



Preparing Students for the Quantum-Safe Era: Examining Academic and Learning Factors Relevant to Physics and Emerging Cryptographic Technologies

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ABSTRACT

Preparing learners for emerging quantum-safe technologies requires strong foundations in mathematics, physics-oriented reasoning, and consistent academic engagement. This present analysis investigated academic and learning related factors of foundational preparedness for advanced quantitative education of 395 secondary-school learners. Study time, educational support, background characteristics (including the use of the internet), previous failure, absences, and academic performance at three assessment stages were evaluated. Patterns were identified with descriptive statistics, subgroup comparisons and Pearson correlations in relation to the final academic achievement. The best correlation with final grade was obtained with the earlier performances with G2 and G1 having both high positive correlations with grade G3. The average achievement outcomes were negatively associated with previous school failures, and positively associated with students' report of study engagement and internet access. The relationships of the other variables, such as absences and grade levels, was not consistently linear, and school or family support variables were not associated with higher grades in simple comparisons. The results suggest that cumulative achievement, continuity in learning, study engagement, and digital access are important factors of academic readiness for future involvement in physics-intensive and technologically demanding disciplines. These factors are to be considered as lower bounds and not as actual competences in quantum computing and post-quantum cryptography. Enhancing quantitative learning at earlier learning levels, therefore, could be helpful in facilitating the advancement of learning to the higher levels of physics and quantum information and new cryptographic education.

Keywords: academic preparedness; physics education; quantum-safe technologies; student achievement; study engagement; digital access; post-quantum cryptography

1. Introduction

Quantum science is rapidly changing the field of computing, the communication sector, sensing, and information security, and they are generating new demands to learn in a technology that is highly mathematical and conceptually complex. Preparation of quantum technologies has gone beyond the limits of the laboratory and extended to other domains of scientific, industrial and educational research, necessitating structured preparation on various levels of the educational system (Acín et al., 2018). In this evolving environment, post-quantum cryptography is becoming especially significant due to the need for future communication and security systems to be robust in the face of increasingly powerful quantum computers. Educating pupils for this context demands a focus not just on teaching particular subject skills, but on the underpinning knowledge that they need to develop for future study in physics, mathematics, computing, and cryptography.

Higher education is playing a growing key role in developing pathways in the new quantum sector, particularly by linking fundamental science with cutting-edge interdisciplinary skills (Fox et al., 2020). But this readiness for this kind of learning can start much earlier, though. It has been demonstrated that students' success in the introductory physics course is significantly dependent on their previous academic background, meaning that any student's differences in background knowledge can affect their performance in more challenging physics courses (Salehi et al., 2019). Mathematics is especially important because physics-intensive learning relies on quantitative reasoning, symbolic manipulation, abstraction, and structured problem solving. Finally, research in physics education shows that mathematical prerequisite also plays a significant role in students' success in a physics introductory course (Burkholder et al., 2021).

The growth of quantum industries has also brought a need for reflection on the knowledge and skills needed in the education system. Constructing a quantum-smart workforce is not just about creating a few quantum specialists, but also about creating educational systems that would produce learners of varying technical depth, multi-disciplinary understanding and adaptability (Aiello et al., 2021). Workforce studies similarly indicate that future quantum-related roles will require combinations of scientific knowledge, analytical thinking, technical competence, and the ability to work across disciplinary boundaries (Gerke et al., 2022). International assessment of quantum education programs has then, highlighted the need to have structured learning paths that will allow to broaden participation but also maintain high scientific standards (Kaur & Venegas-Gomez, 2022).

These learning needs have immediate relevance to the technologies of quantum safety. Post-quantum cryptography features concepts that rely on algorithmic reasoning, mathematical maturity, and knowledge of state-of-the-art information security. There is a growing need for formal education to have curricular preparation of post-quantum concepts, and teaching materials covering this topic are increasingly being developed (Holden, 2023). Practical course designs have also started to show how to incorporate PQC within a structured teaching that makes use of theoretical content combined with practical security challenges (Borrelli et al., 2024). These developments indicate that the preparation should start prior to when students are exposed to more advanced material in cryptography.

