Research Square

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The Impact of Intelligent Tutoring Systems on Mathematics Performance in Higher Education Students

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Research Article

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Abstract

This study investigates, using arandomized controlled trial (RCT) (N = 271), the effectiveness of an Intelligent Tutoring System (ITS), specifically Area9 Rhapsode, compared to traditional web-based training (WBT) in improving basic mathematics performance among first-semester economics students at iba | University of Cooperative Education.

Conducted across eight campuses in Germany, the RCT evaluated the effects of a 45-minute adaptive learning intervention compared to a non-adaptive WBT. The evaluation included pass rates at two grading thresholds (50% and 66%), final grade distributions, and metacognitive competence using a 4-field competence matrix.

ITS students significantly outperformed WBT students in pass rates at the higher threshold, grade distribution, and conscious competence, indicating improved alignment between knowledge and self-awareness.

These findings support broader literature emphasizing the benefits of adaptive systems on learning outcomes. To our knowledge, this is one of the first cluster-randomized studies investigating ITS effectiveness in German higher education.

Introduction

Context and Background

Mathematical literacy is a foundational requirement for success in economics-related higher education programs. Yet, in recent years, alarming trends have emerged. The OECD's PISA 2022 report highlights a widespread decline in school-level mathematics competence across industrialized nations, including Germany [1]. In Germany, educational disparities remain particularly high for students with a migration background, driven by language barriers at home and socio-economic disadvantages. Students with a migration background scored, on average, 59 points lower in mathematics than their peers without such a background. Even after accounting for socio-economic differences, a substantial performance gap of 32 points remained.

This trend presents a critical barrier to success in university-level business mathematics courses. Students often lack basic algebraic and arithmetic fluency, resulting in high failure rates in introductory quantitative modules. These challenges are particularly acute in programs such as Business Administration, where mathematics underpins finance, statistics, and decision-making.

The demographic decline in the number of first-year students in Germany, coupled with the underrepresentation of children from migrant backgrounds in higher education, poses a significant threat to the availability of qualified labor in the future [2].

At iba | University of Cooperative Education, which operates a dual-study model combining academic learning with on-the-job training, students are challenged by time constraints: they spend only two days per week on campus, while the rest is dedicated to practical training at partner companies. As such, academic instruction must be both highly effective and time-efficient to meet the needs of a diverse, time-pressed student population.

Traditional approaches to bridging these gaps often rely on WBT. WBT typically involves static, linear content: standardized, self-paced modules that offer theoretical refreshers in mathematical fundamentals.

While cost-effective and scalable, research suggests that WBT lacks responsiveness to learner variability and provides no adaptive feedback to correct misconceptions [3].

A growing body of research suggests that Intelligent Tutoring Systems (ITS) offer a promising alternative. ITS emerged as a scholarly discipline more than 40 years ago [4]. A variety of definitions and terminologies exist for the core concept, but most research agrees that ITS are closely associated with personalized and adaptive learning across different educational fields [5]. ITS platforms use adaptive algorithms and metacognitive feedback to tailor content to each learner's pace and confidence level [6]. ITS are designed to interact directly with students, adapting content in real time based on learners' performance and self-reported confidence. These systems provide formative feedback and personalized pacing to improve learning outcomes, especially for low-performing students [4].

ITS represent a transformative approach to higher education by offering individualized learning experiences that dynamically adjust to each student's needs [7].

Furthermore, these systems continuously assess not only what a student knows, but also what they think they know—and what they are unaware they are missing. This facilitates more effective, targeted remediation [4] and fosters metacognitive development, enabling students to monitor and regulate their learning processes more effectively [8].

The ITS platform investigated in this study, Area9 Rhapsode, embodies the principle of high-interaction granularity [4].

By modeling not only the correctness of a student's response but also their self-assessed confidence, the system supports metacognitive regulation. On each question, the system prompts learners to make an explicit judgment of their confidence, a process designed to foster self-monitoring and self-regulation. The system engages in a fine-grained feedback loop designed to mimic the responsive dialogue of a human tutor. Area9 Rhapsode is an adaptive learning platform that integrates algorithmic personalization and metacognitive feedback mechanisms. Vendor documentation claims that the system incorporates research from cognitive science; however, independent empirical validation remains limited [9].

