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ORIGINAL ARTICLE

Reflection on the program requirements of doctoral students majoring in science, engineering, agriculture, and medicine in China

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ABSTRACT

The cultivation of frontier science and technology talent to adapt to social needs and national rejuvenation is a challenging task faced by doctoral education in science, engineering, agriculture, and medicine in China. Ensuring the quality of doctoral education should begin with improving the related program requirements. Investigating 1142 frontier science and technology talents, this article summarizes the high-level abilities and essential characteristics that frontier science and technology talents should master from five perspectives: knowledge, ability, values, motivation, and traits. Using this as a reference, the problems in the current program requirements for 72 first-level disciplines in science, engineering, agriculture, and medicine are analyzed. The study found that the program requirements highlighted high-level ability; however, the essential character was not sufficiently stressed. Therefore, it could be adjusted by following the overall cultivation concept of doctoral students' core quality and adding the content of essential characters with clear guidance and discipline characteristics.

Key words: frontier science and technology talents, core competencies, doctoral students, program requirements

INTRODUCTION

To compete the global technological high ground, China has elevated the cultivation of frontier science and technology talents to a strategic level. These talents are those who have achieved forward-looking, pioneering, and theoretical results and had a significant impact on current and future scientific development. Educating talents to adapt to social needs and national rejuvenation is a challenging task faced by doctoral education in science, engineering, agriculture, and medicine in China. The core competencies of frontier science and technology talents should be the main emphasis of the program requirements and basic requirements for doctoral students in science, engineering, agriculture, and medicine. The core competencies is a key universal ability and essential characteristic which can be adapted to talents development and used to promote social progress in scientific research activities.[1] The current doctoral program requirements and basic requirements in China are based on the *Basic Requirements for Doctoral and Master's Degrees in First-level Disciplines* (hereafter referred to as the Basic Requirements) published in January 2014. They were compiled by the 6th Discipline Evaluation Group of the Academic Degree Committee of the State Council. So, what are the core competencies skills that frontier science and technology talents should master? Do the program requirements match the core competencies? These issues are discussed in this

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article in an attempt to determine whether revision is required.

LITERATURE REVIEW

Educating frontier science and technology talents is a complex task that involves many complex factors. But from what perspective to solve this issue, the ultimate goal is to cultivate the talents' core competencies. This raises a directly related question: What core competencies should talents master? From the existing literature, Zhu pointed out that talents should master insight, humanistic spirit, and the habit of diligence.[2] Kong found that talents in the history of science and technology have 30 competencies, such as daring to question and adhering to truth, *etc*.[3] Huang believed that talents should master six types of competencies: knowledge structure, research ability, practical ability, interests and hobbies, internal qualities, and interpersonal communication ability.[4] Liao pointed out that talents should include five competencies: innovative knowledge, innovative thinking, innovative ability, and innovative character.[5] Most of the existing literature used empirical descriptions to research the competencies that talents should master, lacking a specific evaluation index system. In addition, the coverage of existing research disciplines is insufficient, making it difficult to comprehensively understand the core competencies that talents should master.

Doctoral education, as the highest level of school education, is an important stage in educating frontier science and technology talents. With the increasing number of practical problems faced by doctoral education, researchers have begun to focus on the research of program requirements. Through literature review, program requirements for educating doctoral students in the fields of science, engineering, agriculture, and medicine can be roughly divided into three categories: research the program requirements from the perspective of education objectives,[6–10] from the perspective of talents' career development,[11–15] from the perspective of the quality of doctoral education.[16–20] They reached some consensus viewpoint: Firstly, the program requirements should be research-oriented; Secondly, the setting of program requirements should fully consider the characteristics of different disciplines; Thirdly, there is a disconnect between the current program requirements and the urgently needed talent needs of society. It is necessary to adjust the program requirements. Fourthly, in addition to traditional knowledge and abilities, the program requirements should also include the content of internal qualities. However, these literature lacks guidance on reality, mainly focusing on macro directional suggestions and empirical descriptions. There is a lack of in-depth analysis of program requirements from the perspective of the core competencies that frontier science and technology talents talents should master.