Recent competency frameworks have tried to operationalize the knowledge and skills that are expected throughout the quantum workforce, emphasizing the need for the skills of mathematics, physics, computation, and transferable problem-solving (Greinert, Müller, Bitzenbauer, et al., 2023). More comprehensive European competence models have also emphasized the importance of linking basic learning with increasingly advanced ideas and applications in the field of quantum [Greinert, Müller, Goorney, et al. (2023)]. At the secondary level, stakeholders have also agreed upon a core set of knowledge in quantum that could be leveraged to support earlier exposure to quantum ideas, but are still suitable to learners' prior preparation (Merzel et al., 2024).

In this context, the present study analyzed academic and learning aspects related to the preparedness for advanced quantitative study. Special focus was placed on previous achievement, study engagement, previous failure, attendance, educational support and access to digital resources. These factors have been examined and joint conditions have been identified which can enhance students' preparedness for further studies in physics intensive and emerging cryptographic education.

The objectives of the study were:

1. To examine patterns of academic performance and learning engagement among secondary-school students as indicators of foundational quantitative preparedness.
2. To assess the relationships between prior achievement, study time, previous academic failures, absences, educational support, digital access, and final academic performance.

3.To evaluate how these academic and learning factors may inform preparation for later progression into physics-intensive, quantum-related, and emerging cryptographic education.

2. Methodology

2.1 Research Design and Data Source

A quantitative secondary research design was used to investigate academic and learning attributes related to student readiness for advanced quantitative study. The academic records of the 395 secondary-school students analyzed in this study were part of the mathematics component of the original Student Performance study from two Portuguese secondary schools (Cortez & Silva, 2008). Demographic and social data, along with information regarding students' experiences at school, were included in the records, and students' achievement was recorded at three points during the mathematics assessment process. The information covered academic performance, study behaviour, educational support, digital access, attendance, and prior academic difficulties. In contrast, the academic achievement was regarded as a proxy for foundational preparedness, rather than being a direct measure of the competence in quantum-tech applications, because continued success in mathematics was taken as a proxy for later engagement in physics-intensive education and cryptography-related education.

2.2 Study Variables and Conceptual Classification

Variables were grouped together to assure consistency between the research objectives and the subsequent analysis, based on the grouping of the variables into conceptually related categories. Academic performance: G1, G2 and G3 scores were included and G3 was considered as the main outcome. The four categories of study time were maintained as they were in the original instrument, and categories two to four were treated as representing more or less weekly engagement with study and were combined and interpreted as "at least moderate" study engagement, as the overall comparison required. Absences and previous academic failures were kept as proxies for student attendance and previous academic difficulty, respectively. Family educational support and school support were included in the educational support. Digital learning access was measured by Internet availability. Demographic characteristics that were selected for descriptive purposes are retained. The classification facilitated the examination of academic preparedness both from a perspective of academic achievement and a perspective of learning environment.

2.3 Data Preparation and Eligibility

The student records were checked prior to analysis to assure that the variables chosen for analysis were appropriate for interpretation. The missing records and duplicate observations were checked and variables that were not part of the study were not included in the main analysis. Categorical responses were grouped into meaningful classes where comparison was required, while original academic grade values were retained. The analysis was limited to the 395 mathematics students since the academic performance, the study engagement, the previous failure, the support, attendance, and digital access variables were listed in their records, which allowed for the planned comparisons and correlation analysis.

2.4 Statistical Analysis

Descriptive and relational analyses were performed to describe the characteristics of the students and investigate associations between student characteristics and final grade performance. Categorical means frequencies and percentages, and academic scores were summarized using means, medians, standard deviations, minimum and maximum values. The performance of the Mean G3 scores were compared at study-time levels, across previous-failure categories, across internet access, school support, and family support. Pearson correlations were computed between G3 and study time, absences, G1, G2 and previous failures. Simple graphical summaries helped to interpret the observed patterns.

2.5 Ethical Considerations and Analytical Interpretation

Student information was anonymized, publicly available, and already collected; the analysis was thus based on existing information and did not involve direct contact with the participants. It was not possible to identify

individual students and there was no attempt to deduce personal identity from the information available. The findings were strictly seen as educational association, and direct competences in quantum physics, cybersecurity or cryptography were not considered. Academic achievement and learning environment were taken as measures of overall quantitative readiness. Conclusions were therefore geared towards fundamental learning patterns that could provide a basis for further development to higher levels of physics and future quantum-safe technology education.