The ITS design relies on the four stages of learning a skill, which is commonly attributed to Thomas Gordon and Noel Burch at Gordon Training International, who developed it in the 1970s [10].

It distinguishes four psychological states a person goes through when learning a new skill:

- **Unconscious Incompetence:** You do not know what you do not know.
- **Conscious Incompetence:** You become aware of what you do not know.
- **Conscious Competence:** You can perform the skill, but it requires active concentration.
- **Unconscious Competence:** You have mastered the skill, and it has become second nature.

The model has successfully transitioned from its origins as an internal corporate training tool into a widely applied educational concept. It is now commonly used to frame the development of skills and metacognitive awareness in learners, with its academic utility researched and employed in various fields, including medical higher education [11].

In today's learning environment, the model is frequently visualized as a 2x2 matrix—defined by the axes of consciousness and competence—rather than the traditional 'ladder' or 'staircase' metaphor. This transition from a linear climb to a quadrant-based visualization is widely attributed to Chapman [12] who popularized the matrix format through the BusinessBalls platform.

In higher education, ITS have gained significant attention as institutions seek innovative solutions to improve student engagement, retention, and academic performance while addressing the diverse learning requirements of increasingly heterogeneous student populations [5,13].

Comparative studies between ITS and human tutoring challenge the common assumption that human tutoring is categorically superior. VanLehn [4] found that ITS can produce comparable learning gains and thus serve as a viable, cost-effective alternative—particularly in large, resource-constrained STEM courses. A recent scoping review of sixty-nine studies found that 59% of investigations reported improved academic performance, and 36% reported increased student engagement when using personalized adaptive learning systems [5].

Ma et al. [6] conducted a meta-analysis showing that ITS outperformed large-group, teacher-led instruction, and non-intelligent computer-based instruction.

However, ITS did not show statistically significant differences when compared with small groups or one-to-one human tutoring. Similarly, a meta-analysis by Kulik and Fletcher [14], based on fifty controlled evaluations, concluded that ITS can be highly effective in improving learning outcomes in higher education contexts.

However, in the context of Bloom's [15] "2-sigma problem": one-on-one human tutoring is the pedagogical benchmark, producing learning gains two standard deviations above conventional classroom teaching, but it is prohibitively expensive and unscalable. The core argument for ITS is that it represents a

technologically feasible and cost-effective solution for a large, multi-campus university where individual tutoring is impractical.

This study utilizes Area9 Rhapsode, an ITS developed by Area9 Lyceum. While preliminary data from twenty higher education institutions suggest significant improvements in student retention, competence development, and exam performance [16] empirical evidence within the European landscape—and specifically the German higher education system—remains limited. To date, peer-reviewed research validating the system's pedagogical efficacy across diverse academic settings is scarce. To address this gap, this study was conducted at the iba | University of Cooperative Education in 2024.

Research Objectives

This study investigates whether ITS can significantly improve mathematics readiness among first-semester students at iba | University of Cooperative Education compared to conventional WBT.

RO 1: To evaluate whether ITS improves mathematics pass rates more effectively than WBT.

RO 2: To assess metacognitive development across instructional methods.

RO 3: To examine whether ITS supports weaker students more effectively.

Research Questions and Hypotheses

RQ 1: Do students using ITS achieve higher pass rates than WBT students?

RQ 2: Does ITS promote stronger metacognitive development?

RQ 3: Is ITS particularly effective for borderline or weaker students, particularly in reducing conscious incompetence?

Hypotheses:

H 1: ITS students will show significantly higher pass rates.

H 2: ITS enhances conscious competence more than WBT.

H 3: ITS is more effective in reducing conscious incompetence than WBT, particularly near the pass threshold.

