Aging and Scientific Performance: An Empirical Study on Korean University Researchers

Sungchul Chung[*]

Abstract

This study aims to contribute to the debate over the age-productivity relationships in scientific and technological research. For this purpose, we conducted an empirical experiment employing a time-series cross-section dataset derived from the KRI of the NRF containing data on individual researchers of fifty major universities in Korea covering the period of 2008–2013. This study has found that: (1) there exists an inverse U-shaped age-productivity relationship at the level of individual researchers; (2) the impact of the average age of a research group on the productivity of individual researchers varies across fields; (3) male and female researchers move along different age-productivity curves; and (4) the inverse U-shaped age-productivity relationship also holds at the level of organizations. The results suggest that the aging of researchers in Korea will soon reach the stage where serious losses in research productivity become a reality. Yet, it is not so clear whether the observed decline in the performance of older researchers is due to declining cognitive capability, which is an unavoidable result of aging, or to declining motivation, which results from an institutional system that discourages older researchers' research activities (such as reduced access to research opportunities or mandatory retirement). What is clear is that it is inevitable for the Korean science system to change the current seniority- and age-based organizational system into one of higher adaptability.

Keywords
Aging, researcher, age-productivity relationship

---

[*] Professor, the University of Science and Technology, Daejeon, Korea, scchung51@gmail.com

1. INTRODUCTION

The Korean population is aging at an extraordinary rapidity; it records a birth rate of 1.23, which is the lowest in the world (Statistics Korea, 2012). Statistics Korea (2012) projects that Korea will enter an “aged society” in the year 2020 when the population aged over 65 is projected to account for more than 15% of the total. Given these trends, it will not take long for the ripples of aging to hit the science and technology system of Korea. According to the National Research Foundation (NRF), the average age of university professors in science and technology in the country reached 48.4 in 2013.This recalls the situation in Japan ten years ago when the average age of the research staff at their national universities was 45.8 (average age of full professors 54.9) in 2001 (OECD, 2003). Aging has long been a serious issue in science and research policy not only in Japan but also in some of the OECD countries. The OECD reports that

> the science systems in OECD countries are being challenged by a number of developments: Research institutions face additional challenges in relation to human resources such as . . .an aging research population in some fields; a weakened capacity of the public sector to expand employment or to provide permanent employment . . . (OECD 2003, p. 3)

In Japan’s case, the problem of aging was reinforced by the mass retirement of the baby boom generation (*dankainosedai*, or those born between 1947–49), who accounted for 7% of the population (“Baby boom sets Japan '2007 problem',” 2006). Korea’s problem looks very similar to that of Japan in that it will enter an aged society at the time when its baby boomers (born between 1955–63) are expected to leave the labor market. Consequently, the aging of population presents two issues to the science and technology system of Korea: one is the possible loss in productivity due to the aging of the research workforce, and the other is related to the replacement of the baby boomer scientists and engineers who will retire *en masse* within five years from now.

Of the two issues, this study focuses on the question of how the aging of researchers would affect their performances. There have been diverse studies to investigate the relationship between age and research productivity; although there is no consensus on the age-productivity relationship, many have found that a kind of quadratic relationship exists between age and productivity. They suggest that in the early stages of a research career, aging is a process of learning and developing research capacity, and therefore at this stage, age is positively related to productivity. However, this relationship ends when productivity peaks, and thereafter further aging is accompanied by declining productivity (Cole, 1979; Tuner & Mairesse, 2003; Weiss & Lillard, 1982; Zuckerman & Merton, 1972). A similar relationship has also been found in studies on Korea (Chang, Kang, & Han, 2013; Chang, Yang, & Choi, 2009; Kim, Choi, Song, Ahn, Baek, & Kim, 2012). It appears that the overall age-research productivity relationship at the individual level takes the shape of an inverse U. But the impact of age at the level of research organizations is less clear. An institute is organized with researchers of diverse ages and experiences who play diverse roles. Experienced scientists, for example, may make up for the decline of productivity by conducting activities that require ample experience, such as mentoring junior researchers, so that productivity at the level of the institution is not compromised. Furthermore, scientists with long and diverse experience may be more capable of directing and coordinating research teams and laboratories. Simply put, little is known about how the age structure of researchers of an organization affects the organization's productivity.

This paper aims to contribute to this debate by examining how age affects the research productivity of professors at Korean universities at both the individual and organizational levels. This study analyzes the age structure of the research workforce of Korean universities, and estimates the effect of age on the productivity of individual researchers as well as research groups or organizations. The data used for this analysis were taken from the Korean Researcher Information (KRI) of the NRF. This paper begins with an analysis ofthe age structure of researchers (professors) at Korean universities, and then discusses the issues related to the relationship between age and research productivity. An empirical analysis of the relationships at both the individual and organizational levels follows the discussions. The paper also attempts to derive policy implications from the analysis.

2. AGING OF RESEARCHERS IN KOREA: RECENT TRENDS

2.1. Data

We analyzed the age structure of the research workforce of Korean universities using the KRI of the NRF of Korea. The KRI covers six years from 2008, when it was first formally established, to 2013, which is the most recent year in terms of data availability. The KRI contains a comprehensive set of information on individual researchers who were and/or are funded by the NRF. For the purpose of this study, we created a cross-sectional time-series dataset out of the KRI that contains personal information as well as academic outputs of researchers (professors) in the fields of science and technology at research-oriented universities (Table 1). In this study, research-oriented university is defined as a university that belongs to the top fifty universities in terms of NRF research awards. Researchers in the dataset do not include temporary hires, such as part-time lecturers, adjunct professors, or visiting scholars, because they are not continuously involved in research and their turnover rate is too high to be included in the panel data. For the definitions and measurements of the variables, see the Appendix.

TABLE 1. Description of the Dataset

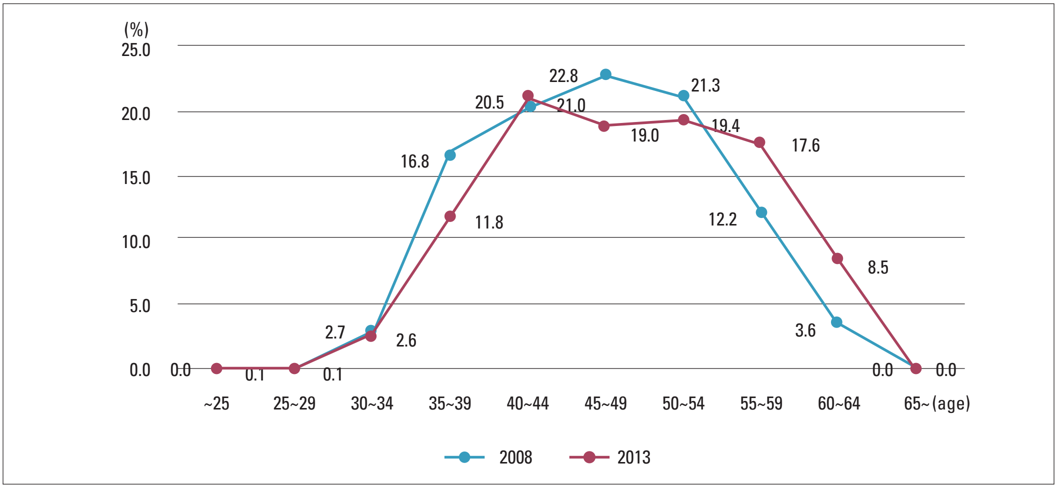
Year	# of professors (observations)	Age			Fund*			Performance+		
		H	L	A	H	L	A	H	L	A
2008	18,509	71	27	46.7	40,450	0	144	17.9	0	1.27
2009	19,666	69	26	47.1	20,863	0	142	30.1	0	1.26
2010	20,234	82	26	47.5	18,804	0	157	40.4	0	1.27
2011	20,868	71	27	47.9	22,738	0	167	61.9	0	1.29
2012	21,551	70	25	48.2	14,231	0	168	39.0	0	1.30
2013	21,846	64	26	48.4	25,417	0	164	25.4	0	1.28
Total	122,674	82	25	47.7	40,450	0		61.9	0	

