 4). Nevertheless the degree of curvature is modest relative to the intercept (Figure 4). The model is also substantially improved by using separate linear terms for PhD students, post-docs, technicians and other researchers ($r = 0.36$, $p<0.001$). Therefore to select the best model we used forward stepwise regression, only including terms that were significant at the 5% level after inclusion, allowing both linear and squared terms for all categories of staff. The best model selected was one in which there were linear and squared terms for post-docs, much in keeping with the overall pattern. However, the model also included a negative linear term for PhDs, indicating that the mean IF declines as the number of PhD students in a group increases. Nevertheless the slope of this relationship ($b = -0.018$, $p < 0.001$)) is very small compared to the intercept (0.642, $p < 0.001$) and the model only explains 14% of the variance in the mean log IF.

Much the same pattern holds true for the log of the number of citations. The mean log number of citations is not significantly correlated to group size ($r = 0.062$, $p = 0.28$) (Figure 5). However, the fit of the model is substantially improved by the inclusion of either a quadratic term ($r = 0.17$, $p= 0.003$)(Figure 5) or separate linear terms for PhDs, post-docs, technicians and other researchers ($r = 0.21$, $p = 0.001$). Model selection in this case yields a model with linear and squared terms for post-docs but also a squared term for technicians. However, the intercept is high relative to any of the other coeeficients and the model explains just 6.3% of the variance.

Discussion

We have shown that the number of papers published by a group is positively and linearly correlated to the research group size, but that the log impact factor and the log number of citations are maximised for a group size of between 10 and 15 people. Conspicuous amongst all these relationships is the high value of the intercept relative to the slope or curvature. This is particularly the case for the IF and number of citations, where group size has little effect on either of these measures (figures 2,4 and 5). The high value of the intercept suggests that the productivity of the group can be large;ly attributed to the PI. We also find differences in the productivity of post-docs and PhD students with post-docs producing on average 3 times as many papers as PhD students and with the mean log impact factor and the mean log number of citations increasing for post-docs at least amongst most groups that are relatively small, and either decreasing or not changing with increasing numbers of PhD students.

Although we have collected data from a large number of groups, we have relied upon self-reporting. This might have potentially biased the results. In particular we may have had under-reporting from small groups or groups that were unproductive. It is difficult to address this problem. Site visits to selected universities may help, but even then there is no guarantee of complete or unbiased results. We have also restricted our analysis to PIs that have remained at the same instutition for 5 years; this might have biased our results away from young researchers, who may move early in their career.

We have found that the relationship between the number of papers and research group size is linear, but with a non-zero intercept. This is in contrast to previous analyses that have reported linear relationships with a zero intercept (Cohen 1981; Seglen & Aksnes 2000). The pattern is however consistent with the analyses of Diaz-Frances et al. (Diaz-Frances et al. 1995) for Mexican research groups, Carayol and Mutt (Carayol & Matt 2004) for a French university and Brandt and Schubert (Brandt & Schubert 2013) for German research groups. Diaz-Frances et al. (Diaz-Frances et al. 1995) and Carayol and Matt (Carayol & Matt 2004) found that the number of papers per group member decreased as group size increased and Brandt and Schubert (Brandt & Schubert 2013) observed a slope of less than one between the log of the number of publications and log group size. Both of these are patterns you would observe if the number of papers increased linearly with group size but the intercept was non-zero and positive.

Cohen (Cohen 1981) and Seglen and Aksnes (Seglen & Aksnes 2000) reported a linear relationship between productivity and research group size but a zero intercept. There might be several reasons why the current analysis yielded a non-zero intercept. First, they were considering research groups within laboratory-work intensive fields, such as cancer research and microbiology, in which progress is difficult without a research group. In contrast we have considered groups across the full spectrum of biology which will include fields such as theoretical biology in which it is possible to be highly productive without a group. Furthermore, biology has become increasingly collaborative so a PI may be productive by collaborating with others - the mean number of authors on papers published by PIs who reported no other member of their group is 12.3. Second, the presure to publish and to get grants has increased in the UK as consequence of the Research Assessment Exercise and the Research Excellence Framework. This means that it is difficult to be an unproductive scientist in the UK.