INVESTIGATION AND ANALYSIS OF THE CORE COMPETENCIES SKILLS THAT FRONTIER SCIENCE AND TECHNOLOGY TALENTS SHOULD MASTER

Research design

Questionnaire design

The design of the survey questionnaire mainly takes the following steps. Firstly, The construction of the core competencies for frontier science and technology talents draws on the "onion model theory".[21] This theory was proposed by American scholar Boyatzzis in 1982. Based on the observability of competencies, he divided them into traits, motivations, values, self-image, social roles, knowledge and skills, which are enveloped from the inner to outer layers. Among them, knowledge and skills are explicit competencies which at the outermost level. They are easy to detect and can be improved in the short term. Values, self-image, and social roles are implicit competencies which at the inner level, traits and motivation are the core competencies which at the innermost level.[22] Both play a decisive role in individual job performance, but they require long-term shaping to form. By using the onion model to construct the core competencies can make this research more targeted. Secondly, a primary survey questionnaire on the core competencies of frontier science and technology talents was formed by analyzing the rooted coding of 27 biographical books in *Old Scientists Academic Growth Data Collection Project*. Thirdly, the authors selected 21 talents from Wuhan for interviews and informal questionnaire surveys in July 2019. Based on the interview materials and questionnaire feedback results, the indicator system was revised. In August 2019, 23 talents from regions such as Beijing and Hefei were selected for interview. The purpose is to further optimize the questionnaire. Finally, based on theory, biography, and interview, the questionnaire covered 40 indicators across 5 dimensions: knowledge, ability, values, motivation, and traits. The questionnaire adopted a Likert-style four-level forward scoring method, with 1 to 4 corresponding to unimportant, relatively important, very important, and extremely important.

Sample selection

With the support of the Chinese Academy of Engineering, questionnaires were distributed to frontier science and technology talent *via* e-mail. These talents include: Academicians of the Chinese Academy of Sciences and the Chinese Academy of Engineering, Leading talents in *Ten Thousand Talents Plan*, distinguished professors of the *Yangtze River Scholars Award Program*, winners of *the National Science Fund for Distinguished Young*

Scholars, and national major scientific and technological special talents. In total, 1142 valid questionnaires were successfully collected.

Results analysis

As shown in Table 1, frontier science and technology talent should master five essential competencies: knowledge, abilities, values, motivation, and traits. The average scores for the five first-level dimensions exceeded 3.50, indicating high levels.

Knowledge

The respondents placed great emphasis on professional knowledge, frontier knowledge, methods, and strategy knowledge. Modern science is showing an increasing trend for interdisciplinary intersection, infiltration, and integration. Mastering these three types of knowledge forms the foundation for interdisciplinary research and solving technical problems.

Ability

The respondents also placed great emphasis on imagination and innovative thinking, sensitivity and insight, and logical and critical thinking abilities. Having these abilities is beneficial for talents to elevate their understanding from perceptual to rational and from concrete to abstract so that they can gain insight into the essence of the research object, grasp the laws of change globally, and judge the direction of development.

Value

The respondents emphasized the scientific concept of seeking truth, a belief in pursuing scientific truth, and academic confidence. The scientific concept of seeking truth is fundamental for talent to pursue their studies and conduct themselves properly. In addition, establishing academic confidence is beneficial for building a characteristic Chinese academic discourse system.

Motivation

The respondents recognized that research interest and curiosity, original research awareness, an enterprising spirit, and a lack of curiosity and originality can constrain talents' subjectivity, initiative, and creativity. Maintaining an enterprising spirit of seeking knowledge helps talents to face difficulties and overcome problems.

Trait

The respondents attached much importance to rigorous work styles, tenacious work will, and self-disciplined work quality. Only by having these characteristics can talent not lose their love of research when facing repeated failures, maintain their focus on technological research, and thus reveal scientific laws and breakthroughs in key core technologies.