Methodology

Participants

A total of *N* = 271 students from eight campuses participated in the study. In a cluster-randomized trial, instead of individuals, entire groups (cohorts within campuses) were assigned to the intervention. As randomization occurred at the campus and cohort levels, the sample was clustered to ensure comparable cohort sizes in each group. At a given campus (e.g., Cologne), one cohort was assigned to the ITS group and another to the WBT group. Additionally, the size of the cities in which the campuses were located was considered during group assignments. This accounts for potential variations in digital readiness, access to educational resources, and prior support structures, which often correlate with urban–rural differences in Germany. This stratified and regionally balanced design enhanced the internal validity of the study and allowed for meaningful comparisons across diverse institutional and geographical contexts.

ITS group (n = 133; 49%) – received instruction via an ITS with metacognitive feedback mechanism (Area9 Rhapsode).

WBT group (n = 138; 51%) – received a standardized, linear training module.

Table 1 Analysis Baseline Equivalence

Characteristic	ITS (n = 133)	WBT (n = 138)	TEST	*p*-Value
Gender	35.3% male 64.7% female	39.1% male 60.9% female	Chi-square ($\chi 2$)	$p = .52$
Age	$M = 19.91$ $SD = 1.85$	$M = 20.26$ $SD = 2.12$	*t*-Test	$p = .148$

Note. Created by the author.

The study was approved by the ethics board of the iba | University of Cooperative Education and all participants gave informed consent.

Intervention/Treatment

Students participated in a supervised in-class training session using either the ITS or WBT format. The intervention took place during a single 45-minute learning unit, with each group assigned to a separate lecture room. While short interventions are considered potentially transient in the literature and subject to 'fade-out' effects [17], this study did not aim to measure long-term gains. Instead, it focused on the ability to pass a targeted test on granular learning objectives in fraction and percentage calculation—skills identified by iba | University of Cooperative Education as critical stumbling blocks for academic success.

Within each room, students worked individually on their respective platforms, either ITS or WBT, under the supervision of a lecturer to ensure standardized learning conditions.

ITS group: Used Area9 Rhapsode, an adaptive, metacognitive learning platform that dynamically adjusted the content based on learners' knowledge, confidence, and misconceptions, providing a personalized learning experience.

WBT group: Used a purpose-built WBT standardized, linear online training module with identical content to the ITS, presented in a fixed, non-adaptive sequence.

Assessment

Both groups received identical supervised in-class assessments. The exam questions were extracted from the ITS and WBT modules. All groups and cohorts were given 15 minutes to complete the exam, which was administered via the same online platform for all participants.

The effectiveness of the two instructional formats was evaluated using a **multi-dimensional assessment approach**:

Final Exam Performance: Assessed at two threshold levels:

50% passing threshold (standard institutional threshold)

66% passing threshold (a more rigorous benchmark to assess deeper understanding)

Grade Distribution: Final grades were analyzed across standard achievement levels (e.g., very good, good, satisfactory) to explore performance variance between groups.

Statistical Analysis: Differences between the ITS and WBT groups were examined using **Chi-square tests** (for categorical variables such as pass rates and grade distributions) and **independent samples *t*-tests** (for continuous variables derived from the competence matrix). Statistical significance was set at $p < .05$.

Competence Matrix: In both groups (ITS and WBT), the assessment platform required students to provide a confidence judgment for each question answered. The options were: "I am sure I know it," "I think I know it," "I am unsure," and "I need help." These self-assessments were used to map students' metacognitive awareness and were subsequently scaled into a competence matrix, enabling the analysis of the relationship between perceived confidence and actual performance.

Findings

Pass Rates

At the conventional 50% cutoff, 244 out of 271 students (90.0%) would pass (M = .90, SD = .30), leaving only 27 failures. This highly skewed distribution produces pronounced ceiling effects and limited discrimination; the variance of the binary pass/fail indicator equals $p(1 - p)$, which is .09 at p = .90, whereas a cutoff yielding roughly two-thirds passing would increase variance to about .224. To ensure that "pass" reflects substantial mastery and to improve measurement discrimination and the stability of subsequent analyses, we therefore set the passing threshold to 66 out of 100 points (two-thirds of the maximum score). The threshold was defined prior to group comparisons.

Table 2 Pass Rate Comparison (ITS vs. WBT)

Passing threshold	ITS	WBT	Δ	Significance
50%	89.5%	90.6%	-1.1%	p = .761 (not significant)
66%	69.2%	56.5%	+12.7%	p = .031 (significant)

Note. Created by the author.

