Modeling gender differences in participation in PhD studies in mathematics

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Abstract: In most subject areas the proportion of women PhD students is around 50%. Mathematics differs despite minimal differences between boys' and girls' school achievements. In this paper we show, drawing on Swedish data from the last 45 years, that low female participation in mathematical PhDs is due to low participative growth rates rather than historical low levels. In comparision, science has twice as strong growth rate, while non-STEM subjects have grown four times faster. The results show that gender differences regarding participation is indeed dynamic, but changes do not occur despite polical initiatives such as laws on non-discrimination and encouragement of equal parental leave. Instead, the results imply that in order for maths departments to avoid continuing being gendered institutions, requires active changes in structures and working environment.

Keywords: gender, higher education, mathematics, mathematics modelling, PhD participation

Introduction

With respect to participation, in most western countries and in many subjects, women not only represent a majority at undergraduate level but also an increasing number at graduate level (OECD 2015); in 2012, women represented 47% of doctoral students across the OECD jurisdictions and 48% across the EU. However, the situation for mathematics is different. Historically, gender differences in both mathematics participation and achievement have been attributed to a lack of ability or differences in interest (Charles & Bradley, 2009) but research in countries like the U.S. and Sweden has shown no gender differences between girls' and boys' mathematical performances at lower, middle, and high school (e.g. Brandell 2008; Hyde, Lindberg, Linn, Ellis & Williams 2008). A meta-analysis of the results of international large scale assessments (ILSA) in mathematics, Trends in International Mathematics and Science

Study (TIMSS) and the Programme for International Student Assessment (PISA), arrived with similar conclusion (Hyde et al. 2008). This parity of performance is not reflected in female participation in PhD studies and beyond, creating an early so called “leaky pipeline” (Hyde et al. 2008; Moss-Racusin, Dovidio, Brescoll, Graham & Handelsman 2012).

However, other factors than those in the “leaky pipeline” contribute too. When trying to understand girls and women partipation in mathematics, the most powerful predictors when studying cross-national patterns of gender differences in mathematics achievements in the two major ILSA were, besides women’s parliamentary representation, gender equity in school enrolment and women’s share of research jobs (Else-Quest, Hyde & Linn 2010), meaning that both enrolment and the ratio men/women in different academic posititions are of relevance. Looking at participation in mathematics at university level, there are variations between countries: for instance, in the U.S. for many years, roughly half of all undergraduate degrees in mathematics are earned by women (Chipman 1996; Hyde et al. 2008), but in Sweden, this proportion, over the academic years 2010/11-2014/15, was just 37% (www.scb.se). This is particularly interesting since Sweden is a country not only with a reputation of its gender equality (Weiner 2005) but also is a country that typically scores very positively on international measures of gender equality: in 2019, Sweden ranks first in the EU on the Gender Equality Index with 83.6 points (out of 100), 16.2 points above EU’s score (eige.europa.eu.). Given this background, it is of interest to further investigate women participation in PhD education with mathematics as a special focus. Similar studies, with respondents from different levels of higher education, can be found, for instance, in engineering, (e.g. Sax et al. 2016), STEM (e.g. Chang & ChangTzeng 2018; Xu 2008), or with a general focus (e.g. Johnson & Muse 2016; Ooms, Werker & Hopp, 2019), but then concentrating on attributions or specific factors more than shifts in participation. In a previous study, Lindberg and collegaues (2011) studied women’s participation in various positions in different subjects and their descriptive analysis show big variations in career patterns both between subjects but also in terms of different positions. Few women reach professor level even in subjects that are dominated by women at lower levels. However, given that methods used were descriptive, their results netiher offer further explanations of how these numbers are a result of high/ low starting values nor do they discuss prediction of the future. Therefore, this paper aim to study womens participation in PhD studies with those aspects in mind.

