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Japan's R&D capabilities have been decimated by reduced class hours for science and math subjects

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The number of published scientific papers and patent applications are indicators of a country's research and development (R&D) capabilities. Since the 2010s, these indicators have declined in Japan. One important reason for this decline is the change in science and mathematics education provided in schools. Education in school can greatly impact the quality of future researchers in science. To examine the impact of the number of class hours in science and mathematics that researchers received in school over the past 50 years, this study analysed data from two surveys conducted in 2016 and 2020. The results show that there is a decline in the number of patents for the younger generation that cannot be explained by age differences, and it is highly correlated with a decline in the total number of hours of science and math in junior high school. Educational policies influence student attitudes towards learning. Changes should be implemented only after validating their effects from a long-term perspective because education policies may have unintended negative impacts on a country's economic growth.

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Introduction

In Japan, class hours and learning content in elementary and junior high schools are basically determined by the curriculum guidelines established by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Therefore, except for a few private schools, all schools devote the same number of class hours to each subject[1]. The purpose of this paper is to show that under an educational system in which class hours and learning content are determined by the government, changes in class hours for science and mathematics subjects can lead to changes in students' academic performance and subsequent R&D capabilities.

Japan's economic growth is often attributed to its superior research and development (R&D) capabilities. However, there has been a decline in Japan's R&D strength relative to that of other countries (Ministry of Education, Culture, Sports, Science and Technology (MECSST), 2013). Japan's decline in R&D capabilities has been accompanied by stagnation in research output (MECSST, 2019). Compared with the total number of scientific papers published in 2006–2008, Japanese researchers published fewer papers in 2016–2018. Of the top 10 countries in terms of the number of papers published annually, Japan is the only country that experienced a decline (National Institute of Science and Technology Policy (NISTEP), 2020a). This downward trend is particularly noticeable when only the number of highly cited papers is counted (adjusted top 10% papers) (NISTEP, 2020a).

Trends in R&D capabilities can be assessed from the perspective of the number of patent applications. On the basis of data published by the World Intellectual Property Organization (WIPO), the number of patent applications by Japanese researchers decreased by 10% between 2005 and 2018 (530,000 vs. 460,000; WIPO, 2020). This declining trend is linked to the decrease in the number of papers published and is another indicator of the decline in Japan's R&D capabilities.

The background to this stagnation in R&D might be a reduction in R&D spending. However, looking at R&D expenditure by sector, corporate R&D expenditure declined by approximately 12% in 2009 due to the 2008 financial crisis, but the long-term trend since 1992 has been a steady increase of 1.6% per year on average (see Fig. 1). University research expenditure also increased at an average annual rate of 1.4% throughout this period. Other public institutions showed a downward trend of −0.2% per year on average, but because the corporate and university sectors account for more than 90% of Japan's total R&D expenditure, Japan's overall R&D expenditure has been on a long-term upward trend. It can, thus, be concluded that the stagnation of research results, including patents, was not caused by a decline in R&D expenditure.

The cause of the decline may be related to changes in R&D human resources. First of all, we can see that the number of R&D personnel has been increasing, although this has slowed down somewhat in recent years (see Fig. 2). However, the number of university students enroled in science and engineering (i.e., potential R&D personnel) peaked in the late 1990s and has been declining, and in recent years it has been approximately 15% lower than its peak level. This trend in the number of students enroled in science and engineering fields at universities and colleges preceded the trend in R&D indicators such as patents. The number of students enroled in master's and doctoral programmes has been stagnant or declining since around 2005.

A report by NISTEP (2010) pointed out that the number and quality of R&D personnel in key fields declined during the decade of the 2000s, especially among young researchers. It also cites the following factors as contributing to this decline: the decrease in the number of new researchers entering the field, the retirement of researchers belonging to the baby-boomer generation, the reduction in the number of faculty members at national universities, the narrowing of research themes in companies due to the recession and the relative decline in the number and quality of Japan's R&D human resources as Asian countries catch up.

This decrease in the number and quality of R&D personnel is also due, in part, to a marked shift away from the sciences, as demonstrated by the fact that the percentage of high-school students taking Advanced Physics II has long been in the 10% range (Science Council of Japan, 2016). The shift away from science among students and pupils may be explained, in part, by the impact of the reduction in the number of hours dedicated to science and mathematics subjects due to changes made to the curriculum guidelines by the government. In other words, in examining the stagnation of R&D human resources and R&D capabilities, it is important to examine the impact of the government's education policies over the past 40 years.

