Cognitive skill development among undergraduate engineering students

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Abstract

This research paper addresses assessment of numeracy and literacy among engineering students, which are core to problem solving and critical thinking, but challenging to consistently measure. The Essential Adult Skills Initiative (EASI) was a research project involving 20 Canadian post-secondary institutions, designed to measure the literacy, numeracy, and problem-solving skills of incoming and graduating college and university students the Education and Skills Online Assessment (ESO). At one participating institution, the ESO was administered over a two-year window in a cross-sectional approach to 112 first year and 65 fourth year engineering students. Statistically significant improvements were observed from first to fourth year in numeracy (W = 2634 , $p < 0.05$), and in literacy (W = 2743, $p > 0.05$). Of the fourth year participants, 38% received scores associated with trouble consistently performing critical written analysis, and 49% received scores associated with trouble consistently performing critical numerical analysis. Time spent on test was found to be correlated to final score (r = 0.35, $p < 0.001$). These results raise questions concerning the baseline skill level of some graduating engineering undergraduates, and when combined with prior literature also question adequacy of low-stakes standardized tests for measuring complex cognitive skills.

1 Introduction

Both employers and students expect the post-secondary system to enhance and hone students' abilities, knowledge, and skillsets, ultimately enabling them to contribute productively in the workplace. Professional programs such as engineering are held to an even more exacting standard through program accreditation requirements. The Business Council of Canada [1] cites adequate literacy and numeracy, problem solving and critical thinking, effective communication skills, and resourcefulness and adaptability as the most required skills necessary for job success.

It is important to examine and measure these job-related skills directly, in order to assess growth and graduate preparedness for the workplace. Large-scale standardized assessments are attractive for wide scale use in the post-secondary context because of their relatively straightforward implementation and ability to benchmark between institutions and jurisdictions. This makes them a valuable tool to investigate the skill change of students' throughout their program of study. There are, however, challenges related to student motivation and alignment with disciplinary curriculum [2], [3], which will be discussed.

2 Purpose

2.1 EASI project overview

The Essential Adult Skills Initiative (EASI) was a large-scale research project undertaken by the Higher Education Quality Council of Ontario (HEQCO) and 20 postsecondary partners in 2017-2018. EASI was designed to measure the numeracy, literacy, and problem-solving skills of incoming and graduating college and university students in Ontario.

The central research goals of the larger project were: a) to determine the suitability of the Education and Skills Online (ESO) assessment to measure post-secondary students' literacy, numeracy, and problem-solving; b) to determine observable differences between incoming and graduating students' skillsets, and; c) to identify practical implications of implementing such a project in post-secondary institutions.

This paper details the results from the engineering program of a mid-size, research intensive university, one of the participating institutions in the EASI project. The following research questions will be addressed:

1. What, if any, are the observable differences between first and final year engineering students' literacy and numeracy?
    a. How do these differences compare with the larger institutional sample, including students from other disciplines and programs?
    b. How do these differences compare with the provincial university sample from the entirety of the EASI project?

3 Literature Review

3.1 Graduate attributes and professional success

Competency in mathematics, analysis and problem solving, and communication are skills demanded by engineering accreditation bodies worldwide (International Engineering Alliance, 2014). These skills are fundamental in the education of undergraduate engineering students and are recognized as key skills in industry [1], [4]–[6].

In a year long research project, the Royal Bank of Canada (RBC) analysed job openings and employee skillsets, projecting skills requirements of graduates in 2018-2021. They found that the strongest demand is, and will be, for foundational skills like communication, emotional intelligence, and analysis. Human skills such as active listening, speaking, and critical thinking were required in 100% of future positions, including STEM areas [7].

These findings are corroborated in the field of engineering by Passow and Passow [8], who identified the ABET competencies that undergraduate engineering programs should emphasize through a systematic literature review. They found problem solving, teamwork, and communications skills to be the most integral competencies to engineering practice, identifying that "technical competence is inseparably intertwined with effective collaboration" (pp. 491).

3.2 University graduate performance for fundamental skills

Several large studies by the Organization for Economic Cooperation and Development (OECD) have been undertaken to examine literacy and numeracy skills in adults, including the International Adult Literacy Survey (IALS) (1994-1998), and the Adult Literacy and Life Skills Survey (ALL) (2003 -2007) [9]. In 2011 and 2012, the Programme for the International Assessment of Adult Competences (PIAAC) was used in an OECD Survey of Adult Skills, showing that significant proportions of adults in OECD countries involved in the study had low levels of literacy and numeracy skills [10].