The knowledge and ability that talents should master will be mutually transformed into high-level ability.[23] This is an interdisciplinary research ability that utilizes interdisciplinary knowledge to identify significant problems in a certain research field and propose creative solutions.[24,25] The values, motivation, and traits are indispensable essential qualities for talents. They have a strong value-leading effect on high-level ability and are an driving force in the formation of these abilities. Due to the high abstraction and cross-situational universality of the core competencies of frontier science and technology talents, only by integrating them organically into the situation and requirements of specific disciplines can they be effectively implemented. The program requirements for disciplines include both the core competencies and the non-core competencies.[26] Therefore, the cultivation of core competencies cannot be separated from the implementation of disciplinary program requirements.

THE PROBLEMS WITH DOCTORAL PROGRAM REQUIREMENTS IN SCIENCE, ENGINEERING, AGRICULTURE, AND MEDICINE

Comparative study

Taking the core competencies that frontier science and technology talents should master as a reference, this study used content analysis to examine the program requirements for 72 first-level disciplines in science, engineering, agriculture, and medicine in China. Specifically, it includes 14 disciplines of science, 38 disciplines of engineering, 9 disciplines of agriculture, and 11 disciplines of medicine. The program requirements in each discipline are explained around three parts: basic knowledge and structure, qualities, and abilities, which have strong guidance. It is the basis or criterion for measuring the quality of doctoral education.

The analysis started with an initial manual coding. A total of 94 keywords were identified by examining original text statements. Second, we summarized the secondary themes through clustering and abstraction of similar keywords. If the summarized secondary themes were consistent with the connotation of a core competency that a talent should master, the corresponding core competency names should be used. There were 30 secondary themes identified. On this basis, the frequency of secondary-themes appearing in the 72 first-level disciplines was determined. If the same phrase appeared multiple times in a discipline, it would only be recorded once. Finally, we summarized the primary themes. Ultimately, five primary themes were determined by abstracting the relationships between the secondary themes. The results are summarized in Table 2.

Table 1: Descriptive statistics of core competencies indicators for frontier science and technology talents

Primary indicators	Mean	Secondary indicators	Mean ± Standard deviation
Knowledge	3.52	Professional knowledge	3.87 ± 0.36
		Frontier knowledge	3.70 ± 0.50
		Methods and strategies knowledge	3.69 ± 0.51
		Interdisciplinary professional knowledge	3.47 ± 0.55
		Practical operation knowledge	3.47 ± 0.60
		English	3.26 ± 0.63
		Mathematics	3.21 ± 0.68
Ability	3.69	Imagination and innovative thinking abilities	3.85 ± 0.38
		Sensitivity and insight abilities	3.84 ± 0.38
		Logical and critical thinking abilities	3.79 ± 0.44
		Analyzing and summarizing abilities	3.75 ± 0.45
		Continuously learning and updating abilities	3.74 ± 0.46
		Judgment and decision-making abilities	3.64 ± 0.53
		Systemic and strategic thinking abilities	3.62 ± 0.53
		Communication and collaboration abilities	3.51 ± 0.57
		Team management ability	3.44 ± 0.61
value	3.60	Scientific concept of seeking truth	3.93 ± 0.23
		Belief in pursuing scientific truth	3.81 ± 0.43
		Academic confidence	3.61 ± 0.55
		Social responsibility	3.55 ± 0.59
		Patriotism through scientific research	3.45 ± 0.66
		Humanistic sentiment of science changing the world	3.26 ± 0.69
Motivation	3.59	Research interest and curiosity	3.84 ± 0.39
		Seeking for originality in research	3.77 ± 0.46
		Entrepreneurship	3.73 ± 0.51
		Academic aspirations	3.61 ± 0.56
		Academic courage to challenge authority	3.30 ± 0.67
		Academic achievement motivation	3.28 ± 0.66
Traits	3.56	Rigorous work style	3.87 ± 0.34
		Perseverance	3.76 ± 0.45
		Self-discipline in working	3.73 ± 0.49
		Innovative scientific spirit	3.67 ± 0.53
		Good working habit	3.64 ± 0.53
		Diligent work habit	3.64 ± 0.55
		Critical and questioning thinking styles	3.62 ± 0.55
		Independence in working	3.60 ± 0.57
		Open-mindedness and inclusive view	3.56 ± 0.56
		Flexible thinking style	3.39 ± 0.62
		Basic intelligence	3.28 ± 0.64
		Talent for research	2.92 ± 0.69

Results analysis

Characteristics of current program requirements

Table 2 shows that the Basic Requirements set clear requirements for the knowledge and abilities that doctoral students should master, taking account of factors such as disciplinary development trends and talent cultivation specifications. They are basically consistent with the requirements of high-level abilities that frontier science and technology talents should master.