** Million won; + publication points (for the measurement of the point, see the appendix); H: highest; L: lowest; A: average*

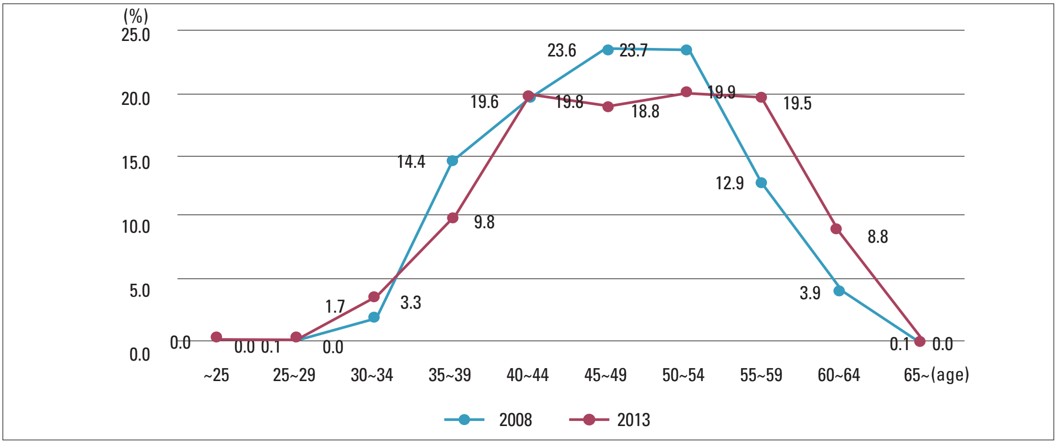
2.2. Aging of Researchers

The dataset shows that significant changes have taken place in the age structure of science and engineering professors at the major universities in Korea during the period of 2008–2013. The average age of professors increased almost two years from 46.7 to 48.4 during the six-year period. As shown in <Figure 1>, the proportion of researchers in the 35–39 age group declined from overall 16.8% in 2008 to 11.8% in 2013, while the proportion of those in the 55–59 age group increased from 12.2% to 17.6% during the same period. The age profile of university professors in science and technology, which had a nearly symmetrical bell shape in 2008, flattened and skewed toward the right. Similar changes in age profile have been observed in each of the fields—science, engineering, and agriculture/marine/animal science, with the exception of medicine/pharmaceuticals (Figure 1–5). To be accurate, the changes are more pronounced in the fields of science and engineering and it is particularly so in the case of agriculture/marine/animal science, which have benefited relatively less from recent developments in science and technology. In contrast, the change is less visible in the case of medicine/pharmaceuticals, which has benefited the most from the recent expansions of research opportunities in biological and medical sciences. Based on the figures, we can predict that by the year 2023, 26.1% of the currently active professors would have retired. The proportion of retirees will be even greater in the case of science (28.3%), engineering (30.3%), and agriculture/marine/animal science (35.3%). This means that massive recruitment has to start now to fill the vacuum that will be created by the massive retirement that is expected to happen soon. Indeed, this presents a tremendous challenge to the Korean science and technology system.

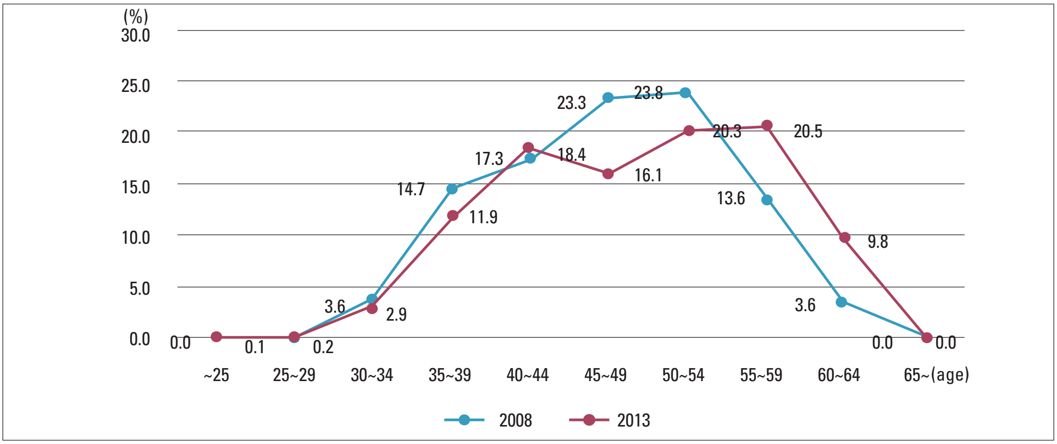
FIGUTE 1. Changes in the Age Structure of Researchers 2001-2013: All Fields



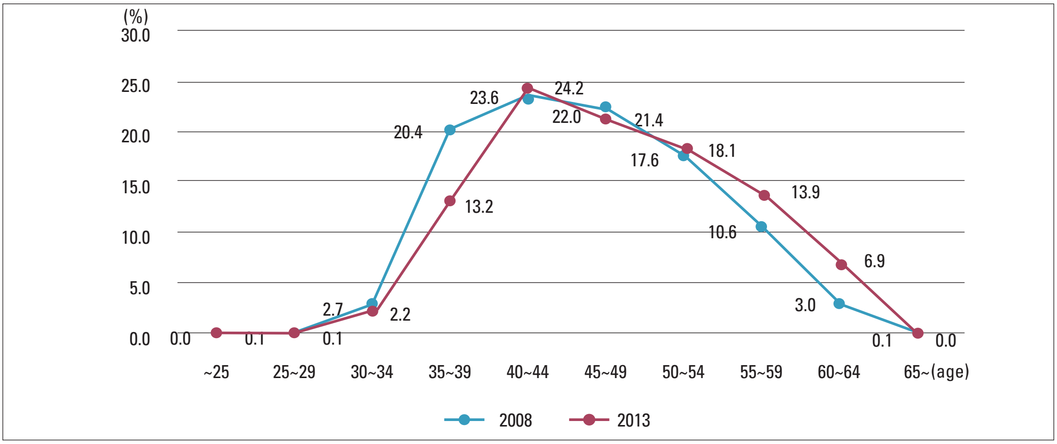
FIGUTE 2. Changes in the Age Structure of Researchers 2008-2013: Sciences