Background

As a context to the study, the background starts with a short explanation of the Swedish gender equality policy that was established officially in the 1970s and was explicit in the national curriculum for schools already from 1969 (Hedlin 2013). It was also during these years there was an increase of pre-schools and other day-care making it possible for women to participate in worklife. Today, the corner stone of the Discrimination Act that is part of Swedish gender equality policy, is that,

> Sweden's overarching objective of gender equality policy is for women and men to have the same power to shape society and their own lives. (www.government.se)

It continues with sub-goals such as equal distribution of power and influence, and equal education. The government's goal of between 40% and 60% female participation provides a clear target for academic institutions (Lindberg et al. 2011). This particular span is considered a balanced group (Kanter 1977). The benefits of having a balanced group is reinforced in research in other areas, such as, collective intelligence. It has been concluded that collective intelligence extends beyond the cognitive abilities of the groups' individual members with strong correlation to the number of women in a group (Woolley, Chabris, Pentland, Hashmi & Malone 2010). This was linked to social sensitivity and speaking turn variance, symbols often linked to women. Taking a more general view, we can see that the more women in power, the more stable democracy and Inglehart and collegaues conclude that

> While men are relatively likely to emphasize competition, women tend to emphasize cooperation; and while men tend to stress domination, women tend to have a more supportive leadership style. For reasons that are deeply rooted in the nature of advanced industrial society, the "female" leadership style tends to be more effective in these societies than the hierarchical, bureaucratic (and masculine) style that prevailed in agrarian and industrial society. (Inglehart, Norris & Welzel 2002, p.43).

It appears that the idea of balanced group is of benefit for everyone and the 40/60 division a reasonable target. To actively use politics as a tool for creating equality and equity is part of the Swedish system, and the Nordic education model is based on a balance between social, economical, and educational aims (Imsen, Blossing & Moos 2016). On a historical note, Sweden had the first female professor in mathematics in the world: Sonya Kovalevsky was employed at Stockholm University by Gösta Mittag-Leffler in 1883. However, it took 114 years since the next one was employed and this was not through the care of the mathematics departments (Sumpter, 2015). It was a political iniative, the so called Tham professors, where three women professors in mathematics were hired. Ultimately, the initiative was considered discriminative and was protested, including a notification to the EU- court (Lundberg n.d.).

The pace at which 40/60 division is achieved depends on the willingness of departments to act and depends on the conceptions of both staff and potential students, along with other social factors. In many institutions and areas of society, where there is segregation along gender, race or other lines, there are social feedback effects (Gronvetter 1978). For example, the rate at which participation in an institution increases depends positively on the current level of participation (Spaiser et al. 2018) and, conversely, a lack of participation can either reduce or slow the growth of further participation.

Explanations for differences in participation based on gender are typically found in social phenomena linked to culture and its structural effects (Halpern et al. 2007; Husu 2005, 2013). In a smiliar manner, Lindberg et al. (2011) differ between the discrimination hypothesis, where women are discriminated actively or passively, and the lag hypothesis, where there is an assumption that women participation is an aftermath of history and the situation will change once formal regulations are in place. First, we examine some cultural explanations. Looking at the factors behind women not getting STEM-related research posts, the main two ones are discrimination, including hostility, and a lack of institutional support, the latter one particularly at times of employment uncertainty (Heilbronner 2013; Husu 2005, 2013; Piatek-Jimenez 2015; Sumpter 2014). It has been concluded, based on data from The Netherlands, that initiatives do increase women representations in academic positions, but it is still insufficient to close the gender balance (Bakker & Jacobs 2016). Similar conlcusions were drawn in a meta-analysis of academic writing, where the prediction is that gender gap is likely to persist in several subjects including mathematics if no active measures are made to try to close the gap (Holman, Stuart-Fox & Hauser 2018). Gender biases exist in the ways that applicants' CVs are ranked (Moss-Racusin et al. 2012), in how grading of research applications are made (Wennerås & Wold 1997), and how recommendations focus on different things (Trix & Pesenka 2003). When they get jobs, women find it difficult to get their ideas heard (Xu 2008). Women then operate in a working environment where actions and the symbols attributed to men and women are very different. As an example, the two symbols 'the hard working female' (e.g. Hermione Granger) and 'the male genius' (e.g. Sherlock Holmes) are often used as an explanation model for success and it is thought of one of the main reason for gender imbalance at university levels (Leslie, Cimpian, Meyer & Freeland 2015). Those women who commence PhD studies do not tend to give a positive view of their working environment (Herzig 2004; Piatek-Jimenz 2015) with descriptions of late scheduling of seminars conflicting with nursery pick up and being described as waste of research funding since women end up next to the stove anyway (Sumpter 2014). As a constrasting example, computer science in most western countries is a male subject whereas in Malaysia the proportions is 50-50 male-female (Mellström 2009). In interviews of female computer scientists in Malaysia, they express that they experience the subject neutral and having the same opportunities as men.