Firstly, they emphasize a diverse and broad knowledge reserve. All 72 disciplines require doctoral students to master professional knowledge, frontier knowledge, methods and strategies knowledge, interdisciplinary knowledge, practical operation knowledge, English, and

Table 2: Code and frequency of doctoral program requirements in science, engineering, agriculture, and medicine

Initial keywords	Secondary themes	Frequency	Primary themes
Basic theoretical knowledge, specialized knowledge, basic knowledge	Professional knowledge	72	Knowledge
Frontier developments, international research frontiers, frontier scientific issues, latest developments	Frontier knowledge	72	
Research methods, methodology	Methods and strategies knowledge	72	
Related subject knowledge, humanities and social sciences knowledge	Interdisciplinary professional knowledge	72	
Experimental skills, operational skills	Practical operation knowledge	72	
Foreign language, English literature	English	72	
Fundamentals of mathematics, mathematics	Mathematics	72	
Innovative thinking ability, innovative research capabilities, ability to achieve innovative aims, imagination	Imagination and innovative thinking abilities	72	Ability
Sharp insight, ability to identify and raise issues	Sensitivity and insight abilities	72	
Critical thinking, logical thinking ability	Logical and critical thinking abilities	72	
Analysis ability, refining ability	Analyzing and summarizing abilities	72	
Ability to acquire professional information, obtain data, obtain literature, ability to acquire research methods	Continuously learning and updating abilities	72	
Discriminant ability, academic identification ability, evaluation ability	Judgment and decision-making abilities	72	
Language and written expression skills, communicate and explore with researchers, academic cooperation ability	Communication and collaboration abilities	72	
Independent research, independently completing a paper	Independent research ability	72	
Project management capabilities, technical management ability, ability to carry out teamwork, ability to cooperate with government, residents, and social organizations	Team management ability	58	
Seek truth from facts, a pragmatic scientific spirit, adhere to academic ethics, research integrity, comply with laws and regulations, eliminate academic misconduct	Scientific concept of seeking truth	72	Value
Love science, advocate science, pursue truth, adhere to truth, respect science	Belief in pursuing scientific truth	60	
High sense of social responsibility, sense of a historical mission	Social responsibility	45	
Serve the socialist modernization construction of the motherland, dedication, based on the needs of national development, safeguarding the interests of the country and the people	Patriotism through scientific research	45	
Full of confidence	Academic confidence	2	
Strong interest, curiosity, and thirst for knowledge, love the technology industry	Research interest and curiosity	54	Motivation
Enterprising consciousness, challenging work, pioneering spirit, pursuing excellence	Entrepreneurship	32	
Lofty scientific ideals, strong willingness to conduct research	Academic aspirations	10	
Having innovative awareness and thinking, innovative scientific consciousness	Seeking for originality in research	8	
Serious, rigorous, rigorous academic style, rigorous scholarship	Rigorous work style	49	Traits
Facing difficulties and failure properly, persistent spirit, resilient perseverance, not afraid of difficulties, unyielding courage, enduring pressure and challenges, the will to overcome difficulties, keep on persevering	Perseverance	31	
Focused, persistent, fully committed, enjoys work, meticulously attentive	Self-discipline in working	16	
Has the courage to question, rational questioning spirit, pursues the root cause, sceptical spirit	Critical and questioning thinking styles	15	
Dependable, diligent in learning	Diligent work habits	14	

mathematics in order to form a composite knowledge structure centred around specialized research directions.