Canadian data from the PIAAC was further examined by Statistics Canada focusing on adults 25-65 who had attained a university degree [11]. In this sample, 27% had literacy skills in the lower range of the test (level 2 or below), and 32% displayed low skill level (level 2 or below) in numeracy. This proportion was higher for individuals who were born outside of Canada. Of the Canadian-born participants, numeracy levels were lower for females. For both literacy and numeracy, the lowest proportions of participants at level 2 or below were in those who had graduated from STEM programs, with 9% low literacy scorers and 12% low numeracy scorers.

The PIAAC has been used to evaluate the impact of schooling quality [12], and to determine skills shortages in under-employed and low-income adults [13], [14].

At the institutional level, many universities collect information internally about incoming students' math and literacy skills, but very few regularly test graduates for fundamental skills as well. Literacy or English proficiency levels are occasionally tested with an exam requirement before graduation, ensuring some level of graduate competency [15]. Numeracy levels, however, are not often tested through wide-ranging or standardized assessments [16].

3.3 Education and Skills Online (ESO) assessment

Data for this study was collected using an internationally benchmarked standardized test, the Education and Skills Online (ESO) assessment. It is the commercial version of the PIAAC, developed by the Organization for Economic Co-operation and Development (OECD) and used in the 2011-2012 Survey of Adult Skills. This test was validated for populations between the ages of 16 and 65.

The ESO is comprised of three major components: a) Literacy and Numeracy (also called the Core Assessment); b) Problem Solving in Technology-Rich Environments (PS-TRE), and; c) a background questionnaire. It is an adaptive assessment tool, becoming easier or more difficult based on the participant's performance.

The focus of the instrument is on real-world applications of literacy, numeracy, and problem-solving, looking at how effectively participants use these essential skills to engage in the world around them [17]. PIAAC and ESO definitions of the measured constructs are provided in Fig. *1*.

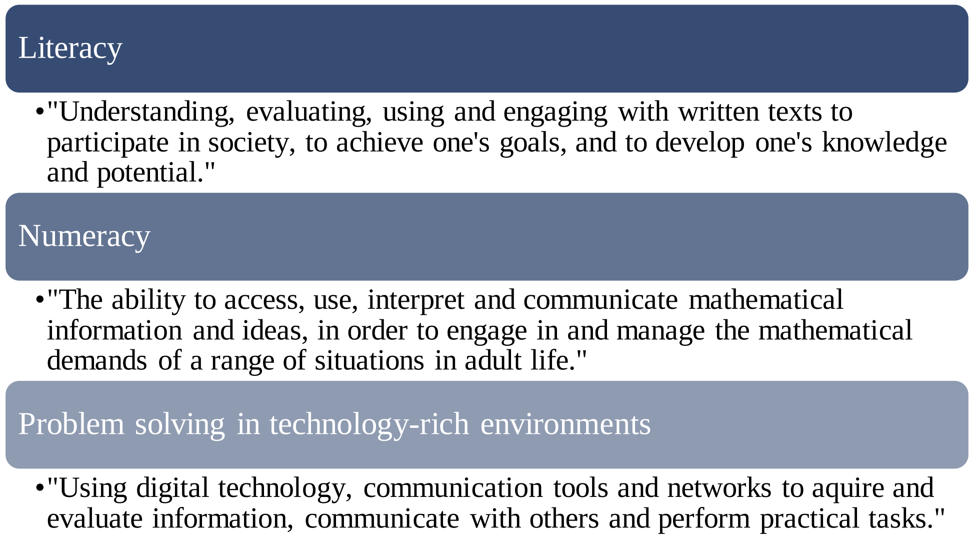

Fig. 1. ESO definitions of measured constructs literacy, numeracy, and problem solving in technology-rich environments, adapted from Organization for Economic Cooperation and Development (2012), p. 20, 32, 47 .

Test-takers are provided with a numerical score for each major component of the ESO, rounded to the nearest 10 points. These raw scores are grouped into a series of levels (ranging from "Below Level 1" to "Level 4/5"), which can be used to describe and provide context for the skills of the participant. The ESO's literacy and numeracy components are scored on the same scale, with a separate scale to score the PS-TRE component. The scale of raw scores and corresponding proficiency levels for literacy and numeracy scores is shown in Fig. 2.