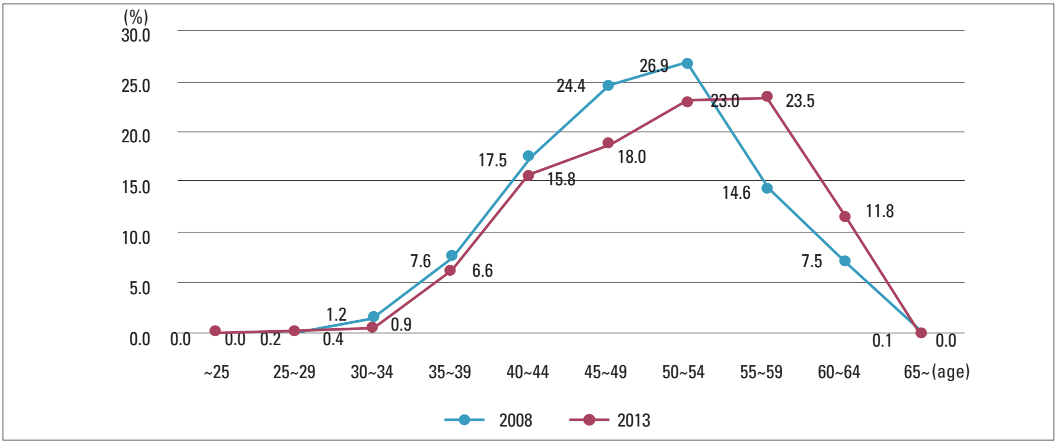
FIGUTE 3. Changes in the Age Structure of Researchers 2008-2013: Engineering



FIGUTE 4. Changes in the Age Structure of Researchers 2008-13: Medicine/Pharmaceuticals



FIGUTE 5. Changes in the Age Structure in Agriculture/Marine/Animal Science



Another way of assessing the degree of aging is to compare the number of older researchers (55years or older) with that of younger ones (less than 40) for each of the fields. Here, we define the aging index = [(number of older researchers)/(number of younger researchers)], which can be used to evaluate the degree of aging of researchers in different fields of science and technology. Therefore, the larger the index, the higher is the ratio of older researchers to younger. Assuming an inverse U-shaped age profile of researchers, an aging index greater than one indicates that more researchers are on the declining segment of the age profile than on the rising portion of the curve. If the conventional view of negative age-productivity relationship is right, an increasing aging index means declining productivity, which can be interpreted as a call for policy action.

The index calculated for the research manpower of Korean universities confirms that aging has become a problem in the Korean science and technology system. Overall, the aging index increased from 0.86 in 2008 to 1.8 in 2013, indicating that older researchers increased almost twice as much as younger ones during the period. Assuming a bell-shaped age-productivity relationship, it means twice more researchers are now clustered along the declining segment of the curve than along the rising portion of the curve, which may result in a serious blow to the Korean science and technology system. We can observe more notable changes if we look into individual fields. In science, the aging index increased from 1.04 to 2.16 during the period, and in engineering, the index more than doubled, while in agriculture/marine/animal science, the index changed from 2.46 to an alarming number of 4.47 during the period. Medicine/pharmaceuticals turned out to be the youngest field, and agriculture/marine/animal science the most aged (Table 2). These are tremendous changes that rarely happen in a demographically stable society. They may stem from two sources: one is the impact of the aging population and the other the relative reduction of new entrants compared to the massive recruitment during the 1980s and early 1990s, when Korean universities were expanding rapidly.

TABLE 2. Changes in Aging Index

Field	Aging index 2008	Aging index 2013
Whole areas	0.81	1.80
Sciences	1.04	2.16
Engineering	0.93	2.02
Medicine/pharmaceuticals	0.59	1.35
Agriculture/marine/animal science	2.46	4.47

2.3. Why is Aging a Problem in Korea?

The university research workforce in Korea has been rapidly aging over the past decade, particularly in some of the traditional fields such as agriculture/marine/animal science. This is largely due to a decline in recruitment that started around the mid-1990s as an aftermath of the rapid expansion of universities in the 1980s and 1990s. In order to maintain the current research workforce of the universities, another large-scale recruitment will be required within five to ten years from now. But a large-scale recruitment of professors will not be as easy as it was in the past because of a smaller pipeline of supply of scientists and engineers that the rapid aging of the population may cause. Unlike in traditional fields, however, aging has been relatively slower in the emerging, popular fields, such as life sciences, medicine, pharmaceuticals. Medicine/pharmaceuticals, which account for 44% of the total research workforce, suffer less from aging as they have been receiving new entrants at a large scale every year.

The concern about the aging of research manpower is related to our society's perception of the productivity differences between age groups, which is based on negative views about the adaptability and productivity of the elderly. This perception persists strongly in Korean society where age is the key variable in determining who gets to remain when organizational reform or downsizing is unavoidable. In 1999 when the Asian financial crisis hit Korea, the government forced the R&D institutions under its control to reduce the research staff size by 20% and lower the mandatory retirement age of researchers from 65 to 61 (Ministry of Budget and Planning, 1999). Age was the key criterion in reforming public-sector organizations. This was based on the stereotypical views concerning the productivity of workers, that elders are less adaptable, less creative, and too cautious.

Furthermore, the fact that wages tend to rise with age is also used as grounds for arguing that it costs too much to employ older researchers when taking into account their productivity. The problem with this argument is that wages are easily verified, while it is difficult in practice to estimate the productivity of individual researchers. Even if we accept the argument for an inverse relationship between age and productivity, there is no well-defined method of explaining how age affects productivity or how productivity varies with age.

What adds to this in Korea is the social or cultural cost of older researchers. Nowhere in the world, perhaps, age matters more than it does in Korea, where the Confucian principle dictates social relationships. The Confucian system of relationships says that older people exist above younger people in the hierarchy, and that older people should care for younger people with benevolence, while younger people should respect and obey the orders of older people (Confucious, 1979). In such a cultural setting, organizational structure by and large takes on a pyramidal shape with a small number of seniors in the upper layer and a larger number of juniors in the lower positions. The harmony and stability of such organizations can be attained only when positional seniority coincides with age seniority, as too much deviation between the two may cause interpersonal conflict that leads to organizational instability. The problem is that it would be impossible for an aged Korea to maintain such an organizational structure with a bulging older population and shrunken younger workforce. This suggests that the effects of aging will not be limited to constraining the supply of researchers and possible losses in research productivity, but also will demand changes in the ways of organizing research, which will also affect productivity.

3. HOW AGE MATTERS IN RESEARCH: LITERATURE REVIEW

As discussed above, our concerns about the aging of researchers derive from the general perception that creativity and productivity decline with age. In fact, many significant breakthroughs in science and engineering have been made by scientists and engineers early in their careers when they were young. Newton was just twenty-three when he developed calculus and his theory of gravitation. Einstein reached his peak year (Annus Mirabilis) at the age of twenty-six when he made remarkable scientific contributions such as the special theory of relativity, Brownian motion, and the photoelectric effect. Heisenberg developed matrix mechanics and the uncertainty principle in his early twenties. This means that scientists and engineers, as they get aged, lose freshness of approach which is the very source of innovativeness (Becker 2008). Einstein said, “A person who has not yet made his great contribution to science before the age of thirty will never do so” (requoted from Brodetsky, 1942, p. 699). Paul Durac went even further by saying, “Age is, of course, a fever chill that every physicist must fear. He’s better dead than living still, when once he’s past his thirtieth year” (requoted from Zuckerman. 1977, p. 164).