Now turning our focus to structural explanations, which could be compared to explanations connected to the organisational level (Lindberg et al. 2011), there are several models that contribute to the understanding of how different the terms of participation are for women and for men. One is the process of homosociality (Lipman-Bluman, 1976) where PhD candidates might be chosen because they are similar to their supervisors, implying that the number of women in a department is an important factor when determining future participation. This is particularly germane since women in male-dominated professions rarely experience the 'glass escalator' offered men in female-dominated professions (Budig 2002; Hultin 2003).

Even before a meeting has been taken place, implicit stereotyping can be part of decisions leading to homo-sociality: in a recent Swedish study looking at if there was a difference between gender regarding which applicant recruiters decided to call for an interview, male recruiters were found to call male applicants to a higher degree (Erlandsson 2019). This included professions where there exists a gender balance, a 40-60 % ratio, where one could assume should be more gender neutral. Women are often seen not to fit in as the 'ideal' worker (Budig 2002). From an individual perspective, this could be expressed as a sense of not belonging (Solomon 2007). Gender division of labour is, therefore, less a question of glass ceilings (c.f. Morrison, Randall & van Velsor 1987) but more about gendered institutions including relations of power and symbolism (Connell 2006). This is a conclusion that is supported by a study using multivariate analyses on data from 44 countries where structural features of educational system and labour market are identified as main reasons for sex segregation (Bradley & Charles 2009). It is therefore of interest to study such structural features.

Aim and Research question

With this a backdrop, we study participation in PhD studies over a period of time using a mathematical model of growth in participation. Here, we are interested if growth rate can help to further understand whether low participation is due to the discrimination hypothesis or the lag hypothesis. If the difference is only related to lag hypothesis, subjects with similar starting levels should follow similar growth rate. If, however, there are big differences in growth rates it could be seen as a sign of the discrimination hypothesis; that some subjects are more gendered instiutions than others. We pose the following research questions, with a particular focus on mathematics: (1) In what ways have the proportion female PhD students in different subject areas followed the same or different growth curves between 1973 and 2010?; (2) Given the growth rates up to 2010 does how well did female participation follow the same growth curve in later years up to 2017, i.e. did participation increase faster or slower than was predicted by the model; and, (3) In what way are these results more consistent with the discrimination hypothesis or the lag hypothesis?

Data

The data for the present study comes from data the Swedish Higher Education Authority database (www.uka.se) and Statstics Sweden (www.scb.se), and it shows the proportion of female PhD students in eleven different subject areas. Since the data are presented according to the national division of subjects, mathematics at this level of division means mathematical sciences and it is not just restricted to pure mathematics but also includes subject such as applied mathematics and mathematics education. The data had the number of recorded PhD students ordered in research subject (according to national division of subjects), sex (female/male), and percentages of activity (full-time/part-time/ null activity). Students recorded with null activity were removed from the data set. The training data (which we used to fit the model) is comprised of figures from the second half of the calendar year from 1973 to 2010, with subjects denoted with capital letters to indicate data category (see Figure 1):