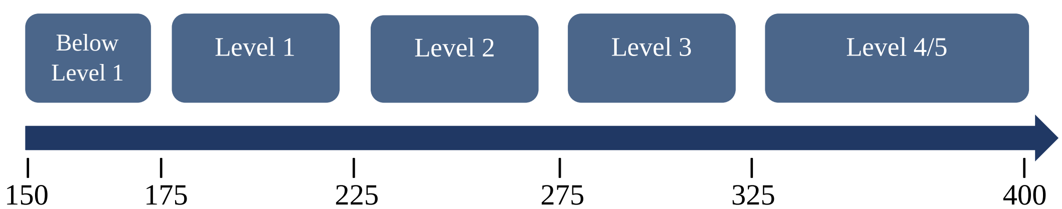

Fig. 2. ESO raw scores for literacy and numeracy, and corresponding proficiency levels.

The proficiency level system indicates the levels of complexity of the tasks that the test-taker can reliably and successfully solve [17]. This does not mean that level-descriptions fully describe the skillset of the participant and that they are incapable of completing higher level tasks; merely that even if a participant can successfully complete some tasks at a higher level, "the probability of consistently doing so is low" [19].

4 Methods

The EASI project tested eight Ontario universities in total, through a cross-sectional approach; first and final year students were tested in the 2017 fall semester. In total, 1040 first year and 1107 fourth year students were tested. Participation was voluntary, but incentivized by giving students access to their personalized ESO score report, and a $10 Amazon gift card. A grand prize draw was also used to increase engagement, with participants entered into a pool to win one $500 and four $100 Amazon gift cards, per institution, per cohort.

General research board ethics approval was obtained at the institution prior to recruitment and testing.

4.1 Sampling

574 students were tested, including 112 first year and 65 fourth year engineering students. Engineering students were recruited in two cohorts: Cohort A, comprised of first year engineering students in 2016; and Cohort B, comprised of first and fourth year students in 2017.

Cohort A was recruited face-to-face and provided with consent forms. First year students completed the ESO in-class during a mandatory engineering course, but only consenting student data was collected for research purposes.

Recruitment of Cohort B occurred through email, with an invitation to participate emailed to all first and fourth year students. An electronic letter of information and consent form was accessed through email link. Based on response numbers, further invitations were sent to attempt to increase participants.

The engineering sample represented approximately 11.8% of the engineering student population at the time of testing.

4.2 Analysis

Data was filtered to moderate the effect of test effort on scores, resulting in the removal of 5 first year participants and 2 fourth year participants from the data pool. This is shown in further detail in 5.2.1 Time to Complete.

Data normality and homogeneity of variance was investigated, revealing non-normal distribution for literacy and numeracy sub-scores. Thus, Wilcoxon rank-sum tests were used to investigate differences between project year and demographic groups. If differences existed, Pearson's r was used to determine the magnitude of relationships, where values are: (a) negligible if less than 0.1; (b) of small effect if between 0.1 and 0.3; (c) of medium effect if between 0.3 and 0.5; and (d) of large effect if greater than 0.5 [20]. A 95% confidence interval was used for all inferential statistics.

Due to low levels of completion for the PS-TRE scores, only literacy and numeracy scores were analysed.

5 Results and Analysis

Results from descriptive and inferential statistical analysis is detailed below, highlighting group sizes, the relevance of test time, and growth in literacy and numeracy from first to fourth year,

5.1 Descriptive Statistics

Sample breakdown by demographic group for the filtered institutional engineering sample is shown in TABLE I, examining percent makeup by year for gender and first language status (split into English native speakers and English as an Additional Language speakers (EAL). These descriptive statistics show the sample after filtering, as described in 5.2.1 Time to Complete.

TABLE I
DEMOGRAPHIC STATISTICS FOR FILTERED ESO SAMPLE IN FIRST AND FOURTH YEAR

Year	***n***	**Gender**	***n***	***%***	**Language**	***n***	**%**
First	107	Male	80	74.8	English	86	80.4
		Female	27	25.2	EAL	21	19.6
Fourth	63	Male	39	61.9	English	50	79.4
		Female	24	38.1	EAL	13	20.6

5.2 ESO Results

5.2.1 Time to Complete

Data exploration revealed some participants who exceeded 250 minutes to complete the core component of the ESO, more than four times the recommended duration for that portion of the assessment. These participant times were removed as outliers for the analysis of completion time and test score.