Previous studies have reported a positive relationship between the proportion of GDP allocated to education and R&D capabilities (Furman et al., 2002; Akhmat et al., 2014). Additionally,

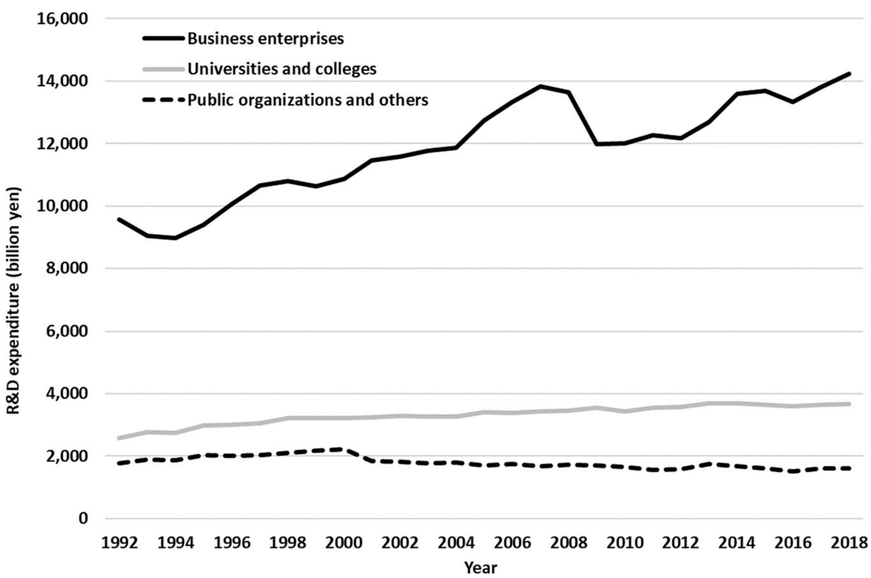

Fig. 1 Trends in R&D expenditure by sector. R&D expenditure is a nominal value. Source: NISTEP (2020b).

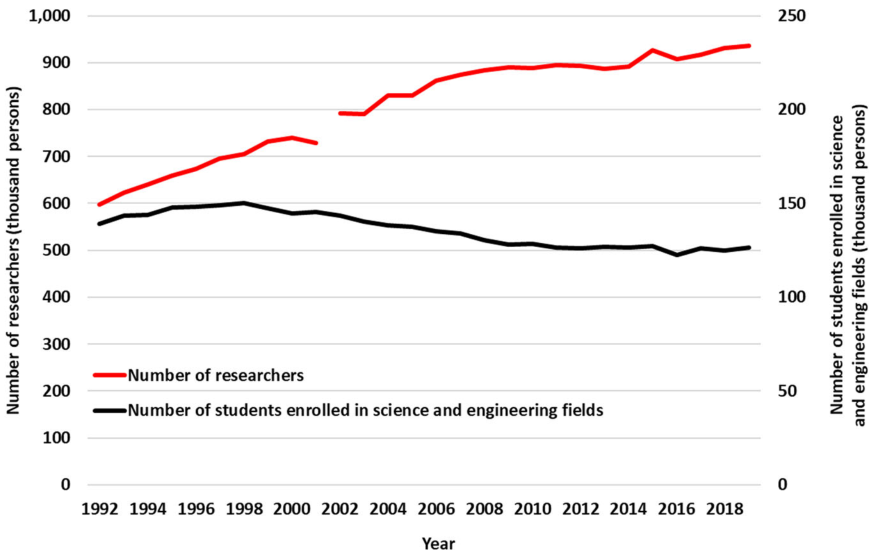

Fig. 2 Trends in R&D personnel. Regarding the number of researchers, the timing of the statistical survey differs between surveys conducted before 2001 (as of April 1) and those conducted after 2002 (as of March 31). Therefore, the graphs are not connected due to the continuity problem. Source: NISTEP (2020b).

positive relationships between researchers' productivity and human capital-related indices such as the literacy rate and the number of students enroled in junior high or high schools have been reported (De Rassenfosse and van Pottelsberghe, 2009). Such reports indicate that education is highly effective for developing high-quality researchers and improving a country's R&D capabilities. Studies have also reported a relationship between the educational background of R&D personnel and patent indicators. For example, in Europe, R&D personnel who hold a doctoral degree produce more patent applications compared with those without one to a statistically significant degree. Furthermore, possessing a doctoral degree has a positive effect on patent quality (Mariani and Romanelli, 2007; Schettino et al., 2013). However, the decline in Japan's R&D capabilities cannot be explained by such causes; hence, the impacts of education policy changes, which were not fully considered in the aforementioned European studies, should also be assessed. Considering that changes in education policy will affect students' learning behaviour, which will eventually be reflected in the quality of R&D human resources, this perspective is worthy of study.