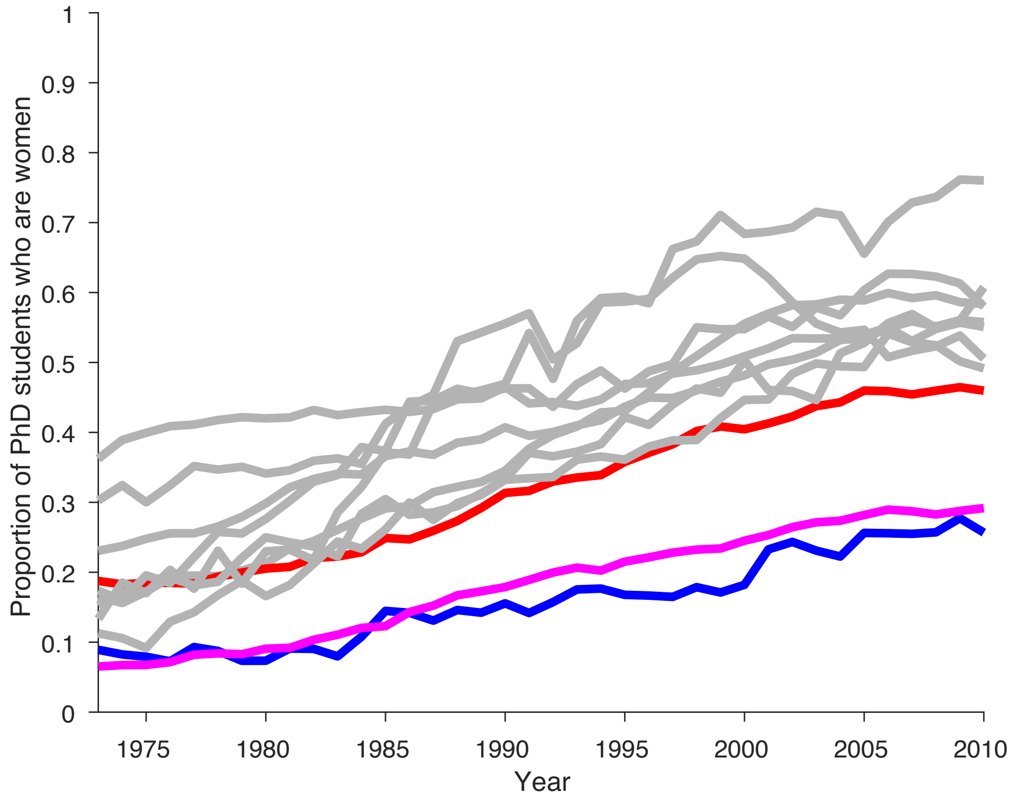

Fig. 1.: Change in the proportion of female PhD students between 1973-2010 grouped by subject area. The grey shaded lines are for Veterinary Medicine, Law, Dentistry, Medicine, Humanities, Social Science and Forest and Agricultural Studies. Natural Sciences (red line), Engineering and Technology (purple line) and Mathematics (blue line) are shown separately.

As Figure 1 shows, nine of these had, by 2010, reached at least 40% female participation. Agricultural studies saw a rapid increase in female participation, from initially low levels in the 1970s. Natural sciences also saw increases, but from slightly higher initial levels. The growth rates of mathematics and engineering and technology are smaller than the other subjects.

The test data from 2011 to 2017 was then used see how well the model explained future changes, i.e. as test data for the model. In 2011, the division of subject areas in Sweden changed. Mathematical and computational sciences became a subset of natural sciences. We thus separated these sub-categories from the main data set in order to recreate a comparable set of measurements to those seen in the 1973-2010 data. In our analysis we have removed all Computer Science students, which has 23.5% female PhD students in 2017. After 2010, Computer Science students were classified as part of the Natural Sciences, while earlier classifications had them spread between Mathematics, the Natural Sciences and Engineering and Technology. By leaving them out of the 2017 analysis we remove a potential bias created by their inclusion in Natural Sciences.

Model

The logistic growth equation provides a parsimonious model of this form of social feedback within institutions described in the background section above (Young 2009). The model assumes that during the initial stages of participative growth, when participation is low, increases are proportional to the current level of participation. The implication here is that the proporition of women working in an area increases faster when more women are already working in the subject, relating to the discussion homosociality above. We thus model the proportion of females p recorded as PhD students in an area as changing according to differential equation

$$\frac{dp}{dt} = rp(1-2p) \qquad (1)$$

The parameter r is then the strength of positive feedback between the current proportion of women and future participation. The smaller the value of r the weaker the feedback between current participation and growth, and the more resistant the institution is to change. Our logistic growth model further assumes that female participation levels will not exceed 50% and are limited by this value. While female participation does (in some cases) exceed this level, the focus of our paper is on the early to middle stages of growth, so the model suffices for our purposes. Figure 1 shows that in most cases, with the most obvious exception being veterinary medicine, female participation in PhDs stabilises between 40 and 60%.