Time spent to complete the core component was found to be correlated to core score ($r = 0.35$, $p < 0.001$), reinforcing the importance of student motivation and adequate time spent in obtaining reliable results in a low-stakes testing situation [21]. To combat this, data was filtered to eliminate students who completed the literacy and numeracy test components in less than one third of the 60 minute recommended completion time [22]. A slight decrease in correlation ($r = 0.35$ to $r = 0.27$) between time to complete and core score was a result of the data filtering, as seen in Fig. *3*.

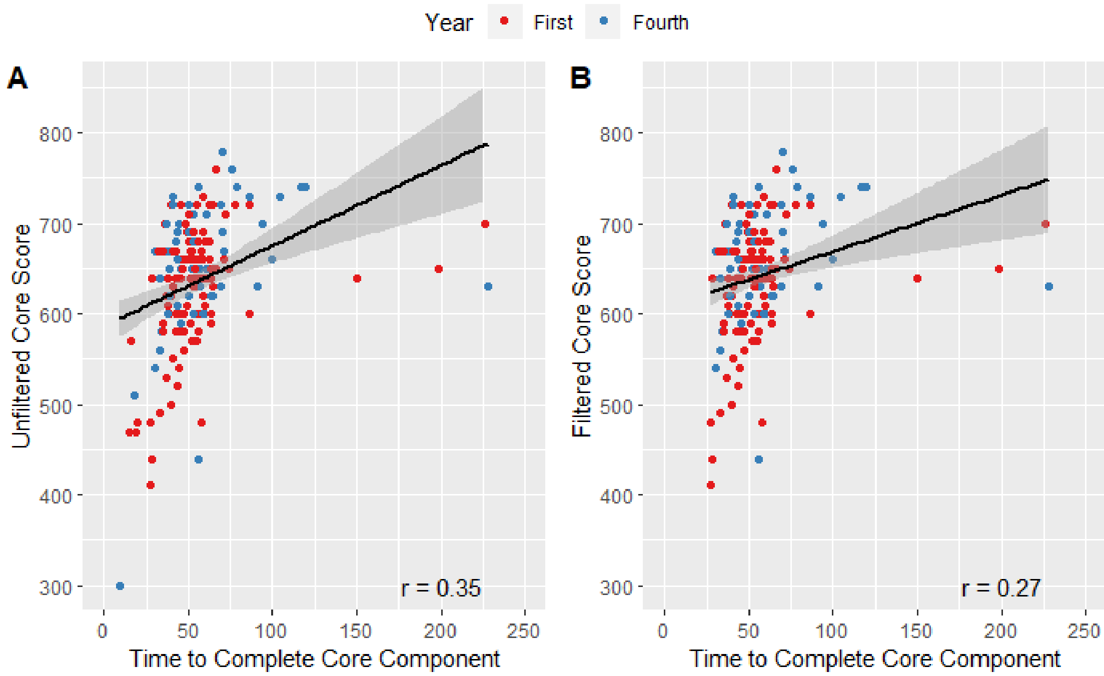

Fig. 3. Core component vs time to complete for unfiltered (A) and filtered (B) dataset, with corresponding correlation coefficients (*r*).

5.2.2 Core Component Scores

Participants showed significant growth from first ($M = 310$) to fourth ($M = 330$) year in numeracy scores ($W = 2364$, $p<0.01$), with small effect size ($r = 0.26$). There was also significant growth in literacy scores between first ($M = 320$) and fourth ($M = 340$) year, ($W = 2743$, $p < 0.05$, $r = 0.25$).

Although increase was observed in both literacy and numeracy sub-scores, linear regression modeling showed that year of study was not a significant predictor of literacy scores ($F(1,168) = 3.575$, $p > 0.05$, $R_2 = 0.02$). Year of study did, however, explain 5.6% of the variance in numeracy scores ($F(1,168) = 10.1$, $p < 0.05$).

Fig. *4* shows literacy and numeracy growth from first to fourth year. Gains can be observed from first to fourth year in both literacy and numeracy, but the 95% confidence interval about the median is very wide for fourth year literacy scores, likely due to smaller sample size and higher score dispersion than first year scores.