3. Results

3.1 Student and Learning Profile

A total of 395 students (208 females and 187 males) were analyzed. The majority of students were in the second study time group ($n = 198$) with 105 being in the lowest group. Thirty-two nine was able to access the internet and 242 students were able to be supported with family education. 51 students reported receiving school based academic support. There were no academic failures in most of the participants ($n = 312$). There were wide ranges in absenteeism, from 0 to 75 days, with 4 days being the median. Table 1 provides a summary of the distribution of the main student/learning characteristics.

Table 1. Student Academic and Learning Characteristics

Characteristic	Category	n	%
Sex	Female	208	52.7
	Male	187	47.3
Study-time category	1	105	26.6
	2	198	50.1
	3	65	16.5
	4	27	6.8
Internet access	Yes	329	83.3
	No	66	16.7
Family educational support	Yes	242	61.3
	No	153	38.7
School academic support	Yes	51	12.9
	No	344	87.1
Previous failures	0	312	79.0
	1	50	12.7
	2	17	4.3
	3	16	4.1

Note. N = 395. Absences ranged from 0 to 75 days, with a median of 4 days.

3.2 Overall Academic Performance

There was little change in academic achievement between the three assessment points. Mean scores were 10.91 for G1, 10.71 for G2, and 10.42 for the final G3 grade. The medians for all three assessments were 11. The final grade was more variable with a standard deviation of 4.58 and a range from 0 to 20. There was a clear difference in achievement between students and the overall achievement level as 265 of the 300 students had a final grade of 10 or higher, while 130 had a final grade of below 10. The results of the three assessment periods are summarized in descriptive measures in Table 2 and the distribution of final grades is represented by a bar chart in Figure 1.

Table 2. Descriptive Statistics of Academic Performance

Academic measure	Mean	Median	SD	Minimum	Maximum
G1	10.91	11.00	3.32	3	19
G2	10.71	11.00	3.76	0	19
G3	10.42	11.00	4.58	0	20

Note. Of the 395 students, 265 (67.1%) obtained a final G3 score of 10 or above, whereas 130 (32.9%) scored below 10.

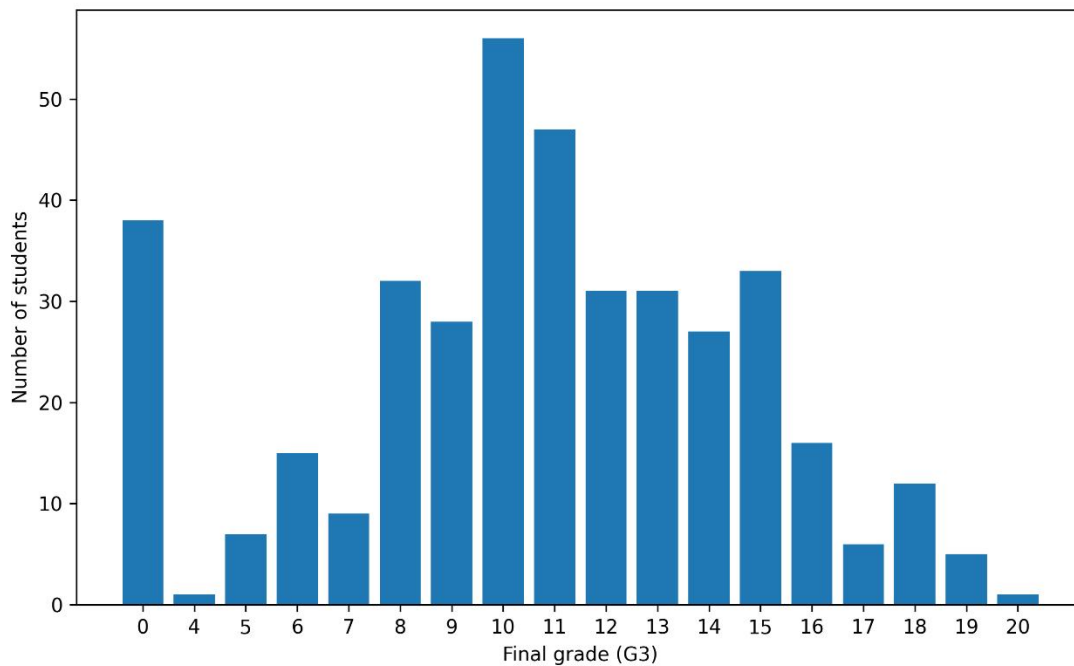


Figure 1. Distribution of Final Academic Performance Among Students.