A 2 × 2 chi-square test indicated a significant association between course type and passing status, $\chi^2(1, n = 271) = 4.64$, p = .031 (Fisher's exact p = .033). Passing was more likely in the adaptive ITS condition (69.2%) than in the linear WBT condition (56.5%). The risk ratio for passing was RR = 1.22, 95% CI [1.02, 1.47]. In absolute terms, the risk difference was +12.65 percentage points (95% CI [1.25, 24.05]), corresponding to NNT = 7.90 (95% CI [4.16, 80.04]). Conversely, the odds of failing were lower in ITS than in WBT (OR = .58, 95% CI [.35, .95]).

Competence Matrix

The comparison of competence awareness between students using an ITS and those engaged in WBT reveals distinct patterns across four key categories:

Conscious Competence was higher among ITS students (M = 63.22%, SD = 18.34%) compared to WBT participants (M = 58.43%, SD = 17.26%), $t(269) = 2.23$, p = .027. This suggests that ITS-supported learners had a clearer understanding of what they knew and were able to perform.

Unconscious Competence, which indicates correct performance without metacognitive awareness, was slightly more pronounced in the WBT group (M = 7.84%, SD = 8.23%) than in the ITS group (M = 5.39%, SD = 6.42%), $t(269) = -2.73$; p = .007. This finding suggests that WBT learners occasionally performed correctly without corresponding metacognitive awareness.

Conscious Incompetence, or the awareness of lacking specific knowledge or skills, was lower in the ITS group (M = 8.77%, SD = 12.56%) than in the WBT group (M = 13.64%, SD = 13.21%), $t(269) = -3.108$; p = .002. This indicates that ITS may reduce the experience of known knowledge gaps, possibly through adaptive feedback mechanisms.

Unconscious Incompetence, reflecting a lack of knowledge and awareness of that lack, was slightly higher in ITS (*M* = 22.78%, *SD* = 11.99%) compared to WBT (*M* = 20.35%, *SD* = 9.94%), *t*(269) = 1.822; *p* = .07. While this category remains elevated in both groups, the data reveals a counter-intuitive finding.

Possible Cognitive Overconfidence Effect

The highly scaffolded and supportive nature of the adaptive ITS might create a generalized sense of confidence or fluency in students, and they may have overestimated their competence in some cases. Furthermore, students in the ITS group were continuously prompted to provide confidence ratings. The WBT platform did not include this feature; therefore, this group of students experienced confidence ratings for the first time and may have been more cautious. Therefore, the observed difference may not reflect a true difference in the students' underlying metacognitive states, but rather a difference in the experience with the platform.

And, as previously discussed, the effects of cognitive development may become more visible in the long term. Within the scope of this study, which focused on basic skills, the clear and immediate finding was that the intervention supported students in successfully passing the targeted assessment. While it is entirely plausible that a brief, 45-minute intervention is insufficient to reduce unconscious incompetence.

The table below presents the competence matrix findings with statistical analyses.

Table 3 Results Competence Matrix

	ITS		WBT		t-statistic (*df* = 269)	*p*-value
	Mean	*SD*	*Mean*	*SD*		
Conscious Competence	63.22%	18.34%	58.43%	17.26%	2.225	.027
Unconscious Competence	5.39%	6.42%	7.84%	8.23%	-2.732	.007
Conscious Incompetence	8.77%	12.31%	13.64%	13.21%	-3.108	.002
Unconscious Incompetence	22.78%	11.99%	20.35%	9.94%	1.822	.07

Note. Created by the author.

Overall, these results suggest that ITS contributes to higher levels of conscious competence while potentially reducing conscious incompetence. However, both systems show room for improvement in addressing unconscious incompetence, emphasizing the need for more effective metacognitive scaffolding.

Grade Distribution

A comparison of final grade distributions between ITS and WBT participants reveals notable differences in performance outcomes:

ITS students were more likely to achieve higher grades, with 12% receiving a very good and 35.3% a good rating. In contrast, only 6.5% of WBT students reached the very good level, and 23.9% received a good.