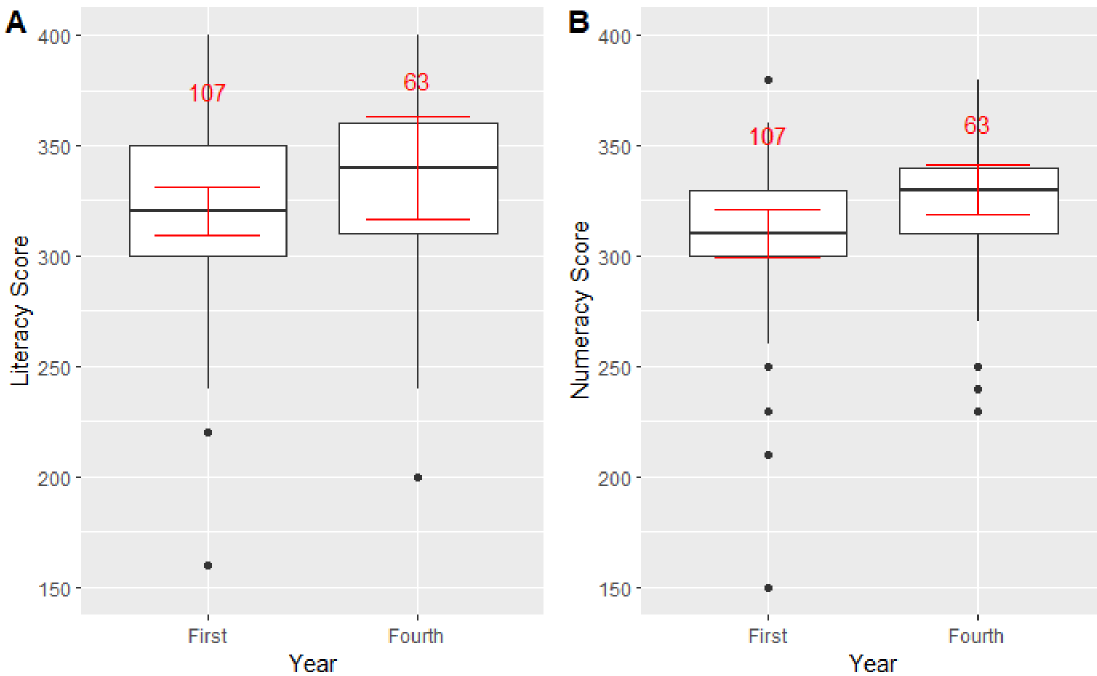

Fig. 4. Literacy (A) and numeracy (B) scores for first and fourth year groups, with 95% confidence interval about the median and group sizes (*n*) in red.

The proficiency level breakdown for literacy and numeracy scores is shown in Fig. *5* and TABLE II. The majority of students in both first and fourth year scored in Levels 3 and 4/5. For literacy, this indicates that they are likely able to "handle tasks with multiple steps and multiple information sources", "evaluate the reliability of a source", and "handle some complex abstract or hypothetical information within a text" [23, pp. 27]

For numeracy, students scoring in Levels 3 and 4/5 are likely able to: "handle moderate amounts of competing or complex information"; "handle tasks requiring several steps", and; "apply number sense and spatial sense; recognize and work with mathematical relationships, patterns, and proportions…and [perform] basic analysis of data and statistics in texts, tables and graphs" [23, pp.29].