The above seems to argue that research performance is very much influenced by age that mirrors such human characteristics as mental ability, physical ability, education, and experience. Mental and physical abilities peak in one’s twenties and early thirties, declining sharply afterwards, while accumulated research experience and learning help compensate for the unavoidable effects of age on productivity (Holden, 2008). In other words, significant scientific contributions, such as Nobel Prize-winning research, are generally made before forty (Lehman, 1953; Simonton, 1991; Zuckerman, 1977), while it has been found that researchers are in general most productive in the middle of their careers or older (Wray, 2004). Bernier, Gill and Hunt (1975) also found that research productivity in terms of publications and citations peaks in the early forties. Based on the analysis of a cross-section of American researchers from six different fields, Cole (1979) found that productivity increases gradually through one’s thirties and decreases almost in the same way over one’s fifties.

As such, best work is done between twenty-five and forty years of age, and researchers eventually reach the point (around the age of fifty) where productivity decreases in an irreversible way. Because of this perception, funding opportunities for old researchers are very often curtailed, and researchers are also forced to retire at a legally set age in many countries. But the age-productivity relationship should not be interpreted as interpersonal differences in productivity between researchers of different ages but as a pattern, with which the individual researcher's productivity changes with age. Also, it has to be noted that studies on the age-productivity relationship using cross-sectional data might have confounded the age effects with cohort effects (Stephan, 1996). If the latest educated are the best educated (Levin & Stephan, 1991), and thus better trained to conduct research, analyses based on cross section data may mistakenly attribute the cohort effects to age effects, overstating the negative age-productivity relationship.

Using a different logical framework, the lifecycle model explains the age-productivity relationship as a result of the individual researcher's decision on time investment in research rather than age itself. That is, researchers invest their time in research in the expectation of receiving a future income, and thus the level of investment will decline when scientists approach retirement (Levin & Stephan, 1991).

Despite the debate over the age-productivity relationship, age has traditionally been the criterion for judging productivity of researchers due to the general perception that it affects not only the cognitive abilities required to conduct top-level research but also motivation to invest time in research. But there is a need for more convincing empirical evidence, in order to make research and science policy decisions, concerning how individuals' productivity and creativity changes with age. Despite severe limitations in information, there have been many attempts to identify the factors affecting research productivity. Some of them found, contrary to expectations, that age was not negatively correlated with productivity or creativity (Cole 1979; Lehman, 1953; Zuckerman & Merton, 1972). These findings support Merton, who considered age as a determinant of relationships within the system of science; that is, scientists, as they get aged, climb up the ladder of hierarchy of the science community, which helps increase their productivity as well as impact and rewards (Merton, 1968). This suggests that the scientific community is a *gerontocracy*, where, as Wray (2003; 2004) found, middle-aged scientists excel in the number of significant discoveries.

As mentioned, one of the serious problems of the empirical analyses is the use of cross-section data. Cross-section analyses may fail to grasp the effect of cumulative advantage that researchers with better past performances enjoy. Since access to research resources is very much influenced by past research performance, researchers with more experiences may become more productive, not because of age but because of better access to resources. For example, Allison and Stewart (1974) used a cross-section of chemists, physicists, and mathematicians in the U.S. and found distributions of productivity among researchers that appear to support the argument for cumulative advantage. Under the current rewarding and funding system, in which past performances determine current and future opportunities, it is quite natural that highly productive researchers could continue to be more productive, while those with relatively poor past records are bound to lose in the game. In this case, inequality widens with career age, which may be misinterpreted as an age effect.

To correct the critical limitations of the works based on cross-sectional data, more recent studies employ longitudinal data. This enables better controls and a more reliable estimation of the relationship between age and productivity, especially the dynamics of productivity over the lifecycle. To identify age, cohort and period effects in scientific research productivity, Hall, Mairesse and Turner (2005) employ a panel data of French physicists. Unfortunately, however, the authors concede that "it appears impossible to estimate age-productivity effects without strong *a priori* assumptions on the model. (p. 20)"

Overall, the studies on age-research productivity relationship suggest the existence of a quadratic relationship between age of researchers and productivity. This relationship has also been found in Korea by several studies (Chang et al., 2013; Chang et al., 2009; Kim et al., 2012) using cross sectional data.

4. HOW AGE AFFECTS RESEARCH PRODUCTIVITY IN KOREA: AN EMPIRICAL INVESTIGATION

4.1. Age and Productivity at an Individual Level

It is very important to make a distinction between the factors that influence the research performance of organizations and those that affect individual research potential. The current productivity of an individual researcher is the result of the cumulative impact of diverse factors, such as physical and mental abilities, education, and experiences. Physical and cognitive abilities change or evolve with age. There is not much argument about the negative relationship between age and physical ability. But the relationship is not so evident in the case of cognitive ability. Horn and Cattell (1966) differentiate between crystalized abilities and fluid abilities. Crystalized abilities refer to the skills that are attained through education and experiences and thus stay relatively undiminished until late in life, while fluid abilities (or reasoning and speed) are known to decline from early adulthood. As scientific research relies on both crystalized and fluid abilities, we cannot define *a priori* age-productivity relationships. Productivity may be more likely to decline at older ages in the areas where speed and reasoning are more important. Even if some cognitive abilities decline with age, senior researchers may be able to maintain their productivity level based on their crystalized abilities. These imply that holding other things equal, individual research productivity is expected to rise with age in the early stage of the career, reach the peak around in the middle of the career, and then decline: a quadratic relationship.

Another issue that requires our attention is the effect of gender. Past studies used a dummy variable to capture the gender-related productivity difference, suggesting that the gender effect is invariant with any of the variables that affect productivity. But the gender-effect may vary with age, because of the social and cultural roles of women that also change with age. This will make it very difficult for women researchers to consistently manage a balance between work and life throughout their entire careers. For example, women's careers are, with rare exceptions, subject to interruptions by pregnancy or childrearing, which may create negative gender effects on productivity in their careers' early stages. But when this stage ends, women will find it easier to manage a balance between work and life. This suggests that the shapes of the age-productivity profile may differ between male and female researchers.

Individuals vary widely in creativity and cognitive ability that cannot be developed through education and experiences. Even though such personal traits are critical determinants of productivity, it is practically impossible to measure these particular personal characteristics. Another issue has something to do with the generational differences in education, experiences, and environment, or cohort effects that affect the productivity of individual researchers. It is not easy to accurately measure the cohort effects, but very often they use cohort dummies to distinguish the effects from those of age. An alternative way of solving the problem may be to use panel data in estimating the age-productivity relationship.

Another important set of variables that affect individual research productivity includes the factors that determine the environment in which individual researchers conduct research. There may be diverse environmental factors that affect the research productivity of individuals, such as the existence of mentors, quality of research colleagues, the age structure of the research group, and a research culture that is conducive to collaboration, research facility, or institutional settings. As such, there may be an endless list of factors that determine the environmental effects on productivity. In this study, we employ three variables for this purpose: research funds available to individual researchers, the average age of the research group, and the average performance of the research group (field), to which the individual researchers belong. The average age of the research group is to estimate the effect of age structure on the performance of individuals. The average performance of a group explains two things. First, it is the combined effects of the environmental factors, such as the quality of the researchers of the group, facilities, culture, and system. Second, it also explains the publishing behavior that varies across disciplines and research organizations. For example, it is well known that researchers in experimental chemistry publish more than those in theoretical physics.