The WBT group showed a higher concentration in the mid-range, with 39.9% rated as satisfactory (compared to 27.8% in ITS) and higher percentages in the lower categories: sufficient (20.3% vs. 9.4%) and inadequate (14.3% vs. 10.5%).

A chi-square test of independence confirmed that these differences in grade distribution were statistically significant, $\chi^2(4, n = 271) = 9.60$, $p = .048$, $V = .19$, indicating that the type of learning environment (ITS vs. WBT) was associated with differences in academic outcomes.

These findings suggest that ITS environments may foster improved academic performance, particularly in promoting higher achievement levels. The distribution of grades is visualized below.

A chi-square test of independence confirmed that these differences in grade distribution were statistically significant, $\chi^2(4, n = 271) = 10.97$, $p = .027$, $V = .20$, indicating that the type of learning environment (ITS vs. WBT) was associated with differences in academic outcomes.

Discussion

Overview

The results provide preliminary empirical support for the proposed hypotheses and suggest that ITS may improve short-term mathematics performance and metacognitive indicators under controlled classroom conditions for first-year economics students.

H1: ITS significantly increased pass rates at a more rigorous 66% threshold.
Following the adjustment of the passing threshold from 50% to 66%, students in the ITS condition achieved a statistically significant higher pass rate than their WBT counterparts (69.2% vs. 56.5%). This finding corresponds with the meta-analytic results of Ma et al. [6] who reported a moderate to strong effect size for ITS compared to teacher-led large-group instruction (g = .42) and non-adaptive computer-based instruction (g = .57). The amplified benefit under stricter conditions suggests that ITS offer more robust instructional support when learners are required to demonstrate deeper understanding.

H2: ITS enhanced conscious competence and reduced conscious incompetence.
Statistically significant differences were observed between the two groups with respect to metacognitive measures. Students using ITS demonstrated higher levels of conscious competence and lower levels of conscious incompetence than those using WBT. These findings are consistent with the assertion that ITS can support metacognitive development by continuously modeling learner knowledge states and delivering individualized feedback loops [6]. Furthermore, the findings are aligned with the

theoretical framework of Hattie and Timperley [18], which identifies feedback specificity and timeliness as critical determinants of learning efficacy

The finding that unconscious incompetence was slightly higher in the ITS group may be best interpreted as a measurement artifact rather than a true decline in metacognitive ability. This difference stems from the distinct platform experiences between the two groups. The ITS platform continuously prompted users for confidence ratings, potentially conditioning them to respond differently or inducing a cognitive overconfidence effect. In contrast, the WBT group encountered this feature for the first time in the final assessment and may have been more cautious in their self-evaluation. Therefore, the observed variance reflects the influence of the platform's design rather than a true difference in the students' underlying metacognitive states.

H3: ITS particularly benefits borderline and weaker students, particularly near the pass threshold. Although extremely low-performing students remained a challenge for both instructional modes, ITS demonstrated clear advantages for borderline students, especially following the increase in exam difficulty. This outcome corroborates VanLehn [4] meta-review, which found that ITS, particularly those capable of fine-grained interaction and adaptive scaffolding, are well-suited to support learners with partial or unstable knowledge structures.

These findings also affirm the relevance of metacognitive theory in understanding the added value of ITS.

Veenman et al. [8] argue that effective learning hinges not only on content acquisition but also on students' capacity for metacognitive monitoring and regulation. The elevated levels of conscious competence and reduced unconscious overconfidence observed in this study suggest that ITS environments can facilitate such reflective capacities by helping students recognize the limits of their knowledge and calibrate their learning strategies accordingly.

In summary, this study extends the ITS literature by confirming prior meta-analytic findings in a higher education context, while also contributing new data on metacognitive effects. ITS, as exemplified by Area9 Rhapsode, demonstrates not only cognitive benefits in terms of test performance but also meaningful improvements in learners' self-awareness — a critical but often underreported dimension of academic success.