Changes in science and mathematics education in junior high schools

In Japan, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) stipulates the curriculum guidelines for content to be learned and the number of class hours for each subject in schools from the first year of elementary school through to the third year of high school. Each time the curriculum guidelines are revised, the textbooks and numbers of class hours for relevant subjects are also revised. In this system, few schools act independently of the curriculum guidelines in terms of adopting different numbers of class hours or teaching content. This study focuses on the five versions of the curriculum guidelines published from the 1960s to the 2000s based on the age groups of the respondents. To clarify the effects of each version of the curriculum guidelines, we divided the time into five periods (1962–1971, 1972–1980, 1981–1992, 1993–2001 and 2002–2011). We grouped people by the year in which they attended the first year of junior high school. The groups can be roughly organised into 10-year age groups: 60 s (61 or older), 50 s (52–60), 40 s (40–51), 30 s (31–39) and 20 s (30 or younger). The total class hours of science and mathematics peaked in 1981. For the five periods, there were 805, 840, 735, 700 and 605 h, respectively (National Institute for Educational Policy Research (NIEPR), 2020; Nishimura et al., 2021). This decline in class hours for science and mathematics corresponds to the reduced content in these subject areas in textbooks used in school.

According to Hino (2016), who examined the changes in and characteristics of science education at the elementary and secondary levels in Japan, the two curriculum guidelines for 1962–71 and 1972–80 developed elementary and secondary curricula that were strongly influenced by American science education. In the 1970s, in particular, the curriculum was richest in terms of both quality and quantity. Furthermore, these curriculum guidelines were issued during the period of Japan's rapid economic growth, and policies were taken to foster R&D human resources that did actually produce a large number of R&D personnel. Indeed, science and mathematics education includes not only the acquisition of scientific knowledge but also the understanding of its role in society. It would be reasonable to suppose that when R&D personnel acquire a social perspective on science, the direction of R&D will be aligned with the needs of society and the development of a scientific and technological society will be advanced. Such a viewpoint is discussed in Godin and Gingras (2000).

The previous curriculum guidelines, however, have been criticised for including an extremely large amount of subject content in line with the increasing sophistication of science and technology, placing a heavy learning burden on students. When the Ministry of Education, Culture, Sports, Science and Technology (MEXT) decided on the curriculum guidelines for 1981–92, it decided to reduce the subject content at all primary and secondary levels under the 'relaxed' education policy. This policy was continued when the curriculum guidelines were decided for 1993–2001 and 2002–2011, and the reduction of subject content continued.

The number of subject content items for science education in elementary and junior high schools was 228 in the 1970s, when it was at its most extensive. In the 1980s, 1990s and 2000s, the number of items decreased to 124 (54%), 79 (35%) and 56 (25%), respectively.

The main topics that have been deleted or reduced from the junior high-school curriculum since the 1980s include Newton's second law of motion; reactions of ions; shapes and distances of celestial bodies; distribution and transitions of plants and animals; chemical reactions and heat; brightness and colours of fixed stars; action of forces; motion, differences in aqueous solutions depending on solutes; content related to the development of information means; and making weather maps.

As a result, the academic performance of Japanese junior high-school students in science has declined significantly.

Mediating factors between class hours and R&D capability

This study examines the relationship between the amount of time spent teaching science and mathematics subjects in junior high school and the ability to conduct R&D at the level of individual R&D personnel in an educational system where the government determines the amount of time spent teaching and the content of learning.

Related to this point, Baker et al. (2004), drawing on data from international achievement surveys such as TIMSS and PISA, examined the relationship between instructional time in science and mathematics in secondary education and achievement in these subjects in approximately 30 countries that participated in the surveys. In the study, Japan showed a positive relationship between instructional time and performance in both TIMSS and PISA data in both science and mathematics (instructional time and class hours are basically the same thing). Our interest is in whether these changes in education at the secondary level will affect R&D capacity in the long run.

We believe that there are several pathways between the class hours for science and mathematics subjects in junior high school and the R&D capabilities of R&D personnel.

First, fewer class hours have led to teaching less content, which has affected R&D capabilities. In Japan, the revision of teaching guidelines since the 1980s has not only reduced class hours but also the content taught in class (Hino, 2016). Therefore, class hours in junior high school can be viewed as an indicator of the quality of educational content as well as its quantity. In addition to the aforementioned study by Baker et al. (2004), previous studies include the results of Hanushek and Kimko (2000), Hanushek and Woessmann (2008), and Breton (2011), which show that high achievement in science and mathematics subjects contributes to economic development. Taken together, the results of these studies suggest that changes in class hours will affect economic development through achievement in science and mathematics subjects. Naturally, R&D capacity is also affected in the process. Thus, previous studies support our hypothesis that the decrease in the number of class hours for science and mathematics subjects due to the changes in Japan's curriculum guidelines since the 1980s has lowered students' academic achievement and R&D capacity.