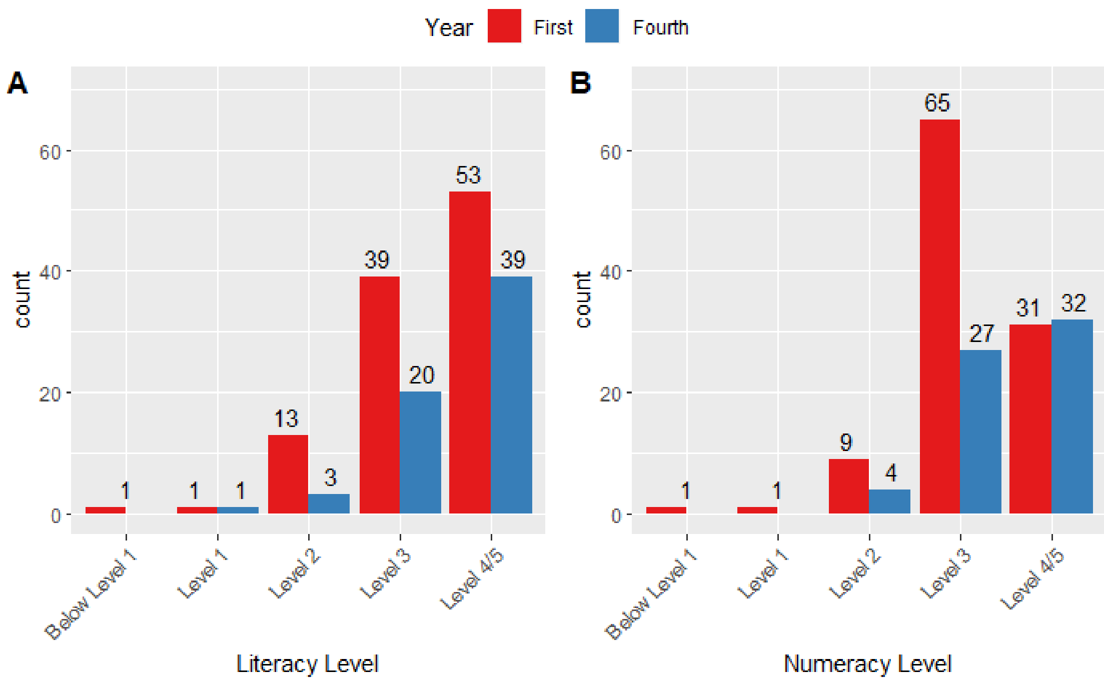

Fig. 5. Literacy (A) and numeracy (B) levels for first and fourth year students.

TABLE II
LITERACY AND NUMERACY LEVEL PERCENTAGE BY YEAR

Year	**Level**	**Literacy %**	**Numeracy %**
First	Below Level 1	0.9	0.9
	Level 1	0.9	0.9
	Level 2	12.2	8.4
	Level 3	36.5	60.8
	Level 4/5	49.5	29.0
Fourth	Below Level 1	0.0	0.0
	Level 1	1.6	0.0
	Level 2	4.8	6.3
	Level 3	31.7	42.9
	Level 4/5	61.9	50.8

5.2.3 Demographics

Due to small group sizes, a two-way ANCOVA was used to examine the effects of gender and first language on literacy and numeracy scores, after controlling for year of study. There was no statistical significance difference for gender or for first language in either literacy or numeracy scores, nor was the interaction between the two variables significant. However, small group sizes (shown in Table 1) significantly reduce the statistical power of tests for demographic group effects ($p < 0.8$), and these results should be interpreted with caution.

6 Discussion

Results as they pertain to research questions are discussed below, focusing on: student gains in literacy and numeracy scores, a comparison of the engineering sample with a larger institutional sample, and a comparison of the institutional sample with provincial data. The impact of student effort on test achievement is also discussed, as are limitations in the research.

6.1 Literacy and Numeracy Gains

First year students demonstrated higher level literacy skills than numeracy skills and made small gains in both literacy and numeracy from first to fourth year. However, year of study was not a significant predictor of literacy scores, suggesting that year study of participants has no effect on their final literacy score. This may be because of differing cohorts and could be addressed by investigating the confounding effect of grade point average on test scores – data that was not available for this project. Longitudinal study would also address this concern, ensuring that student ability did not vary by year of study.

The literacy levels of graduating students also call for further investigation, with the scores of approximately 38% of the test participants at level 3 or lower. Critical thinking and information analysis are important skills in the engineering profession [8], and according to the ESO test documentation [24], students who score a literacy level of 3 or lower may find it challenging to consistently “identify and filter out high volumes of competing or irrelevant information” within texts, or “handle complex, abstract or hypothetical information within and across multiple complex texts”. This result adds to literature that remarks on the lack of literacy skills possessed by engineering undergraduates particularly [25], [26], and aligns with similar trends from other tests of cognitive skills among the same population [27].