To fit equation (1) and estimate parameters *a* and *r* we first transformed the data so we could perform linear regression (e.g. Rossman, Chiu & Mol 2008),

$$\ln\left(\frac{2p(t)}{1+2p(t)}\right) = -a + rt \qquad (2)$$

For subject areas with a greater than 50% female gender balance we omit all data values where $p(t) \geq ½$ since these lie outwith the range of interest for the current study. We estimated the parameters *a* and *r* along with standard error for each value using the linear regression equation. Note that $a = \ln\left(1/p(0) - 2\right)$ sets the initial proportion in 1973 (t=0), and *r* is the positive feedback determining the rate of increase of female PhD students. The data up to 2010 was used to fit our model parameters (i.e. as a training set), thus giving us both a historical measure of how women in mathematics increased over time. The hypothesis we aimed to test was whether the growth of female participation in Mathematics, Natural Sciences and Engineering and Technology followed the logistic curve seen up to 2010. Did female participation increase in these disciplines, albeit at a slower rate, in a way seen in other academic disciplines?

To compare the predicted and obtained levels we created 95% confidence intervals for the parameter $p(0)$ and *r* for each subject individually. We then solved the logistic equation numerically for both the lower and upper confidence intervals. If the actual measurement in 2017 lay outside the confidence interval then we could reject our model as a realistic description of the growth of female participation between 2010 and 2017.

Results

Table 1 gives the parameter values for the logistic growth model when it is fit to the data:

Subject area	Initial proportion female (range): *p*(0)	Growth rate: *r*±(std. error	R-squared, adjusted
Pharmacology	[0.199, 0.321]	0.230±0.022	0.7412
Humanities	[0.189, 0.273]	0.188±0.015	0.8028
Mathematics	[0.063, 0.069]	0.054±0.002	0.9320
Medicine	[0.026, 0.055]	0.266±0.018	0.8553
Natural Sciences	[0.119,0.132]	0.094±0.003	0.9667
Dentistry	[0.065, 0.101]	0.253±0.012	0.9236
Law	[0.031, 0.068]	0.219±0.019	0.7768
Social Sciences	[0.059, 0.108]	0.217±0.016	0.8314
Forest and Agricultural Studies	[0.027, 0.052]	0.206±0.016	0.8102
Engineering and Technology	[0.061, 0.065]	0.067±0.002	0.9739
Veterinary Medicine	[0.056, 0.115]	0.276±0.019	0.8448

Table 1.: Parameter estimates from fitting logistic growth (equation 1) to data. The range for *p*(0) is then determined by $\frac{1}{2+\exp(-a \pm s_a)}$ where s_a is the estimated standard error of *a*. The range of *r* is the estimated value plus/minus its estimated standard error. R-squared is for the fit of logistic model to each data set.

As we can see in Table 1, for eight of the eleven subjects, the growth rates *r* are between 0.186 and 0.276. Three subjects have a lower growth rate: Mathematics, Natural Sciences and Engineering and Technology. If we instead look at the subjects with the highest growth rate, Pharmacology, Medicine, Dentistry, and Vetrinary Medicine have a *r*-value of 0.230 or above. This would mean it takes five years to double the amount of women in an subject.

Following on from this table of parameters, we picked four subjects with four different patterns and anlysed these further, see Figure 2:

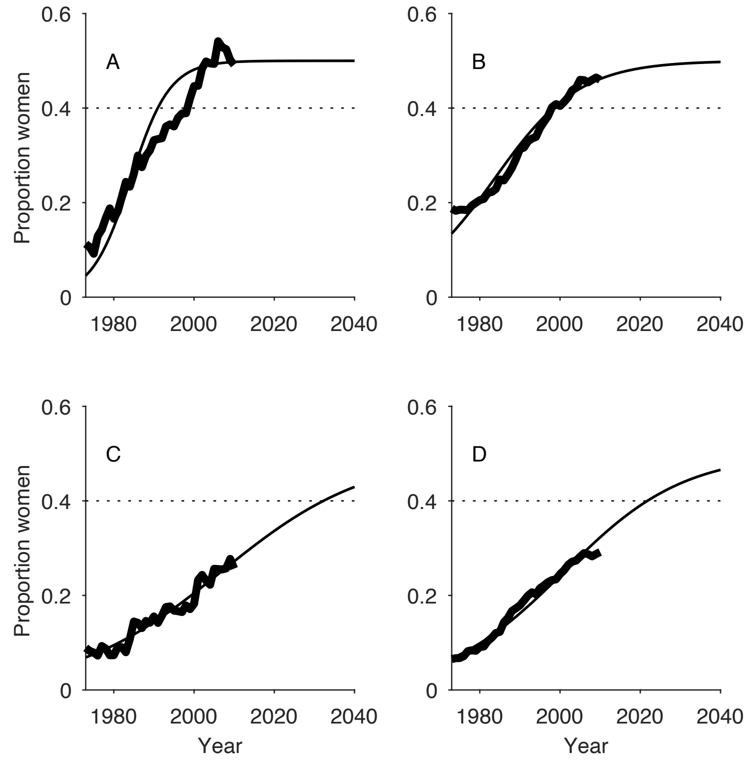

Fig. 2.: Change of proportion of PhD students between 1973-2010 for four subjects: **A** Forest and Agricultural Sciences; **B** Natural Sciences; **C** Mathematics; and **D** Engineering and Technology. Thicker line is data from Figure 1. Narrower line is fit of logistic growth model. For parameter estimates see table 1. Dotted line is threshold of 40% women.

Figure 2a shows the growth for agricultural studies, comparing data with model fit. A growth rate of r=0.2, for example, implies that, during the initial stages of participation, the proportion of females doubles every five years. In other words, since a typical Swedish PhD takes five years, then by the time one student has completed her studies she will have 'contributed' two new students to the subject area. This is a rapid positive feedback, and has led to substantial changes in the gender composition of these seven areas. Feedback in the natural sciences (Figure 2b; r=0.094) has been slower, but since natural sciences already had nearly 20% female participation in 1973, it has reached now parity.

The growth rates are very different in both Mathematics (Figure 2c; r=0.054) and Engineering and Technology (Figure 2d; r=0.068). The contrast between feedback rates in these areas and the other nine shows that failures to increase the proportion of female participation is not simply due to the low initial levels, which are accounted for in the model. The main difference between Mathematics, Engineering and Technology, and other subjects is that the feedback between current participation and future growth is much weaker than in the other subject areas. From this perspective in 2010, if mathematics departments continued in the same way, it would appear to take a further 20-25 years before they pass the 40% level.

To test whether the growth in female participation in Mathematics, Natural Sciences and Engineering and Technology continued to follow the logistic curve seen up to 2010, we looked at the levels in 2017. These are shown, in comparison with the growth curve, for the three research areas in Figure 3.

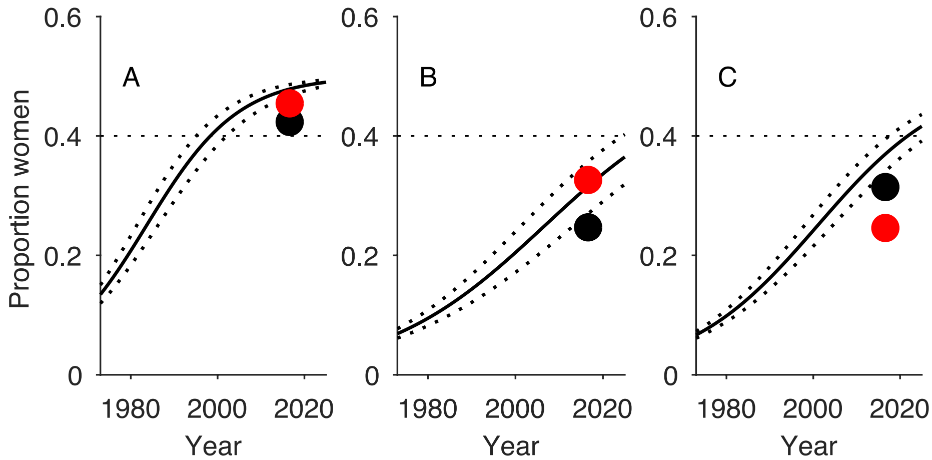

Figure 3: Growth predicted of female participation in (A) Natural Sciences (B) Mathematics and (C) Engineering and Technology by the logistic model (solid line ± confidence intervals as dotted lines). These are compared to the actual proportion of female PhD students registered in 2017 (black dot) and the proportion admitted for PhD studies in 2017 (red dot).

In all three cases the model significantly underestimates the actual proportion of females working in the area (black dots). For Natural Sciences the proportion remains similar (at 42%) to the level in 2010. The continued growth experienced in other academic disciplines, whereby they eventually fluctuate around 50%, did not occur in Science and, at present, an equilibrium appear to be closer to around 40%, which is the Swedish governments target.