Second, having fewer hours of science learning influences students' attitudes towards science. The number of class hours in junior high school is positively related to the level of strength in science and mathematics subjects in high school (Nishimura et al., 2017). In addition, the data that we used in this study asked students whether they liked science during their college years, and there was a weak but positive correlation between this and the amount of time spent in science classes in junior high school ($r = 0.037$, $P = 0.089 < 0.1$). Thus, the decrease in class hours for science and mathematics in junior high school may have affected students' attitudes towards science and mathematics subjects through a decrease in their level of skill and loss of interest.

Third, having fewer hours of science classes in junior high school has led to a reduction in the percentage of students who choose to study physics in high school. In Japanese elementary and junior high schools, students have long been required to study science, which consists of the fields of physics, chemistry, biology and geology. The number of class hours for these subjects has been decreasing. In addition, in high school, students do not have to study all four disciplines but are required to choose two of them to take. In our data, there is a positive correlation ($r = 0.209$, $p = 0.000$) between the number of hours of science classes in junior high school and the choice of physics in high school, and the decrease in the number of class hours in junior high school has led to a reduction in the number of students choosing to study physics.

Fourth, having fewer hours of science classes in junior high schools has degraded the ability of prospective teachers to teach science. In fact, since the 1980s, when the number of hours of science and mathematics classes was reduced, the number of high school students who wanted to study science and engineering at universities has decreased (Science and Technology Agency, 1994). As a result, the quality of teachers who teach science and mathematics subjects has been declining, which has led in turn to a decline in the quality of their teaching and ability to evaluate students.

As described above, the decrease in class time in junior high school in Japan since the 1980s can be considered to have led to a decline in R&D capabilities through various pathways.

Methods

This study used data obtained from an online anonymous survey, 'Questionnaire Survey on Work and Education and Training of Technical and Research Workers', conducted by the Research Institute of Economy, Trade and Industry (RIETI) in March 2020, which outsourced this survey to the research firm Rakuten Insight in March 2020 (hereinafter, the '2020 Survey'). The participants were people working in engineering or research jobs, or "R&D personnel", in March 2020. To participate in the survey, the respondents completed registration with a survey monitor in advance. All participants agreed to the survey's privacy policy before answering the questionnaire.

Figure 2 also used data obtained from another survey, which was conducted online in March 2016 and used the same questionnaire as the 2020 Survey (hereinafter, the '2016 Survey'). The 2016 Survey was titled 'Questionnaire Survey on the Attitudes of Technical and Research Workers.' It was outsourced to NTTCom Online Marketing Solutions. The number of valid responses for the 2016 Survey was 4129.

Sample. In the 2020 Survey, the participants were screened by the first question, which asked whether they were technical or research workers. The screening continued until 5000 valid responses had been collected. Among the valid respondents, 92.9% were male and 7.1% were female. The respondents' average age was 48.5 years. The youngest was 23 and the oldest was 69. The average working years was 26.2, with a minimum value of 0 and a maximum value of 51 years reported. In terms of educational history, 73.3% of respondents had graduated from university or graduate school and 2.2% had a doctoral degree. Most of the respondents were working at private companies, with only 4.9% employed at universities or research institutes. The current main area of responsibility for research and technology workers is basic and applied research (6.7%), with development and other areas accounting for more than 90%.

Dependent variables. First, we discuss the distribution of the R&D personnel who responded to the survey in terms of the R&D output-related index. Of the survey participants, 3668 R&D