Based on the above, we derive a model for the estimation of the age-productivity relationship at the level of individual researchers as follows:

$$P_{it} = f(A_{it}, A^{2}_{it}, F_{it}, \overline{A}_{it}, PG_{t}, P_{it-1}, G_{i})$$

Where the subscripts i and t denote individual i and year t, respectively, is the individual researcher's research productivity, A age of researcher, F research funds available to the researcher, $\overline{A}$ average age of the research group, PG average productivity of the research group, and G a dummy for gender (G=1 if male, G=0 otherwise).

4.2. Research Productivity at an Organizational Level

Another dimension of the aging issues that requires our attention is the impact of aging on research productivity at the organizational and/or national level. The aging of researchers unavoidably brings about changes in the age structure of the research workforce of an organization and/or a nation, which may then lead to changes in the productivity of the organization and/or the nation. The question is how these changes would affect the performance of the organization. Guest and Shacklock (2005) argue that the way of combining young and old affects the productiveness of the working environment. A heterogeneous workforce may be more productive as a group because young researchers bring in new ideas that can be combined with the knowledge and experiences of seniors to accomplish what new ideas or experience alone cannot achieve. However, age diversity may also create difficulties in communication and coordination (Hansen, Owan, & Pan, 2006).

There is no optimum age mix that maximizes the productivity of a research organization. Yet, it is important to combine older and younger researchers so that they complement each other. Many studies emphasize the positive aspect of age diversity (Barrington & Troske, 2001; Hansen et al., 2006; Garibaldi et al., 2010). As Breton, St-Amour, and Vencatachellum (2006) explains, two young inexperienced researchers cannot provide training to each other, and thus a young researcher who needs training will prefer to be teamed up with an experienced senior researcher. Or, if it is possible to enhance individual productivity by working with a senior researcher with a clearly good reputation, the young researcher will also prefer working with a senior researcher. In contrast, if the existence of a famed senior scientist in the group is likely to obscure the contributions of a young researcher, he would rather try to avoid working in the group. Therefore, the effect of age diversity on the productivity of a research organization is hard to determine.

But as the productivity of an organization is determined in large part by the productivity of individual researchers comprising the group, we can safely say that the aging of individual researchers would affect the organization's productivity in the same way as it does for individual productivity. Using the above framework, the following model is suggested for the estimation of the impact of aging of researchers on the average productivity of an organization:

$$PG_{jt} = f(\overline{A_{jt}}, \overline{A}^2_{jt}, FG_{jt}, AI_{jt}, PG_{jt-1}, PU_t, (\tfrac{M}{F})_{jt})$$

where the subscripts j and t denote jth group and year t, respectively, PG is the productivity of the organization (product per researcher), $\overline{A}$ the average age of researchers of the organization, FG the research funds per individual researcher in the group, AI the aging index of the group (researchers older than 55 or researchers younger than 40) which is for measuring the effect of the age-mix of researchers on productivity of the research group, the productivity of the group in the previous year, PU the productivity of the university to which the group belongs (a variable explaining some aspects of the environment in which the research group operates), and M/F the gender ratio (number of male/number of female researchers) of the researchers of the group.

4.3. Empirical Analysis

4.3.1. Age-productivity Relationship at an Individual Level

The data set taken from the KRI of the NRF was used in estimating the effects of age on the research productivity of individual researchers (professors) at fifty universities in Korea. Here, the productivity of an individual research is defined as the number of scientific papers that the researcher published in a given year. The method of counting publications is explained in the Appendix. Without question, the number of publications is far from being a perfect indicator of research productivity, as it ignores the quality aspect or scientific impact of the research output, which may be much more important in terms of the contribution to scientific advancement. Furthermore, research output includes not only such visible products as publication and patents, but also tacit knowledge that cannot be codified. This suggests that it is practically impossible to measure research productivity with a single metric. Because of the technical problems and the lack of data, this study analyzes and compares the productivities of individual researchers and research organizations using the number of publications.

It is also assumed that researchers in the same discipline within a university collaborate with each other in an organized manner towards the same objective of advancing knowledge. Therefore, the productivity of the research group in this analysis refers to the average performance of the researchers who belong in the same field of discipline (for the classification of disciplines, see the Appendix). To estimate the relationship, we used time series cross-section data, which was modified as follows: (1) we excluded the research groups with less than five researchers (professors) because the average values of too-small groups may distort the real picture; (2) the annual data for individual researchers were matched with those of the previous year in order to enable the generation of lagged variables. For example, observations from 2009 data were matched with those of 2008, discarding the observations in 2009 data that do not exist in the 2008 data. In the same manner, the 2010 data were rearranged to match the original 2009 data in order to save the observations discarded in the previous process. The same processes were repeated for the whole dataset.

The model for empirical analysis is as follows:

$$P_{it} = \alpha + \beta \ln (A_{it}) + \gamma (\ln(A_{it}))^2 + \delta G^* \ln(A_{it}) + \varepsilon G^* (\ln(A_{it}))^2 + \zeta \ln (F_{it})$$
$$+ \eta \ln(\overline{A}_t) + \theta \ln(PG_t) + \kappa \ln(P_{it\text{-}1}) + u_{it}$$

For estimation, we took the natural logarithm of all the independent variables except G, and conducted regression analyses employing the ordinary least squares method (OLS) method. The use of the OLS in analyzing cross-sectional time-series data creates statistical problems as it assumes that the estimates of intercept and coefficients of independent variables do not vary with time or individual, suggesting that the estimates may not be BLUE (best linear unbiased estimate). But the OLS was used because other methods to correct the statistical problems also require strong *a priori* assumptions (see Beck (2001) for the problems of using OLS and other methods in analyzing cross-sectional time-series data). Regression analysis has been done for all and each of the fields of science, engineering, medicine/pharmaceuticals, and agriculture/marine/animal science. The results are shown on the tables below (Tables 3-5).

4.3.1.1. Age Effects

The results show that age affects the productivity of individual researchers significantly. It has been found that the productivity of individual researchers increases with age in the early stages of one's career, and then declines after reaching the peak, showing the shape of an inverse U. The results concur with the findings of Bernier et al (1975), Cole (1979), Levin and Stephan (1991), Turner and Mairesse (2003) and Gonzalez-Brambila and Veloso (2007) that there exists a quadratic form of relationship between age and research productivity. Recent studies in Korea also present similar results (Chang et al. 2013; Kim et al. 2012). The same relationship has been confirmed in all fields of science and engineering, except the influence of gender over the way age affects productivity.