The proportion of female PhD students in Mathematics is 31% in 2017, compared to 26% in 2010. This is an increase, but falls short of the predictions made by the logistic growth model. It appears that growth of female participation in PhD studies in mathematics has slowed and it will take longer to reach the 40% threshold than the 20-25 years predicted by the model. Engineering and Technology has also shown an slight increase in female participation, but also falls significantly short of projections based on the data up to 2010.

Of the newly recruited PhD students in Natural Sciences in 2017, 45% were female (red dot in Figure 3). Intake in 2017 to PhD studies in Mathematics also showed an upturn, to a level consistent with the model. In Engineering and Technology intake in 2017 was low. It is important to note that fluctuations in intakes are bigger than in the number studying at any one time, and thus less importance should be assigned to these results. For now, the conclusion is that, in the absence of a major event, there is a very low probability that Mathematics or Engineering and Technology will have 40% female PhD students within the next 10 years, or even within the next 20 years.

Discussion

With regard to our first research questions we found that all STEM subjects experienced slower growth rates in participation (even accounting for differences in intial levels) than non-STEM subjects up to 2010. Non-STEM subjects experienced doubling of participation over 5 years, the time taken for a students to obtain a PhD from start to finish. Mathematics and Engineering and Technology grew slowest, with a doubling in participation of around 20 years, while Natural Sciences had a doubling of near to 10 years. Our analysis provides macro-level quantitative support to a large body of micro-level qualitative literature on gender structures in university mathematics departments, where women leave for reasons of hostility, sometimes subtle, and lack of support (e.g. Husu, 2005; Sumpter 2014).

With respect to our second research question, we found that, since 2010, none of the STEM subjects were experiencing the level of growth predicted by the model. Natural Sciences had levelled off at 40% female participation, maths and engineering had both grown at a level lower than predicted by the model. This casts a high degree of uncertainty as to when the Swedish governments 40% target will be reached for these subjects. A reasonable estimate would be at least another 15 or 20 years. This is in line with research from other countries (e.g. Holman, Stuart-Fox & Hauser, 2018), and it supports conclusions that active actions are needed (Bakker & Jacobs 2016). Hence, legislation is not enough in order to create balanced groups (e.g. Kanter 1977), despite a growing body of research in different areas showing that women participation in groups strengthen collective intelligence and provide stable enivronments (Inglehart et al. 2002; Woolley et al. 2010). Just as Bradley and Charles (2009), we conclude that there is room for improvement, however instead on focusing on individual preferences, we would like to target institutional norms.

Thirdly, the results are more consistent with the discrimination hypothesis than the lag hypothesis (Lindberg et al. 2011). Here, the comparison of growth rates in the different subjects shows that the mathematics departments have not been as successful in attracting and retaining women, this despite decades of equity legislation and equal opportunity promotions. Focusing on the main difference between Mathematics, Engineering and Technology, and other subjects, the weak feedback between current participation and future growth could be seen as an indication of gendered institutions (Connell 2006), including both cultural and structural elements. Looking at cultural aspects, previous research has concluded that the two main ones are discrimination and a lack of institutional support (Heilbronner 2013; Husu 2005, 2013), supporting the discrimination hypothesis. The latter one is particular important when employment are uncertain and when women report that they find it difficult to get their ideas heard (Sumpter 2014; Xu 2008). It appears that willingness from the departments is an determining factor much more so than the lag hypothesis, something that needs to be further investigated. We therefore suggest this as a topic for further research, this including motivation to increase the diversity of graduate students and students' motivation to continue studying mathematics.

When men are around two times more likely to be invited to submit papers (Holman, Stuart-Fox & Hauser 2018) and with an explicit measured stereotyping effect ranking of CV and grant applications (Moss-Racusin et al. 2012; Wennerås & Wold, 1997), working for gender equality means that one need to be aware of that goes beyond making sure of equal representation regarding plenary speakers and editorial boards, or when seminars are scheduled. One implication is that if other countries look to Sweden as a gender equity role model, the results of this study show that although much can be learnt from that country's successes with respect to extended nursery care and parental leave, much can also be learnt from its failures with respect to overcoming its gendered institutions.

Compliance with Ethical Standards

Disclosure of potential conflicts of interest: No funding to declare. No conflict of interest to declare.

Research involving Human Participants and/or Animals: Data received from open data source, SCB: https://www.scb.se/en/.

Informed consent: Ethics approval, consent of participation, and consent of participation were part of SCB, Statistics Sweden.

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