3.3 Academic Performance Across Learning Conditions

The average final performance differed among the learning conditions. Students in study-time categories three and four scored a mean of 11.40 and 11.26 on G3, respectively, while students in the lowest category scored a mean of 10.05 on G3. The mean score of students who had no previous failure was significantly higher at 11.25, while the mean scores of those with one failure, two failures and three failures were 8.12, 6.24 and 5.69 respectively. The mean grade for students with Internet access was higher (10.62) than for students without Internet access (9.41).

The study-time pattern is shown in Figure 2 and the mean final grade patterns across the principal conditions of learning in Table 3.

Table 3. Final Academic Performance Across Major Learning Conditions

Learning factor	Category	n	Mean G3	SD
Study time	Category 1	105	10.05	4.96
	Category 2	198	10.17	4.22
	Category 3	65	11.40	4.64
	Category 4	27	11.26	5.28
Previous failures	0	312	11.25	4.17
	1	50	8.12	4.71
	2	17	6.24	4.84
	3	16	5.69	4.19
Internet access	Yes	329	10.62	4.58
	No	66	9.41	4.49
School support	Yes	51	9.43	2.87
	No	344	10.56	4.77
Family support	Yes	242	10.27	4.55
	No	153	10.64	4.64

Note. Values represent descriptive group comparisons; statistical significance was not inferred from these differences.

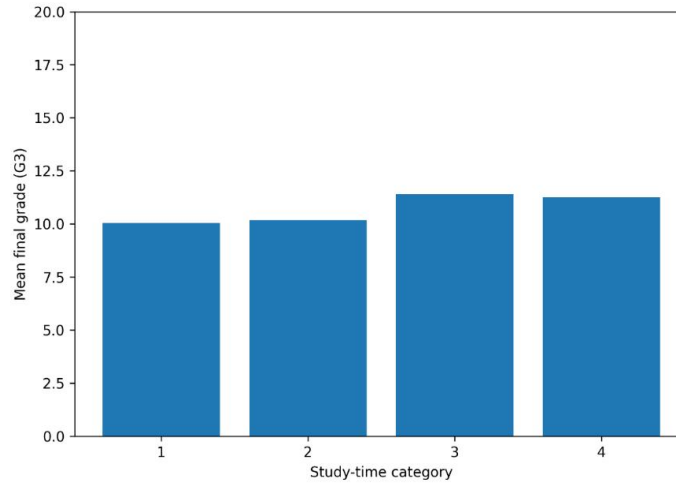


Figure 2. Mean Final Academic Performance Across Study-Time Categories.

3.4 Relationships Between Learning Factors and Academic Achievement

The correlation analysis revealed that the better the students' previous academic performance, the closer they were to the final grade. G2 was strongly associated with G3 ($r = 0.905$), followed by G1 ($r = 0.801$). The previous failures had a moderate negative correlation with final achievement ($r = -0.360$), with the students who experienced repeated academic failure having poorer final achievement. When study time and absences were considered on a continuous scale, there was a weak positive association between study time and G3 ($r = 0.098$) and little association between absences and final performance ($r = 0.034$). The results of the correlation coefficients are summarized in Table 4 and compared in Figure 3.

Table 4. Relationships Between Academic and Learning Factors and Final Performance

Variable	Correlation with G3 (r)	Direction
G1	0.801	Positive
G2	0.905	Positive
Study time	0.098	Positive
Previous failures	-0.360	Negative
Absences	0.034	Negligible positive

Note. Pearson correlation coefficients are reported. G3 represents final academic performance.