What do the results imply for the funding of science? Although, the number of papers per researcher declines with group size (figure 3) this does not imply that we should invest in smaller groups for two reasons. First, there is no evidence of diminishing returns as group size increases; post-docs and PhD students in large groups contribute on average as much to the number of papers produced as post-docs and PhD students in small groups. There is a decrease in the IF and the number of citations obtained by very large groups, but this decrease is minimal. Second, it is clear that some types of science can only be conducted by large groups. Hence, if there is a set number of PIs, then there is no reason to restrict group size. However, it is nevertheless evident that PIs contribute considerably more productivity than other team members so it might pay to establish more permanent researchers than more post-doc and PhD student positions. We estimate that PIs contribute approximately 3-times more productivity than post-docs, so if the cost of setting up and maintaining a PI is less than 3-times as expensive as a post-doc then this is where we should make our investment. This makes sense, at least as far as academic research is concerned. A huge proportion of post-docs never obtain a permanent position, which means that the training they received is wasted, at least within academia.

We find that PIs are approximately 3 times more productive than post-docs, who are in turn about 3 times more productive as PhD students in terms of the number of publications. This might reflect the training and experience that PIs and post-docs have, but it might also reflect the fact that only productive PhD and post-docs move onto the next stage of their career.

In summary we have shown that the number of papers, the impact factor and the number of citations increases with group size, although the impact facor and the number of citations decrease for very large groups. However, the relationships are weak, both in terms of the variance that group size explains and the slopes of the relationships. Our results suggest that investment in permanent researchers may be the most productive avenue for funding research.

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	Post-doc	Technician	Other
PhD	0.27***	0.18***	0.02
Post-doc		0.21***	0.12*
Technician			0.24***

Table 1. The correlations between the numbers of PhD students, post-docs, technicians and other group members.

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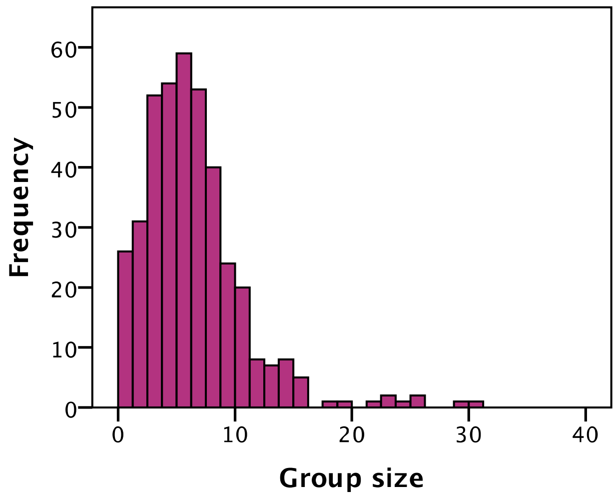

Figure 1. The distribution of group size amongst 398 PIs within the Life Sciences in the United Kingdom.

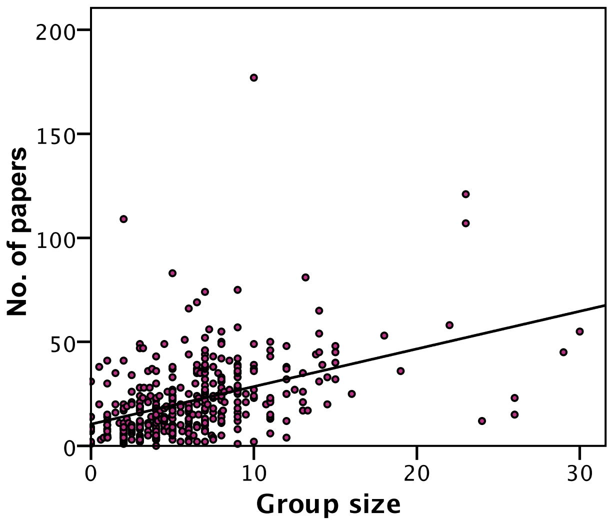

Figure 2. The number of papers versus group size. The line of best fit is shown.