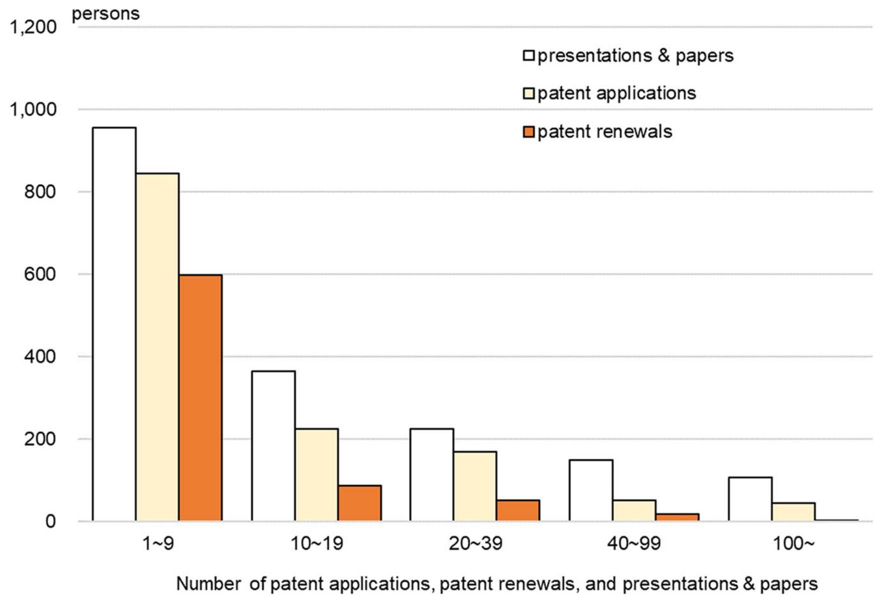

Fig. 3 Distribution of respondents for R&D output-related indices. Number of patent applications and renewals represents the total number of patent applications and renewals made throughout the respondent's career in R&D. Number of presentations & papers represents the total number of presentations that a respondent has given at academic conferences and papers published in academic journals.

personnel (73.4%) had not filed any patent applications and 4248 respondents (85.0%) had not applied for a patent renewal. Moreover, 3203 R&D personnel (64.1%) had not given any invention-related presentations or published papers. Figure 3 shows the respondents who had produced one or more outputs ($n = 1332$ for patent applications, 752 for patent renewals and 1797 for presentations or papers). In all indices, the 1–9 range has the largest number of respondents. The increase in output (patent applications, renewals and presentations/papers) for the respondents follows a power-law distribution with a long right tail.

These three indices were all impacted by the number of class hours of science and mathematics in junior high school. The analysis treats the number of patent applications as a dependent variable. In this paper, our discussion is limited first to patents and papers as outputs, and then to variables related to learning that are significantly related to these outputs as inputs. Indeed, the inputs and outputs that represent the scientific and technological society are not only hours of teaching science and mathematics subjects and patents. Godin and Gingras (2000) discuss how to define scientific culture and present a multi-dimensional model of it, providing several indicators that are useful in evaluating the level of scientific culture. In their paper, they use class hours in high school as an input, but in this paper, we use class hours in junior high school as an input. This is because physics, chemistry, biology and geology are elective subjects in Japanese high schools, but are required in junior high schools.

The data in this study showed that the amount of time and content of science and mathematics classes taught in junior high school affected the percentage of students who chose to study physics in high school, and the status of physics and advanced calculus in high school affected the acquisition of specialised knowledge in college. This, in turn, affects the ability to do research and development after graduation. Therefore, we believe that the number of hours dedicated to science and mathematics, which are required for all students, in junior high school is representative of the many variables involved in R&D capability.

To understand the relationship between the number of patent applications and the number of class hours of science and mathematics in junior high school, this section examines the responses to the study mentioned in the previous section. Notably, the number of patent applications is adjusted because R&D personnel with more working experience generally produce a larger number of patent applications. Thus, we divided the number of patent applications for each respondent by the total number of working years to control for the effect of the length of working years.

Procedure. Statistical software (STATA MP Ver. 13, STATA-Corp, TX, USA, and SPSS Statistics 26, IBM, IL, USA) was used to process the raw data for analysis. STATA is an analysis package developed for cross-sectional data analysis that is used by many researchers in the field of economics, whereas SPSS is the statistical analysis package with the largest number of users in the world, with many business users, as well as academics as customers. This study used the following R&D output indices as dependent variables: the number of patent applications, the number of patent renewals and the number of presentations and papers. The respondents were asked to indicate the numbers of patent applications, patent renewals and presentations/papers produced throughout their entire career as R&D personnel. The distribution of these three indices follows the power law, with the highest number of responses of 0 (Fig. 3). As these values represent the total numbers for each output item produced throughout the career of each R&D worker, it is natural that R&D workers with more work experience should report a higher output. To eliminate the effect of working years, the number of each output per working year was used as a dependent variable. This was obtained by dividing the total number of outputs produced throughout a career by the total number of working years after their completion of education (Table 1). Among the 5000 responses, four respondents reported '0' as their number of working years. Consequently, they were excluded in the analysis of the output per working year, and the number of observed values was 4996. In this study, the analysis of the number of patent applications per working year ($n = 4996$) provided an average value of 0.1255, a standard deviation of 0.4619, a minimum value of 0 and a maximum value of 10.0.