TABLE 3. Estimation of Age-individual Research Productivity Relationship: All fields and all fields excluding MP

Variable	All fields		All fields excl. MP+	
	Coefficient	t value	Coefficient	t value
$\ln(A_{it})$	14.614***	12.94	15.200***	9.49
$(\ln(A_{it}))^2$	-1.926**	-12.97	- 2.005***	-9.51
$G^* \ln(A_{ti})$	0.152**	2.19	0.212*	1.72
$G^*(\ln(A_{it}))^2$	-0.041***	-2.28	-0.055*	-1.73
$\ln(F_{it})$	0.019***	25.03	0.024***	16.22
$\ln(\overline{A}_t)$	-0.303***	-3.83	0.213**	2.00
$\ln(PG_t)$	0.649***	80.74	0.667***	68.38
$\ln(P_{it\text{-}1})$	0.468***	173.22	0.484***	138.50
Constant	-26.775***	-12.33	-30.011***	-9.76
Observations	89,625		50,637	
R^2Adjusted	0.366		0.395	

*+MP: Medicine/pharmaceuticals; ***, **, and *Significant at* α *= 1%, 5%, and 10%*

TABLE 4. Estimation of Age-individual Research Productivity Relationship: Science and Engineering

Variable	Sciences		Engineering	
	Coefficient	t value	Coefficient	t value
$\ln(A_{ti})$	14.347***	5.44	15.008***	6.77
$(\ln(A_{it}))^2$	-1.898***	-5.51	- 1.967***	-6.52
$G^* \ln(A_{ti})$	-0.306**	-2.04	0.551*	1.79
$G^*(\ln(A_{it}))^2$	0.079**	2.06	-0.143*	-1.75
$\ln(F_{it})$	0.020***	8.82	0.026***	12.72
$\ln(\overline{A}_t)$	-0.053	-0.29	0.283**	1.97
$\ln(PG_t)$	0.634***	37.68	0.677***	51.60
$\ln(P_{it\text{-}1})$	0.536***	94.95	0.456***	97.06
Constant	-27.296***	- 5.36	-30.108***	-7.21
Observations	17,250		29,411	
R^2Adjusted	0.443		0.319	

****, **, and *: Significant at 95%, 95%, and 90% confidence level*

TABLE 5. Estimation of Age-individual Research Productivity Relationship: MP+ and AMA++

Variables	MP		AMA	
	Coefficient	t value	Coefficient	t value
$\ln(A_{ti})$	10.962***	7.15	28.237***	4.75
$(\ln(A_{it}))^2$	-1.441***	- 7.14	- 3.696***	-4.66
G* $\ln(A_{ti})$	0.147*	1.86	0.130	0.28
G*$(\ln(A_{it}))^2$	-0.038*	-1.86	-0.043	-0.36
$\ln(F_{it})$	0.024***	27.00	0.031***	6.71
$\ln(\overline{A}_t)$	-0.574***	-4.08	0.741**	2.26
$\ln(PG_t)$	0.656***	33.00	0.775***	22.48
$\ln(P_{it-1})$	0.423***	96.44	0.432***	33.29
Constant	-18.826***	-6.37	-57.148***	-5.11
Observations	38,988		3,976	
R^2Adjusted	0.271		0.374	

**MP: Medicine/pharmaceuticals;*
++ Agriculture/marine/animal science;
****, **, and * Significant at* α *= 1%, 5%, and 10%*

The model specifies the effects of age on the productivity of individual researchers as:

$$(\beta+\delta G)\ln(A_{it}) + (\gamma+\varepsilon G)(\ln(A_{it}))^2$$

This says that gender affects productivity by changing the slope of the age-productivity curve. In all the fields except for science, the slope of the age-productivity curve for male researchers turned out to be steeper than that for female researchers on both the rising and falling segments of the curve (see Table 6 for the signs of the estimated coefficients of age and gender). It is only in science that female researchers' productivity responds more sensitively to age than that of their male counterparts. In other words, in science, female researchers' productivity grows faster with age in the early stage of their career (when they are young), and also declines faster than their male colleagues after hitting the peak. In all other fields, the opposite phenomena have been observed.

It is hard to explain why the impact of gender on age-productivity relationship differs between science and other fields. The only clue is that female researchers in science are on average older and more experienced, and perhaps more productive than their counterparts in other fields. For example, in science 37.03% of female researchers are aged 44 or less, while in engineering, almost 65% of female researchers are younger than 45. In science, the size of female workforce is also larger relative to other fields (except medicine/pharmaceuticals). In science and medicine/pharmaceuticals, female researchers account for around 20% of the research workforce, but the two fields differ in age structure: female researchers in science are much older on the average and more experienced than their counterparts in medicine/pharmaceuticals. In engineering and agriculture/marine/animal science, female researchers are still very small minorities, accounting for only about 4% and 7% respectively of the research workforce. They are also younger compared to their male colleagues. Therefore, science has older and more female researchers than any other fields. It is not clear if such a difference has anything to do with the difference in gender effect on the age-productivity relationship. But it seems clear that male and female researchers are moving along different age-productivity curves in their careers as researcher.

TABLE 6. The Signs of the Estimated Coefficients of Age and Gender

	β	δ	γ	ε
All fields	+	+	-	-
Science	+	-	-	+
Engineering	+	+	-	-
Medicine/pharmaceuticals	+	+	-	-
Agriculture/marine/animal science*	+	+	-	-

**Statistically insignificant*

4.3.1.2. Environmental and Other Factors

In all of the four fields, the environmental variables including research funds, average productivity, and average age of the researchers of the group to which the researcher belongs turned out to be important determinants of productivity. Of the greatest interest among these is the effect of the average age of the researchers in the group on the productivity of individuals, because it would enable us to understand how the aging of the research workforce would affect the productivity of individual researchers. Interestingly, in all the fields except agriculture/marine/animal science, the impact of average age turned out to be consistently negative. The opposite result for agriculture/marine/animal science seems to reflect the fact that the field remains comparatively stagnant, and has benefitted the least from recent advances in science and engineering. Finally, it was found, as expected, that the individual researcher's productivity is highly influenced by their past performances, which may be the result of personal ingenuity, cohort effects, period effect and/or other factors.

4.3.2. The Effect of Aging on Productivity at an Organizational Level

To estimate the impact of aging on productivity at an organizational level, the following model was used:

$$PG_{jt} = \lambda + \mu \ln (\overline{A}_{jt} + \nu (\ln(\overline{A}_{jt}))^2 + \xi \ln (FG_{jt}) + \pi \ln (AI_{jt}) + \rho \ln (PG_{jt\text{-}1}) + \sigma \ln(PU_{jt}) + \tau \ln(M/F)_{jt} + \omega_{jt}$$

For analytical purposes, we classified the research workforce of a university into thirty groups according to their fields of specialty, which are the units of this analysis. As discussed earlier, these groups are far from being organizations in a strict sense, but due to lack of information, it is assumed that researchers of the same disciplines within the same university collaborate in an organized manner for the common scientific and technological goals under the same academic and institutional environments. The results of the analysis are shown in <Tables 7-9>.

TABLE 7. Effect of Aging on Productivity at an Organizational Level: All Fields

Variable	All fields		All fields excluding MP	
	Coefficient	t value	Coefficient	t value
ln($\overline{A}_{jt}$)	19.088***	3.81	19.053***	3.26
(ln($\overline{A}_{jt}$))^2	-2.516***	-3.86	-2.510***	-3.29
ln(FG_{jt})	0.010**	2.28	0.014**	2.54
ln(AI_{jt})	0.0004	0.41	0.0003	0.28
ln(PG_{jt-1})	0.617***	56.19	0.626***	54.52
ln(PU_{jt})	0.509	24.16	0.511***	23.57
$(M/F)_{jt}$	0.0004*	1.72	0.0003	1.28
Constant	-36.440***	-.380	36.447***	-3.25
Observations	4,731		4,207	
R^2 adjusted	0.561		0.574	

****, **, and * Significant at α = 1%, 5%, and 10%*

TABLE 8. Effect of Aging on Productivity at an Organizational Level: Science and Engineering