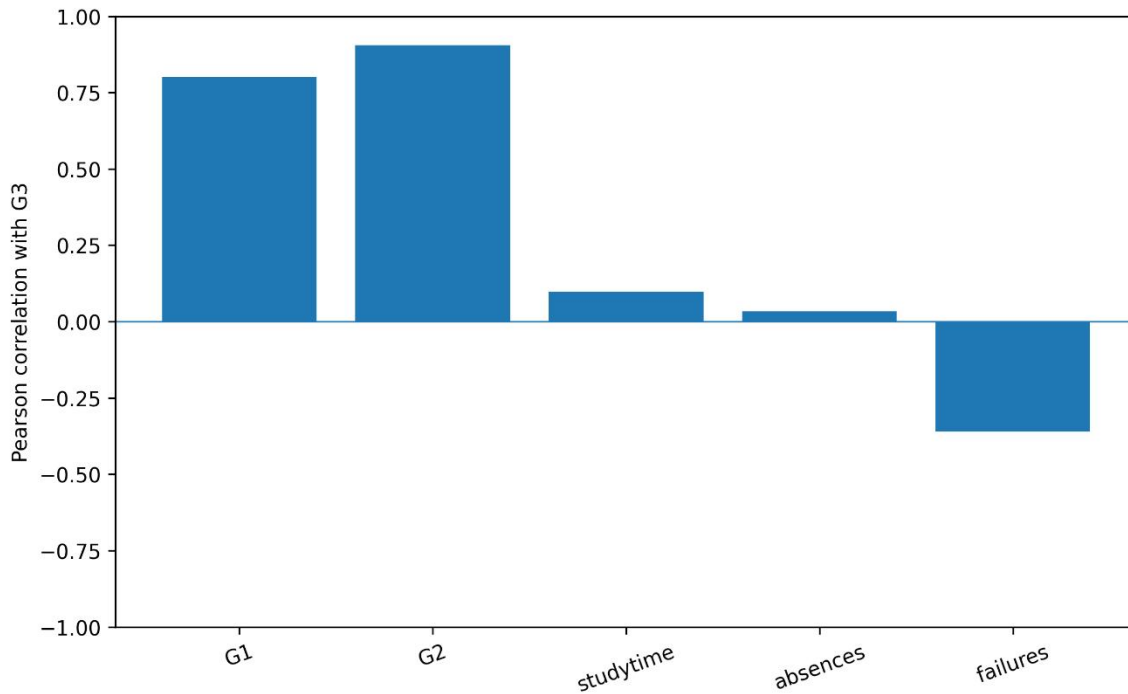


Figure 3. Correlations of Academic and Learning Factors With Final Academic Performance.

3.5 Integrated Preparedness Pattern

The findings together suggest that the strongest correlations with educational preparedness were for students who demonstrated sustained academic achievement and had no prior academic failures. Students who had never failed averaged 11.25 on the final assessment and students in study time categories 2-4 (interpreted as at least moderate study engagement) averaged 10.55 on the final assessment. Comparatively higher achievement also was associated with access to the Internet. However, the categories of school and family support were not consistently associated with higher grades in simple group comparisons. Overall, prior achievement, academic continuity, study engagement, and digital access emerged as the most relevant foundational factors for advanced quantitative learning.

4. Discussion

The results indicated that the greatest factors that were found to be related to students' academic readiness were prior achievement and continuity in the learning process. The correlation of G1 and especially G2 with the final G3 score were strong, suggesting continuity across the different assessment stages. These grades were considered temporally related measures within the same course of math instruction, so the correlations were interpreted as a measure of cumulative academic performance, rather than as a prediction. The consistency of this trend indicates that academic attainment has remained fairly stable at each assessment stage, or that attainment in earlier stages might be linked to attainment in later stages. There are also similarities in the evidence that variation in mathematics achievement is significant because of factors related to the students' level of competence and school-related conditions, suggesting a need for sustained academic growth rather than just performance at one point in the school curriculum (Tomul et al., 2021).

There was a weak positive correlation with hours spent studying and the final grade, but students in the higher hours spent studying categories did tend to get higher average scores than students in the lowest category of hours spent studying. This finding indicates that the quantity of time spent studying is a factor that could be beneficial, but that the impact of that time may vary depending on how it is spent. Longitudinal research has also shown that higher levels of study time are associated with higher mathematics outcomes at various levels of instruction (Spitzer, 2022). Given that, the present findings have validated the importance of frequent involvement and suggested that instructional time is not the only determinant of academic achievement.