Limitations

While promising, the findings of this study should be interpreted with caution. The assessment design may have favored ITS-trained students due to its alignment with the system's feedback structure. In addition, the intervention consisted of a single 45-minute session, which may be insufficient to support sustained metacognitive development. Because some campuses included only one teaching group, observed effects may partially reflect unobserved campus-level characteristics. Finally, the limited

effects observed for very low-performing students suggest that ITS alone may be insufficient for this subgroup and should be complemented by targeted human tutoring.

Implications for Practice

The findings highlight several practical implications for higher education institutions facing increasing student heterogeneity and declining mathematical preparedness:

Adaptive ITS such as Area9 Rhapsode can be used as levelling tools in the first semester to address foundational mathematics gaps.

Granular ITS data enables educators to identify specific learning obstacles (e.g., fractions or percentages) and allocate classroom time more efficiently.

As ITS alone is insufficient for the weakest performers, a hybrid model is advised—combining adaptive systems for most students with targeted human tutoring for those with persistent deficits.

Future Research

Future research should investigate the long-term sustainability and transferability of learning gains produced by adaptive ITS, particularly with regard to formal assessments and complex problem-solving. Studies should further differentiate learner profiles to determine which students benefit most from adaptive systems and where blended or human support remains necessary. Comparative and large-scale evaluations are needed to assess the scalability and cost–effectiveness of hybrid intervention models in time-constrained higher education contexts.

Conclusion

This case study suggests that Area9 Rhapsode, as an adaptive ITS, was associated with higher mathematical performance and metacognitive competence in a dual-study university context. The strongest effects were observed at the more demanding 66% threshold, where differences between ITS and WBT became most pronounced. By addressing foundational knowledge gaps and providing granular, learner-specific insights, ITS suggests a promising and potentially scalable response to declining mathematical preparedness among incoming students. These findings add to the growing body of evidence supporting the use of adaptive tutoring systems in higher education and practice-oriented study programs.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval

This study adhered to institutional ethical guidelines and was approved by the ethics committee of iba | University of Cooperative Education.

Consent to Participate

Informed consent was obtained from all individual participants (*N*=271) included in the study. Participants were informed that their participation was voluntary and that their data would be anonymized for analysis.

Consent to Publish

The authors affirm that human research participants provided informed consent for the publication of the research findings in an anonymized and aggregated format.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the authors on reasonable request.

Authors' contributions

Prof. Youssef El Ouadoudi: Contributed to the study design, conducted the statistical analysis, interpreted the experimental data, and drafted the results section.

Dr. Guillermo Ribes Vicente: Contributed to the study design, performed the literature review, and drafted the theoretical background and discussion sections of the manuscript.

All authors read and approved the final manuscript.