Looking specifically at numeracy growth in undergraduates, the small gains from first to fourth are an encouraging sign. However, the numeracy level possessed by graduates is still cause for concern. Hango [11] indicates that the “lower range” for numeracy includes test-takers who score at a level 2 or below. In our sample, most students at both a first and fourth year level surpassed this, but we argue that even students at a level 3 are not demonstrating numerical skills that are expected of an engineer. A score of level 3 or lower in numeracy indicates that students may find it challenging to consistently perform and understand “analysis and complex reasoning about quantities and data; statistics and probability; spatial relationships; rates of change; proportions; and formulas” [23, pp. 29], all of which are fundamental skills required in the engineering profession. Indeed, most of these concepts are covered in first year undergraduate mathematics and statistics courses. These results suggest that half of the students in the sample may struggle to consistently perform these skills.

Yao [28] examined PIAAC data from the United States and the U.K., looking at individuals from age 25-65 with a college degree, and who are active workers (N = 2485). That data shows that approximately 32% of engineering, manufacturing, and construction majors scored in the mid-range of Level 3 or below in numeracy, while 41% scored in the mid-range of Level 3 or below in numeracy. This aligns with the findings in the study presented in this paper, suggesting that the prevalence of average engineering skillsets extends beyond one institution.

Employer feedback about graduating engineering students has identified communication skills as a weakness, which aligns with the significant number who fall at Level 3 or below in literacy. However, engineering students are generally perceived to have strong mathematical skills, and employers of engineering graduates have been satisfied with mathematical competence in the past [29]. It is possible that graduating students with poorer numeracy skills self-select out of traditional engineering roles, as a significant proportion of engineering graduates take on employment outside of traditional engineering.

6.2 Comparison with Larger Institutional and Provincial Samples

The larger institutional sample included students from Commerce, Arts and Science, Computing, and Fine Art. Excluding students from engineering, this sample contained 200 first year students and 173 fourth year students. 48% of graduating students in the larger sample scored at a literacy level 3 or below, while 75% scored at or below level 3 in numeracy skills. In the engineering-only sample, 38% and 49% of graduating students scored at or below level 3 for literacy and numeracy respectively. This suggests that, although the engineering sample performed well comparatively, there may be a larger problem with literacy and numeracy skills in graduating students. The literacy and numeracy skillsets required of graduates in other degree programs will differ, however, and should be considered when making recommendations.

Compared to the provincial EASI sample, the institutional sample of students performed slightly better in literacy and poorer in numeracy [23]. The provincial sample analysis was completed by institution rather than program, however, so direct comparison of engineering programs across the province is not possible. In general, these results suggest that most graduating students across faculties province-wide present average skillsets, with too few instances of the high-level baseline skills required in the engineering.

6.3 Time Spent on Test and Student Effort

Student effort is known to be a significant predictor of performance on low-stakes tests [22]. During ESO testing, proctors observed that some students testing in-class clicked through questions toward the end of the test, reflecting decreasing effort. Results from the ESO showed a correlation between time spent on the core test components and final core score, suggesting that student effort did impact achievement.

However, previous work on PIAAC engagement suggests that the proportion of disengaged respondents from Canada with educational attainment greater than high school is less than 5% [30]. Only 4.2% of the students in this sample were filtered out because of low time spent on test, which aligns with this previous evaluation of disengaged respondents from a national sample of a similar demographic. To increase student effort, high-stakes authentic assessment for these skillsets may be beneficial [31], [32].

6.4 Limitations

These results are based on a small sample with limited statistical power and should be treated with caution. The cross-sectional nature of data collection also introduces uncertainty about the cause of skill growth from year one to four, which could be moderated in future work through longitudinal study or inclusion of some general intelligence measure.

Testing also occurred in the fall semester of year four, and thus students did not have exposure to the entirety of the final year curriculum prior to testing. Thus, any literacy and numeracy skills taught in final year curriculum are not considered in these results.

7 Conclusions

Two recommendations arise from this work. Firstly, the results raise questions about the baseline skill level of some graduating engineering undergraduates. Any deficiency in foundational numerical and literacy skills would pose significant challenges for graduates entering the workforce. More investigation into baseline proficiency is called for, to ensure that graduates can contribute consistently in a professional engineering environment.

Secondly, this work reinforces that low-stakes standardized tests are subject to issues of student motivation and correlation of performance with time spent. Although a low percentile of low-effort participants was observed in this sample, a significant correlation was found between time spent on test and student achievement. When combined with other literature, this suggests supports the recommendation for developing domain-specific assessments for literacy and numeracy skills [33].

8 Acknowledgements

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