The previous failures were negatively related to final achievement, while students who had not previously failed

had a significantly higher level of achievement. The result shows that students who have had academically challenging experiences might need to be supported earlier in the academic setting to avoid the risk of further disadvantage in learning. Having supportive learning environments can enhance students' self-control and math skills by helping them to manage learning demands and keep up with challenging tasks (Niu et al., 2022). Students' motivation, attitudes and learning behaviours can be influenced by family involvement and this may have an impact on achievement; however, the impact may differ depending on the nature of the family involvement (Ferraces Otero et al., 2021).

Comparatively higher performance was associated with access to the internet, which can also be seen as a reflection of exposure to greater opportunities for practice, learning, and access to learning materials. Variations in access and usage of ICTs have been found to be associated with variation in mathematics outcomes (Namome & Moodley, 2021). However, having access to digital tools should not be taken as the sole factor, as wider digital readiness gaps may impact on the ability of students to access online learning opportunities (van de Werfhorst et al., 2022). As the use of advanced science and technology education heavily depends on technology platforms and internet-based teaching materials, these findings are significant.

The final scores were almost not linearly related to the absences in the present analysis. Attendance, however, is not inconsequential, since the impact of the absence on learning may be related not only to the number of absences, but also to their timing, frequency and academic context (Keppens, 2023). The weak association observed here therefore needs to be interpreted cautiously rather than as evidence that attendance has little educational value.

The significance of these patterns is that they may be of general interest to preparation for physics-intensive and quantum related education, where quantitative foundations are important but were not directly measured in this present analysis. Pupils need to have a high level of mathematical thinking, conceptual knowledge and the ability to use increasingly abstract scientific ideas to emerge new quantum technologies. Some interactive methods, such as the quantum games and digital learning materials, have been suggested as helpful tools to help students understand quantum concepts better (Seskir et al., 2022). Appropriate teaching strategies have also been found to be effective in enhancing conceptual understanding of quantum topics, which indicates that research informed pedagogical design can support students' movement from basic to advanced understanding (Donhauser et al., 2024).

It is also necessary to provide flexible learning pathways in order to expand access to advanced quantum education. Open postgraduate models have demonstrated how wider participation can be encouraged by reducing conventional barriers to specialized quantum training (Goorney et al., 2024), while online courses have provided another route for introducing quantum information and computation to broader audiences (Hellstern et al., 2024). These methods are significant because future generation of students in quantum-safe education cannot be completely relied upon to be highly specialized learners coming on in advanced stages.

This trend is also suggested by the industry-oriented evidence of the necessity of the combination of theoretical knowledge, technical skills and interdisciplinary skills to be adapted to the needs of the quantum sector (Greinert et al., 2024). Workforce demand analysis in recent years also underscores the importance of preparing a workforce with the requisite skills and knowledge that the emerging quantum industry expects (Devendrababu et al., 2025). The results indicate that a more solid background in mathematics, fewer previous setbacks, consistent academic involvement, and better opportunities for online support and learning materials could be features of students who make a more stable start and go on to study physics, quantum information and new mathematical education in cryptography.

5. Conclusion

Training students for the quantum-safe future involves the academic preparation for later engagement with physics, maths, computing and cryptographic technologies. The results indicated that student's previous academic performance was the most robust predictor of the students' performance at the conclusion of the course, and that previous failure in academic achievement was linked to significantly less successful performance at the end of the course. There was also comparatively better achievement among students who studied higher and used the internet, but with less significant links. Attendance and support variables demonstrated more restricted trends, reflecting that academic readiness builds up over time through good learning behaviours and through the use of educational resources. The findings highlight the importance of cultivating the quantitative skills early on, prior to starting specialized courses in quantum or cryptography. In turn, educational planning could benefit from increased focus on maintaining mathematics success, addressing students who are having sustained difficulties, learning strategies,

and access to digital learning. These can offer a more predictable trajectory into more physics-based education and the concepts of new quantum technologies. There is no straight correlation between academic grades and the ability to perform in quantum computing or post-quantum cryptography; grades are a measure of a student's basic preparation for a more advanced education in science and technology.

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