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Figures

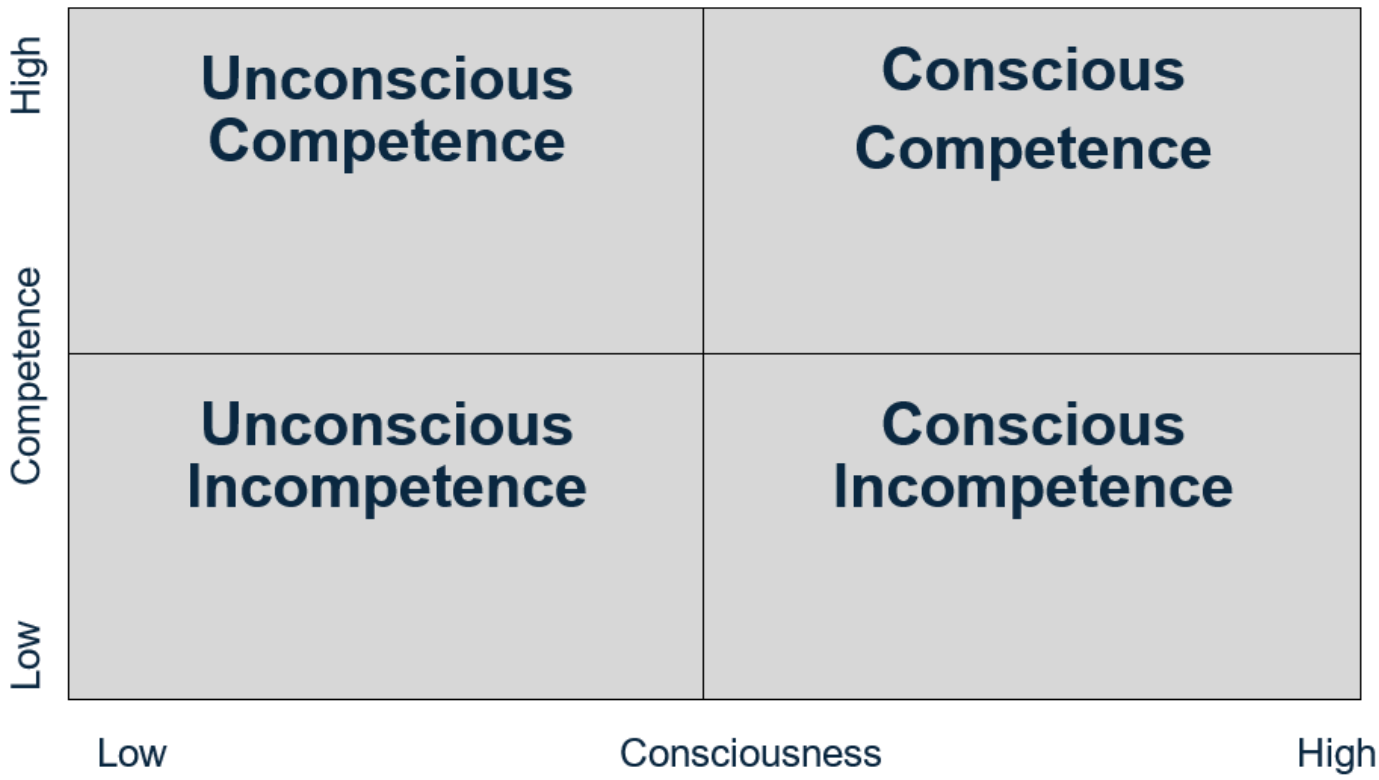


Figure 1

Competence Matrix

Note. Adapted from "Conscious competence learning model," by A. Chapman [12]