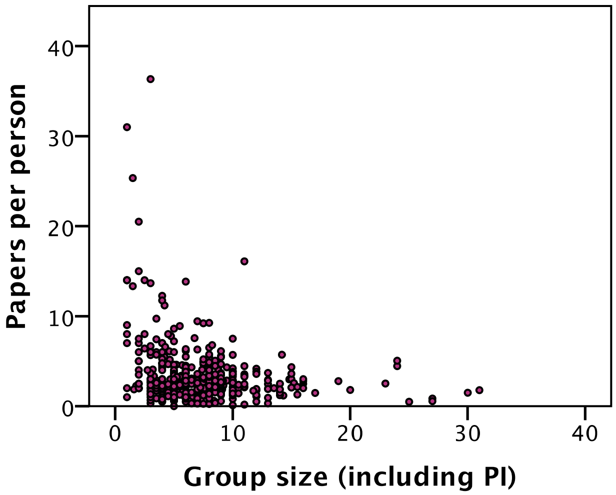

Figure 3. The number of publications per group member, including the PI, versus group size.

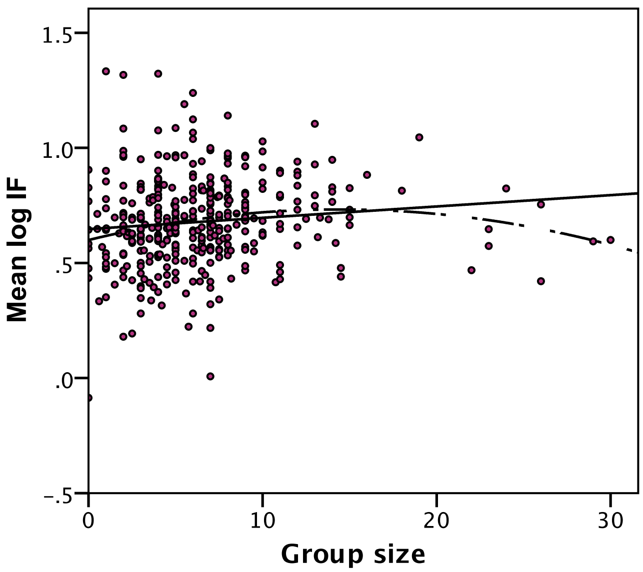

Figure 4. Mean log IF versus group size. The best fitting linear (solid line) and quadratic (dashed) lines are shown.

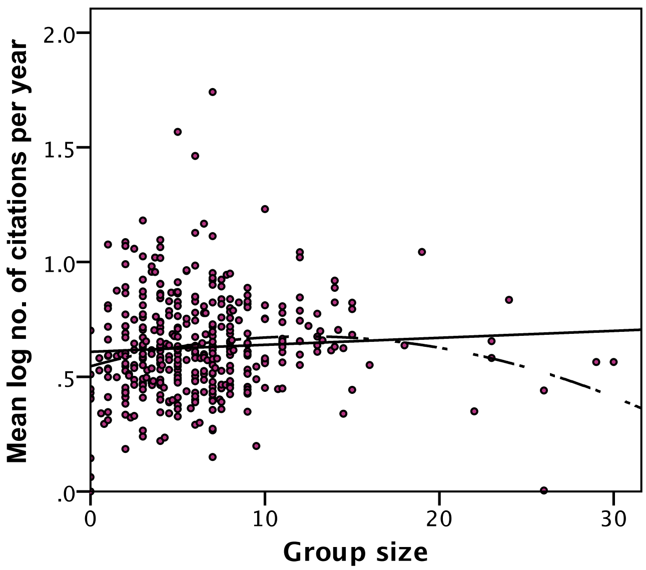

Figure 5. Mean log number of citations per year versus group size. The best fitting linear (solid line) and quadratic (dashed) lines are shown.