Next, for the class hours of science and mathematics in junior high school, this study used the following three indices: the

Table 1 Analysis results: number of patent applications per working year.

	Model 1			Model 2			Model 2		
Variable	Coef.	Std. err	*P*-value	Coef.	Std. err	*P*-value	Coef.	Std. err	*P*-value
Female dummy	−0.2169	0.094	0.021	−0.2869	0.094	0.002	−0.2230	0.094	0.018
Univ dummy	0.3802	0.054	0.000	0.3826	0.054	0.000	0.3829	0.054	0.000
Master dummy	0.7626	0.063	0.000	0.7157	0.063	0.000	0.7539	0.063	0.000
Ph.D dummy	1.0297	0.113	0.000	0.9643	0.113	0.000	1.0134	0.113	0.000
Class hours in junior high school:									
Science	0.0046	0.001	0.000						
Mathematics				0.0047	0.001	0.000			
Total							0.0029	0.000	0.000
(constant)	−1.8959	0.196	0.000	−2.0380	0.361	0.000	−2.3766	0.268	0.000
$1/\sigma$	0.8800	0.018	0.000	0.8863	0.018	0.000	0.8821	0.018	0.000
N	4996			4996			4996		
χ-square	1758.7			1691.1			1739.8		
Pseudo R^2	0.2467			0.2372			0.2441		

Dependent variable: Patent applications per working year.
This table shows the results of the analysis for the three models. These models are divided by independent variables for the number of class hours in science and mathematics in junior high school (grey part). Model 1: Science, Model 2: Mathematics, Model 3: total class hours of science and mathematics. The reference group in terms of education history is a group of individuals whose final education is a high-school diploma, junior college degree or technical college degree. As control variables, in addition to those shown here (female and education history-related ones), we used the type of business, the research/technical area in which the respondent was engaged immediately after joining the company and the company size.

number of class hours of science, the number of class hours of mathematics and the combined total number of class hours of science and mathematics. The numbers for class hours were stipulated by the curriculum guidelines, which are set by MEXT. We obtained the class hours data using the curriculum guidelines database provided by the National Institute for Educational Policy Research (Nishimura et al., 2021). Approximately every 10 years, the curriculum guidelines are revised, and the number of class hours per subject changes. Thus, we identified the version of the curriculum guidelines corresponding to the period during which each respondent attended junior high school using the respondent's age and summed up the class hours of science and mathematics for each version. The age range represents the current age of the respondents who studied in junior high school under each of the versions of the curriculum guidelines. The numbers for science, mathematics and total class hours for each age group were as follows: 420, 385 and 805 for age groups of 61 or older; 420, 420 and 840 for the 52–60 age group; 350, 385 and 735 for the age group 40–51; 315, 385 and 700 for the age group 31–39; and 290, 315 and 605 for the age group of 30 or younger. Notably, the version of the curriculum guidelines used from 1993 to 2001 (age group 31–39) allowed junior high schools flexibility in determining the number of class hours of science. The number of hours ranged from 315 to 350 h (NIEPR, 2020). Here, the number of class hours for science was assumed to be 315 because all the students studied science for at least 315 class hours under this version of the curriculum guidelines.

Statistical analysis. As shown in Fig. 3, a Type I Tobit model with zero as the lower bound was used as the estimation method because the dependent variables follow a power-law distribution. This study used STATA for the analysis. For each model of the hours dedicated to science, mathematics and the total of these two subjects, a likelihood-ratio chi-square test was performed. All the models were valid at the 1% significance level.

As control variables for attributes, this study used a female dummy variable to control for sex, as well as a university graduation dummy, master's degree dummy and doctoral degree dummy, with reference groups of high school, junior college and technical college graduates. We used other control variables, including the type of business, the research/technical area in which the respondents were engaged immediately after entering the company and the company size. As they are not directly relevant to the discussion of this study, we omit the inclusion of those results.

Results

The dependent variable follows a power-law distribution, and therefore the Type I Tobit model with zero as the lower bound was used as the estimation method. Table 1 shows the analysis results using the number of patent applications per working year as a dependent variable ($N = 4996$ in all models of Table 1). First, there are statistically significant positive correlations between the number of patent applications and the class hours in science and mathematics (Model 1: Coef. = 0.0046, Std. err. = 0.0005, $P < 0.01$, 95% CI = [0.0037; 0.0055], Model 2: Coef. = 0.0047, Std. err. = 0.0009, $P < 0.01$, 95 % CI = [0.0030; 0.0065]). Furthermore, the total class hours in science and mathematics also have a statistically significant positive correlation with the number of patent applications (Model 3: Coef. = 0.0029, Std. err. = 0.0003, $P < 0.01$, 95% CI = [0.0022). 0.0035]). The number of class hours for science and mathematics in junior high school has a positive effect on the number of patent applications, that is, the output of R&D activity. In other words, the decrease in class hours in science and mathematics in recent years has contributed to the decrease in the number of patent applications.