Variable	Science		Engineering	
	Coefficient	t value	Coefficient	t value
ln($\overline{A}_{jt}$)	18.787	1.51	30.416***	4.15
(ln($\overline{A}_{jt}$))^2	-2.446	-1.52	-4.007***	-4.18
ln(FG_{jt})	-0.024**	-2.40	0.044***	6.30
ln(AI_{jt})	0.006**	3.30	-0.002	-1.35
ln(PG_{jt-1})	0.617***	56.19	0.533***	31.92
ln(PU_{jt})	0.509***	24.16	0.346***	14.19
$(M/F)_{jt}$	0.0004*	1.72	0.0004	1.27
Constant	-36.440***	-3.80	57.998***	-4.14
Observations	1,219		2,451	
R^2 adjusted	0.561		0.428	

****, **, and * Significant at α = 1%, 5%, and 10%*

TABLE 9. Effect of Aging on Productivity at an Organizational Level: MP and AMA

Variable	MP		AMA	
	Coefficient	t value	Coefficient	t value
ln($\overline{A}_{jt}$)	20.973**	2.41	-13.297	-0.78
(ln($\overline{A}_{jt}$))^2	-2.806**	-2.48	1.652	0.75
ln(FG_{jt})	0.004	0.60	-0.013	-0.66
ln(AI_{jt})	0.005*	1.86	-0.004	-1.12
ln(PG_{jt-1})	0.401***	9.81	0.560***	14.65
ln(PU_{jt})	0.459***	6.49	0.739***	5.57
$(M/F)_{jt}$	-0.0003	-0.47	-0.001	-1.22
Constant	-39.084**	-2.34	26.677	0.81
Observations	524		447	
R^2 adjusted	0.307		0.81	

****, **, and * Significant at α = 1%, 5%, and 10%*

The results, as a whole, seem to say that there exists not much of difference between the age-productivity relationships at individual and organizational levels. It turned out that the age-productivity relationship at an organizational level is also inverse U-shaped in all the fields except for agriculture/marine/animal science. Yet, the analysis is short of giving us a clear idea on how the age-mix of researchers (measured as the ratio of the number of researcher over 55 to the number of those under 40 within the group) affects the performances of research groups or organizations. The statistical exercise has shown that in the case of science and medicine/pharmaceuticals, the higher the ratio of seniors to juniors, the better the performance of the research group. This may mean that the works of the research groups in the fields of science and medicine/pharmaceuticals at the Korean universities during the period of the analysis were such that required experience and coordination rather than new ideas and dynamism. In other fields, we have not been able to find statistically significant relationships between the age-mix of researchers and the productivity of the research groups.

A university's research performance reflects the quality of faculties, physical infrastructure, institutional system, and academic culture that the university offers. In order to analyze how environmental factors influence the productivity of a research group, we employed university research productivity (research output per researcher of the university) as a proxy for the variables explaining the quality of environment in which research groups operate. It has been found that research environment has a strong positive effect on the productivity of research groups. The analysis also confirmed the importance of the cumulative effect of past research on the current productivity of the groups. This finding supports the conventional view that the research capability of a research group is the result of evolution over time rather than one-shot large investments. It has been found that gender-mix does not have any significant effect on the productivity of research groups.

This analysis, however, suffers serious shortcomings. Because of data constraints, we defined research productivity as the number of publications of research, which is far from being an ideal measure of research productivity. For the same reason, we defined "research organization" as the group of researchers of the same discipline within a university, assuming that researchers of the same disciplines within a university collaborate in an organized manner toward the same scientific and technological goals under the same environment. But such a group can at best be a "department," which in practice tends to be not a closely coordinated research organization. Despite this problem, the analysis provides a glimpse into how the aging of researchers would affect productivity at organizational levels.

5. CONCLUSION

The purpose of this study has been to contribute to the debate over age-productivity relationships in scientific and technological research. For this purpose, an empirical experiment was conducted employing a time-series cross-section dataset derived from the KRI of the NRF that contain data on individual researchers at fifty major universities in Korea covering the period of 2008–2013. This is the first study that employed panel data in analyzing the age-productivity relationship in the setting of the Korean R&D system.

The study's main findings are: (1) there exists an inverse U-shaped age-productivity relationship at the level of individual researchers, which concurs with the findings of other recent studies; (2) the impact of the average age of a research group on the productivity of individual researchers turned out to be mixed. The impact was positive in agriculture/marine/animal science and engineering, while negative in the case of medicine/pharmaceuticals. The impact is negative in dynamic, life science-based fields as medicine/pharmaceuticals, whereas the opposite holds in less dynamic fields such as traditional engineering, and agriculture; (3) it has been found that male and female researchers move along different age-productivity curves. In science, the age-productivity curve for female researchers has been found to be steeper than that of their male counterparts, while in all other fields, female researchers face flatter curves. It will require further study at the micro-level to identify the factors underlying the difference; (4) the inverse U-shaped age-productivity relationship also holds at the level of organizations, suggesting that the productivity of a research organization increases with the age of its researchers, and declines after reaching a peak as its researchers grow older; (5) as a variable to explain age-mix of researchers in an organization, we employed the aging index measured as the ratio of older researchers (55 or older) to younger researchers (less than 40 years old). It has been found that in science and medicine/pharmaceuticals, research groups with higher aging indexes performed better, but in the other fields, no statistically significant relationships were found. This may suggest that the current research works in science and medicine/pharmaceuticals at Korean universities are such that require more of coordination and networking at the organizational level; and (6) most importantly, the study has confirmed rapid aging of researchers at Korean universities that require immediate and significant policy responses.

From the findings of the study, we can identify several important policy issues. First, the aging of researchers in Korea will soon reach the stage where serious losses in research productivity become a reality. But considering the increasing inter-sector competition for talent due to the shrinking pipeline of supply caused by the rapid aging of the population, it will not be as easy as it was in the past for the public sector to recruit the best talents into the research sector. To bring more talented young people into public sector research, the government has to take significant action to make research more attractive as a career. Second, as it becomes increasingly difficult to maintain the current age structure of researchers owing to rapid aging, the current seniority- and age-based research management system must be changed into one of higher adaptability. Third, further in-depth research on age-research productivity has to be done in order to clearly understand the relationship, because it is a key issue in human resource management in the fast-aging era. It is still not clear whether the observed decline in the performance of older researchers is due to declining cognitive capability, an unavoidable result of aging, or to declining motivation, which results from the institutional system that discourages older researchers' research activities such as reduced access to research opportunity or mandatory retirement. Researchers in their late fifties will seldom pursue serious scientific research if they are bound to retire at the age of sixty or in their early sixties.

In conclusion, this study contains certain points of caution. The measurement of productivity solely based on the number of publications is far from being appropriate. The analysis on the age-productivity relationship at the level of the organization also involves shortcomings stemming from the definition of research group/organization. There are many other problems worthy of noting, such as statistical issues with the use of the OLS method in analyzing time-series cross-section data. Despite these shortcomings, this study has added some new findings to the current debates over the age-productivity relationship in research.

REFERENCES

Allison, P. D., & Stewart, J. A. (1974). Productivity differences among scientists: Evidence for accumulative advantage. *American Sociological Review, 39*(4), 596-606.

Baby boom sets Japan '2007 problem'. (2006. August 18). *BBC News*, Retrieved from http://news.bbc.co.uk/2/hi/asia-pacific/5263514.stm

Barrington, L., & Troske, K. R. (2001). *Working diversity and productivity: An analysis of employer-employee matched data. Economics Program. Working Paper Series* (EPWP #01 – 02). N Y: The Conference Board.