Second, they emphasize higher-order thinking and research abilities. All 72 disciplines propose cultivating doctoral students' imagination and innovative thinking, sensitivity and insight, logical and critical thinking, analysis and summarizing, continuous learning and updating, judgment and decision-making, communication and cooperation, and independent research abilities. In addition, 58 disciplines emphasize

that doctoral students should have the ability to manage research teams. The purpose is to make doctoral students into comprehensive researchers.[27]

Shortcomings of the current program requirements

Based on Table 2, it was found that the cultivation of scientific research values, motivations, and traits that doctoral students should master in the Basic Requirements is not clear. The written expressions are relatively vague. There is a certain gap between them and the program requirements for shaping the essential qualities of talents.

In terms of research and values, the 72 disciplines generally require doctoral students to establish scientific beliefs in pursuing truth. However, the emphasis on the sense of social responsibility and spirit of serving the country through science is insufficient, with only 45 disciplines mentioned this. In addition, although academic confidence can enhance the research ambitions of doctoral students, only two disciplines emphasized it. Only by internalizing these values can doctoral students make rational judgments and decisions regarding their future work when faced with multiple values and conflicts of interest.[28]

In terms of research motivation, the Basic Requirements do not emphasize the motivational qualities that doctoral students should master. Only 54 disciplines require stimulating doctoral students' research interests and curiosity, 32 disciplines require doctoral students to form an enterprising spirit, 10 disciplines require shaping doctoral students' academic aspirations, and 8 disciplines require seeking for doctoral students' originality in research. If doctoral students lack the intrinsic motivation to explore their natural essence, they are prone to only meeting the minimum degree requirements rather than focusing on research themselves.[29]

In terms of research traits, the Basic Requirements do not pay enough attention to the research traits of doctoral students. Only 49 disciplines emphasize the rigorous work style of doctoral students, 31 disciplines emphasize the perseverance, 16 disciplines emphasize the cultivation of self-discipline in working, 15 disciplines emphasize critical thinking and questioning, and 14 disciplines emphasize that doctoral students should maintain diligent work habits. Having these traits can help doctoral students learn self-regulation in scientific research, thereby stimulating their subjective initiative to overcome difficulties.

CONCLUSIONS AND RECOMMENDATIONS

Improving the quality of doctoral education should start with improving program requirements and promoting the concept.[30] The formulation of program requirements for doctoral students in science, engineering, agriculture, and medicine should incorporate the overall concept of cultivating core competencies. While emphasizing the cultivation of high-level abilities, it should also emphasize the cultivation of essential qualities in order to stimulate the spirit and motivate the development of doctoral students. Second, the program requirements content should be improved. In the text of the Basic Requirements, essential qualities should be added with clear guidance, and the characteristics of the discipline should be highlighted: (1) enhance the sense of social responsibility of doctoral students and combine their personal values with the nation's needs; (2) have a positive research motivation, maintain their original research curiosity, and establish awareness of scientific research originality and confidence; (3) possess the rigorous, persistent,self-disciplined, questioning and diligent research spirit; (4)mobilize their enthusiasm to tackle frontier technological challenges. Only in this way can doctoral students take on the research tasks facing those on the forefront of world science and technology and the strategic needs of major national development in the future.

DECLARATION

Author contributions

Xu XD: Methodology, Writing—Reviewing and Editing. Zhi YZ: Data curation, Writing—Original draft preparation. Chen M: Conceptualization, Writing—Reviewing and Editing.

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Conflict of interest

The authors declare that there is no conflict of interest.

REFERENCES

1. Lin CD. [*Research on the core literacy of student development in the 21st century*]. Beijing Normal University Press; 2016: 24.
2. Zhu QS. [Understanding from famous scientists at home and abroad]. *China High Educ.* 1999;(1):3–5.
3. Kong XY, Kong QX. [*On the competencies of natural scientists*]. Science Press; 2018: 1–228.
4. Huang L, Jiang YL, Kong CQ. [On the optimization of education ecology structure from the perspective of quality feature of top-notch talents—Investigation on the alumni from N university]. *J High Educ.* 2017;38(1):55–61.
5. Liao ZH. [Research on the construction of lnnovational science and technology talents competence model]. *Sci Tech Prog Policy.* 2010;27(17):149–152.
6. Berelson B. *Graduate education in the United States.* McGraw-Hill Book