For the effects of other attributes, a statistically significant negative correlation was observed between the number of patent applications and the female dummy variable. This shows that female R&D personnel have fewer R&D outputs compared with their male R&D counterparts. The effect of educational background is that as the educational background increases, the number of patent applications increases compared with high-school graduates. This shows the effect of human capital investment in educational institutions.

Discussion

In addition to data from the survey conducted in 2020, we used data from a survey carried out in March 2016. The two surveys have the same contents (Nishimura et al., 2017). First, we analysed the trends in the number of patent applications by age (3-year moving average) from 2016 to 2020 using the data from the two surveys, where orange and blue represent data from 2016 and 2020, respectively (see Fig. 4). It is certain that as age increases,

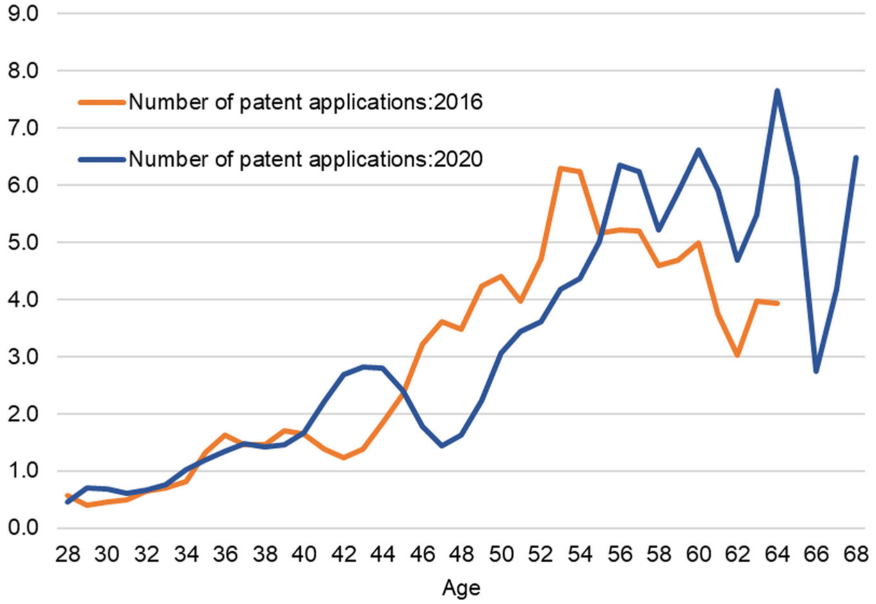

Fig. 4 Trends in the number of patent applications by age: 2016 and 2020 survey data. The graph plots the average values of the number of patent applications by age (3-year moving average, which is the average of data for 3 years: the preceding year, the represented year and the following year).