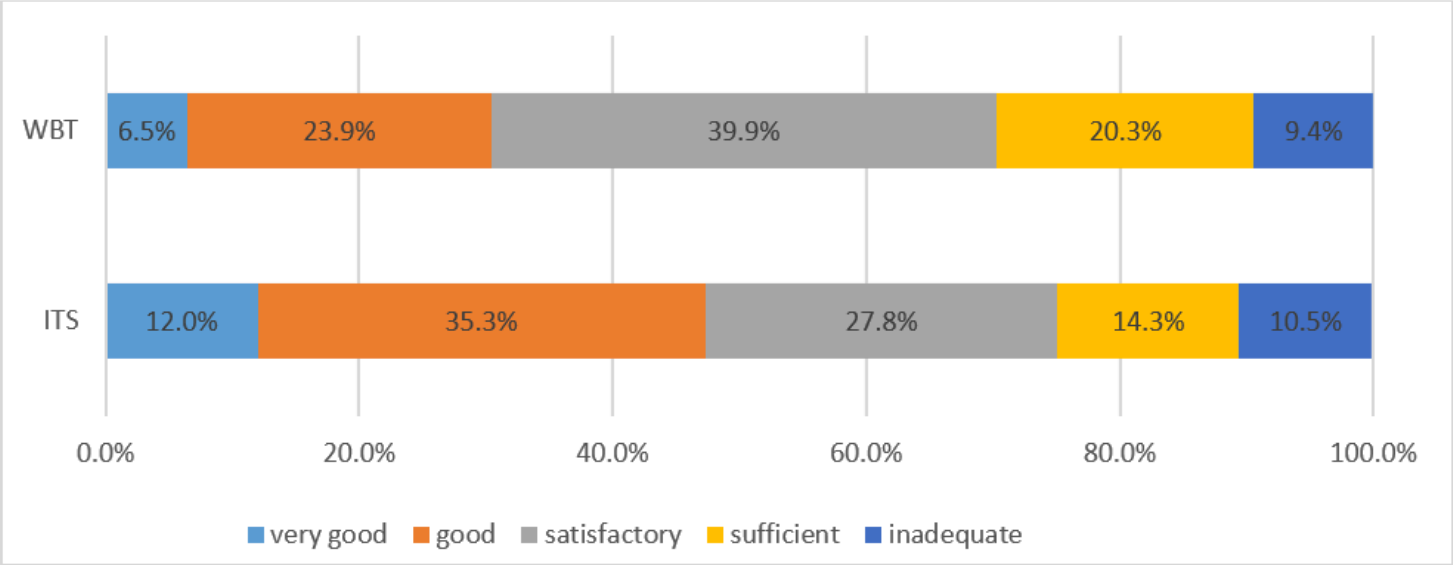


Figure 2

Grade Distribution Analysis 50%

Note. Created by the author.

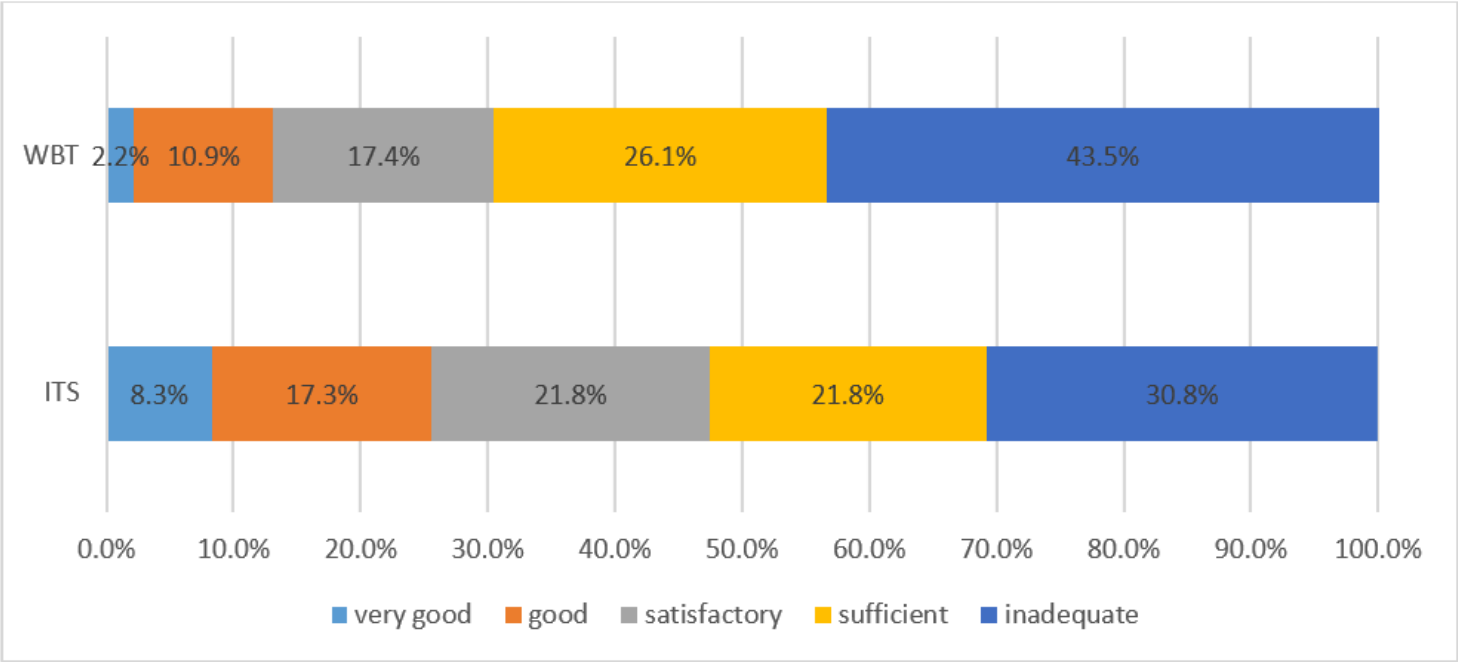


Figure 3

Grade Distribution Analysis 66%

Note. Created by the author.