Company; 1960: 44.
7. Hockey J. Change and the social science PhD: supervisors' responses. *Oxf Rev Educ.* 1995;21(2):195–206.
8. Pearson M. The changing environment for doctoral education in Australia: Implications for quality management, improvement and innovation. *High Educ Res Dev.* 1999;18(3):269–287.
9. Bao SM. [The study about the training objectives of Ph.D. graduate education and their quality structure]. *Educ Sci.* 2015;2:71–78.
10. Liu J, Liu SX. [Differences in the understanding of doctoral education objectives between academia and industry]. *Res High Educ Eng.* 2018;(4):113–119.
11. Park C. *Redefining the doctorate.* The Higher Education Academy; 2007: 31.
12. Pan JL, Gong F. [Multiple academic abilities: New connotation of doctoral education objectives in the United States]. *Acad Degrees Grad Educ.* 2010;212(7):73–77.
13. Gu JX, Luo YZ. [Ph.D.'s career development in the america—Based on the analysis of three surveys of Ph.D.'s career development]. *Stud Foreign Educ.* 2015;42(4):106–116.
14. Wang DF. [Evaluation of doctoral education quality: Challenges and inspirations in the new context]. *Acad Degrees Grad Educ.* 2012;(2):14–19.
15. Zhuang LJ, Liu SX. [Effects of the scale of programs and employment situation on doctoral education]. *J Grad Educ.* 2012;(4):7–10+26.
16. Griffiths PA. Reshaping the graduate education of scientists and engineers. *Acad Med.* 1995;70(9):826–827.
17. Liu Q, Yan S. [The new system of British doctorate education based on employer's demand: doctor's employ ability development]. *Int Comparative Educ.* 2008;(1):20–24.
18. Zhao F. [Improving the quality of doctoral education with innovative abilities as the core]. *China High Educ.* 2011;(Z1):77–78.
19. Chris MG, George EW. *Reshaping the future of doctoral education.* Liu J, trans. Shanghai Jiao Tong University Press; 2015: 212.
20. Liu J, Liu SX. [Analysis and suggestion on the target setting situation of engineering doctor training]. *Res High Educ Eng.* 2019;(2):167–170+177.
21. Boyatzzis RE. *The competent manager: A model for effective performance.* Wiley; 1982: 308.
22. He P, Wang XP. [Research on the competency model of new engineering science and technology talents: based on the Onion Model]. *China Univ Sci Tech.* 2020;(4):63–66.
23. Li YG. [*From students to researcher: Academic socialization of doctoral students in science*]. Economic Science Press; 2019: 138.
24. Peng ZM, Wu SY, Deng L. [How to develop higher-order skills: A perspective of "Visible Learning" by John Hattie]. *Educ Res.* 2019;40(5):76–85.
25. Ma SF, Yang XD. [A conceptual framework of higher-order thinking]. *J East China Normal Univ.* 2022;40(11):58–68.
26. Wang JM, Ding CC. [Analysis on the concept and essence of key competencies—Analysis of the relationship between key competencies, basic competencies, higher-order competencies and specific competencies]. *Educ Sci.* 2018;34(1):33–40.
27. Phillips EM, Pugh DS. *How to obtain a doctoral degree.* Huang J, Yao YJ, trans. China Agriculture Press; 1996: 27.
28. Wu DJ, Ma YH, Zhang FL. [Survey and research on doctoral students' core socialist values: based on data analysis of 4476 questionnaires from 35 universities]. *J Chongqing Univ.* 2019;25(1):207–220.
29. Zhao JL, Jia XM. [On the affection of different motivations of doctoral candidates on their professional identity]. *Acad Degrees Grad Educ.* 2022;(3):74–81.
30. Yang Y, Xia HX. [On conception of diversified cultivation of doctoral students and implementation path: Retrospection on 20 years of research on doctoral education quality in China]. *J Grad Educ.* 2020;(1):15–21.