Beck, N. (2001). Time series cross section data: What have we learned in the past four years?. *Annual Review of Political Science, 4*, 271-293.

Becker, G. (2008, June 7). *The graying of college faculties.* (The Becker-Posner Blog) Retrieved from www.becker-posner-blog.com/2008/week28/index.html

Bernier, C. L., Gill, W. N., & Hunt, R. G. (1975). Measures of excellence of engineering and science department: A chemical engineering example. *Chemical Engineering Education, 1,* 194-197. Also available at http://ufdcimages.uflib.ufl.edu/AA/00/00/03/83/00048/AA00000383_00048_194.pdf

Breton, M., St-Amour, P., & Vencatachellum, D. (2006). *Inter- vs. intra-generational production teams: A young worker's perspective. Working Paper* (CIRANO 2002s-57). Retreived from http://www.cirano.qc.ca/pdf/publication/2002s-57.pdf

Brodetsky, S. (1942). Newton: Scientist and man. *Nature, 150*, 698–699.

Chang, D., Kang, K., & Han, D. (2013). *An empirical study on the impacts of public funding on academic patenting*. *Research Paper* (2013-03). Seoul: Korea Institute of Intellectual Property. (in Korean)

Chang, D., Yang, J., & Choi, Y. (2009). Government funding and research performances of male and female researchers: A comparative study. *Han-Guk-Haeng-Jeong-Yeon-Gu* (Korea Public Administration Research), *18*(3), 97-124. (in Korean)

Cole, S. (1979). Age and scientific performance. *American Journal of Sociology, 84*(4), 958-977.

Confucious. (1979). *The analects (Lunyu).* Translated by D. C. Lau. NY: Penguin Books.

Garibaldi, P., Martins J. O., & van Ours J. C. (2010). *Health, longevity and productivity*. Oxford: Oxford University Press.

Gonzalez-Brambila, C. & Veloso, F. (2007). The determinants of research productivity: A study of Mexican researchers. *Research Policy, 36*(7), 1035-1051.

Guest, R., & Shacklock, K. (2005). The impending shift to an older mix of workers: Perspectives from the management and economics literatures. *International Journal of Organizational Behavior, 10*(3), 713-728.

Hall, B. H., Mairesse, J., & Turner, L. (2005). *Identifying age, cohort and period effects in scientific research productivity: Discussion and illustration using simulated and actual data on French physicists. Working Paper* (NBER 11739), Retrieved from http://www.nber.org/papers/w11739.pdf

Hansen, Z., Owan, H., & Pan J. (2006) *The Impact of group diversity on performance and knowledge spillovers – An experiment in college class room. Working Paper* (NBER 12251). Retrieved from http://www.nber.org/papers/w12251.pdf

Holden, C. (2008). Incredible ageing investigator. *Science, 319*(5862), 391.

Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *Journal of Educational Psychology, 57*, 253-270.

Kim, J., Choi, H., Song, W., Ahn, S., Baek, S., & Kim, Y. (2012). Patent productivity of Korean researchers. *Han-Guk-Gyeong-Je-Eui-Bun-Seok* (Korean Economic Analysis), *18*(2), 1-44. (in Korean)

Lehman, H. C. (1953). *Age and achievement.* Princeton University Press: Princeton.

Levin, S. & Stephan, P. (1991). Productivity over the life cycle: Evidence for academic scientists. *The American Economic Review, 81*(1), 114-132.

Lunyu: Analects, the teachings of Confucius. (D. C. Lau, Trans. Books) Retrieved from http://fudanphilosophyassociation.weebly.com/ uploads/1/8/2/8/18280699/36541650-analects-the-sayings-ofconfucius-translated-by-d-c-lau.pdf

Ministry of Budget and Planning. (1999). *White paper on the government reform*. Seoul: The Government of Korea. (in Korean)

Merton, R. (1968). The Matthew effect in science: The reward and communication systems are considered. *Science, 159*(3810), 56-63.

OECD. (2003). *Ad hoc working group on the steering and funding of research institutes, management of human resources – Report of the sub-group* (DSTI/STP(2003)9/Ann4), Paris: OECD.

Simonton, D. K. (1991). Emergence and realization of genius: The lives and works of 120 composers. *Journal Personality and Social Psychology, 61*(5), 829-840.

Statistics Korea. (2012). *Population projection for Korea: 2010-2060* (Based on 2010 Census). Daejeon: Statistics Korea.

Stephan, P. (1996). The economics of science. *Journal of Economic Literature, 34*(3), 1199-1235.

Turner, L., & Mairesso, J. (2003). Exploring individual productivity differences in scientific research productivity: How important are institutional and individual determinants? An econometric analysis of French CNRS physicists in condensed matter (1980-1997). *Annale d'Economie et de Statistique* (Special Issue in Honor of Zvi Griliches).

Weiss, Y., & Lillard, L. A. (1982). Output variability, academic labor contract, and waiting times for promotion. *Research in Labor Economics, 5*, 157-188.

Wray, S. (2003). Connecting ethnicity, agency and ageing. *Sociological Research Online, 8*(4), Also available at http://www.socresonline.org.uk/8/4/wray.html

Wray, S. (2004). What constitute agency and empowerment for women in later life?. *The Sociological Review, 52*(1), 22-38.

Zuckerman, H. (1977). *Scientific elite: Nobel laureates in the United States*. N.Y.: The Free Press.

Zuckerman, H. A., & Merton, R. (1972). Age, ageing and age structure in Science. In Johnson, M. & Foner, A. (Eds.), *A Sociology of age stratification: Aging and society* (Vol. 3). NY: Russel Sage foundation. Reprinted In N. W. Storer (Ed.) (1973), *The sociology of science: Collected papers of R.K.* Merton (497-559). Chicago: University Chicago press.

APPENDIX: DESCRIPTIONS ON THE VARIABLES IN THE DATASET

- Personal information of researchers:
  - Institutional affiliation (university)
  - Field of specialty
  - Position (professor, associate professor, assistant professor)
  - Age
  - Gender
- Research fund: annual funds individual researchers received from the NRF and other sources (in Korean won)
- Publications: Scientific papers published during the year. Individual performance is calculated following the NRF method, such as:
  - 1 point is given to a single-authored paper
  - In the case of co-authored paper with n authors, the first or corresponding author are given 2/(n+2) point
  - Other co-authors are given 1/(n+2) point
  - In cases where the number of coauthors exceeds 15, it is considered n=15.
  - The same weight is given to journals regardless of their reputation.
- Classification of fields: The data set excludes social sciences and humanities and includes the following:
  - Four categories: sciences, engineering, medicine/pharmaceuticals, and agriculture/marine/animal science
  - Science (6): Mathematics, physics, chemistry, biology, earth science, and others.
  - Engineering (16): Mechanical engineering, electric and electronic engineering, material engineering, Aerospace engineering, chemical engineering, biological engineering, computer engineering, civil engineering, architectural engineering, industrial engineering, resource engineering, naval architecture, medical engineering, miscellaneous 1 and 2
  - Medicine/pharmaceuticals (4:) Medicine, pharmaceuticals, Korean medicine, and others.
  - Agriculture/marine/animal science (4): Agriculture, fisheries, animal science, and marine science.