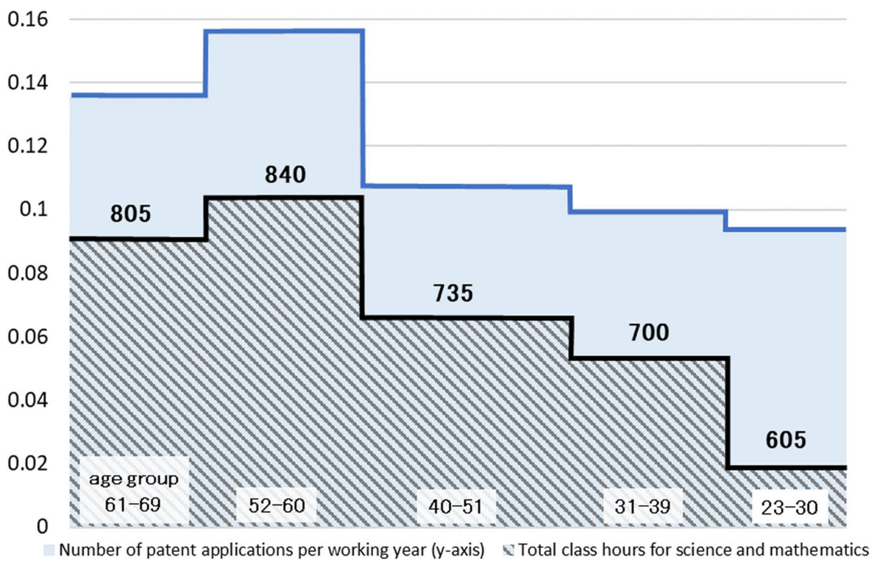

Fig. 5 Total number of class hours of science and mathematics and the number of patent applications. The number of patent applications per working year is the average number per year of employment, averaged for each age group. The total class hours for science and mathematics is the total number of hours of science and mathematics for the 3 years of junior high school. The trend in class hours (shaded) is overlaid over the trend in the number of patent applications (light blue). The height of each graph is not the stacked value. The horizontal axis shows the respondents' age. To clarify the relationship between the number of class hours and the number of patent applications, the respondents are grouped by the edition of the curriculum guidelines under which they studied in their first year of junior high school.

know-how accumulates and R&D productivity increases. However, by comparing the graphs for 2016 and 2020, this paper will reveal that there are factors other than increasing age that affect productivity.

Both graphs show an upward trend due to the combined effects of age and differences in characteristics between generations. If the upward trend were only due to the age effect, the graphs should overlap. However, the 2020 graph has shifted slightly to the right. When looking at the 2016 Survey data, although some fluctuation occurs in the 20 s and 30 s, an upward trend appears in the number of patent applications with age, especially from age 43 to the early 50 s. In contrast, when looking at the 2020 Survey data, some peaks occur in the latter half of the 30 s, but there is a rapid increase around age 47, which is sustained until the middle of the 50 s. The two surveys have a 4-year gap between them, and the starting points of the rapid increase also have a 4-year gap. These graphs have a nearly identical shape, allowing them to overlap when one is moved by 4 years.

If the graph of the 2016 patent applications is shifted to the right by 4 years, the calculated correlation coefficient between the 2016 graph and the 2020 graph is 0.923, indicating a strong positive correlation. As they have nearly identical shapes, there is an overlap but with a 4-year gap. This indicates that there is a certain effect that is stronger than the age effect. A similar trend is observed in the graph for the number of patent renewals. Moving the 2016 graph to the right by 4 years causes it to overlap with the 2020 graph and has a correlation coefficient of 0.895.

Next, we consider the distributions of the number of patent applications and the total number of class hours of science and mathematics in junior high school by age group. There is a positive correlation between these two variables at the 1% significance level (Table 1). Figure 5 shows the number of patent applications as average values, which are obtained by averaging the number of patent applications per working year within each age group. The number of class hours and the number of patent applications are higher in the 52–60 age group compared with the 61–69 age group. In the 40–51 age group and younger, fewer class hours meant a smaller number of patent applications. We can confirm that the direction of movement between the two variables is completely consistent. Thus, the decline in the number of class hours of science and mathematics beginning in 1981 is one cause of the recent stagnation of Japan's R&D capabilities.

Conclusion

The results of this study show that the reduction of science and mathematics subjects in junior high school led to a reduction in the research output of R&D personnel. In Japan, the stagnation of R&D since the 1990s has contributed to the slowdown of economic growth. The stagnation of R&D has occurred in both the public and private sectors, with low growth in human capital as well as R&D expenditures (Ziesemer, 2020). In light of these relationships, science and mathematics education greatly impacts the long-term R&D capabilities of a country. Consequently, education fundamentally affects economic growth, and curriculum guidelines must be revised only after verifying their effects sufficiently from a long-term perspective.

Finally, it is ironic that the university reforms since 2004, mainly at national universities, have reduced the R&D capacity of universities (Kikuchi, 2021). The accumulation of human capital as students progress from primary and secondary education to higher education generates research results for universities and other research institutions, in turn spilling over to R&D in the private sector (Fukugawa, 2017). Hence, university reforms without improving primary or secondary education may not lead to improvements in R&D capacity. To improve Japan's R&D capacity, it is essential to examine the effect of human capital accumulation, including during primary and secondary education as well as higher education.

Data availability

The datasets generated and/or analysed during the study are not publicly available due to legal reasons but are available from the corresponding author on reasonable request.

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Note

1 Incidentally, the percentage of students attending private junior high schools was 3% in the 1980s and 10% recently. It is only in some private junior high schools that class hours are set differently from the government guidelines. The content of textbooks is set by the government, and all schools, whether private or public, use textbooks that have been approved by the government, so it is safe to assume that all schools teach the same content.

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Author contributions
KN and TY conceived of the study, and DM and KN wrote the manuscript. DM and TY analysed the data. KN, TY, and DM collected the data. All authors discussed the results and contributed towards improving the final manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
Not applicable. This article used data obtained from anonymous surveys.

Informed consent
Not applicable.

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