Heliyon 9 (2023) e20894

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

The impact of national culture in the development of complexity reasoning skills: An international comparison

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A R T I C L E I N F O

Keywords:
Diversity gap
STEM
complex thinking
National culture
Higher education
Educational innovation

A B S T R A C T

There is a clear inequality in gender distribution for the STEM areas (Science, Technology, Engineering, and Mathematics). Furthermore, there is a noticeable lack of diversity and a socio-economic gap that requires actionable solutions. To explore potential factors that affect the participation of women in STEM, this paper reviews two possible groups of determinants: national culture and complexity thinking. A survey with 684 respondents from higher education institutions in Chile, Ecuador, Mexico, and Spain was undertaken. The instrument measured four components of complexity thinking namely critical, scientific, innovative, and systemic). Using analysis of variance between two groups and between multiple groups, differences were observed between the countries' samples and between genders. Once the significance was confirmed, boxplots for each dimension were elaborated to facilitate the visualization of the distributions. The scores were compared with the national culture values to seek possible behavioral patterns in the data. The results reveal two groups between the observed countries. Also, there are clear indications of a relationship between the national culture dimensions and the complex thinking components.

1. Introduction

The need for enhanced STEM (Science, Technology, Engineering, and Mathematics) education becomes apparent due to several factors: the profound shifts in technology, culture, and economics; rising disparities in socio-educational opportunities; a noticeable lack of diversity; and a persistent gender gap in academic and professional spheres. A robust foundation in STEM disciplines is crucial for addressing real-world challenges, promoting inquiry, fostering collaboration, nurturing creativity, encouraging thoughtful analysis, and cultivating complex, multidimensional, multiscale, and multitemporal thinking. These competencies are integral to advancing any society and aligning with contemporary demands and requirements [1–3].

With this goal in sight, a range of factors operating at individual, familial, institutional, and societal levels have the potential to impact the participation, progression, and success of girls and women in STEM education [4]. As a result, family dynamics, social networks, and educational institutions all have significant roles to play in fostering diversity and guaranteeing equitable access for females in STEM fields [5,6]. These initiatives are aimed at narrowing the diversity gap, which is frequently influenced by

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https://doi.org/10.1016/j.heliyon.2023.e20894
Received 6 March 2023; Received in revised form 25 September 2023; Accepted 10 October 2023
Available online 11 October 2023
2405-8440/

socio-cultural factors [7].

In this context, we highlight two crucial factors for enhancing the success of women in STEM fields: national culture and complex cognitive thinking. According to Hofstede [8], people's mental processes are influenced by three levels: universal, collective, and individual. Most individuals share the universal level, the collective level applies to specific groups, and the individual level shapes each person's unique personality. Thus, culture can be described as "the collective programming of the mind" [8, p. 13]. Hofstede [9] suggests that from early childhood, individuals acquire patterns of thought, emotions, and behavior, forming mental programming that evolves within their home, community, school, workplace, and surroundings. Studies like those conducted by Kelley and Sung [10] and Li et al. [11] demonstrate the way in which students can grow their complex thinking abilities and enhance their mathematical and scientific reasoning skills through STEM education.

It is from this point of view that our study attempts to examine gender-related variations in complex thinking within the STEM context in Ibero-America. We intend to propose measures that bridge gaps and promote diversity in STEM.

An earlier version of this study [12] was presented at the Technological Ecosystems for Enhancing Multiculturality Conference (TEEM 2022) and has since been revised, expanded, and submitted to the Heliyon Journal following an invitation from the guest editors of the Special Issue titled "Technological ecosystems for enhancing education processes" within the Heliyon Education section.

2. Theoretical background

In the realm of higher education, there's an increasing demand to integrate advanced thinking skills that effectively address the contemporary challenges of society. Complex thinking can be defined as a form of holistic thinking, necessitating a mastery of cognitive abilities that enhance scientific, critical, and innovative thought processes [13]. Some scholars highlight how elements such as stereotypes, mindsets, gender dynamics, and cultural influences underscore the importance of STEM education in contributing to academic and social development, subsequently impacting career choices [14–17]. Thus, the significance of introducing STEM education at an early stage and promoting complex thinking from childhood becomes apparent in fostering diverse cognitive and disciplinary pathways toward university careers.

2.1. Reasoning complexity

Given the anticipated Society's dynamics and uncertainties, the capacity for complex reasoning assumes a pivotal role within the framework of education 4.0. Students who acquire complex reasoning skills obtain a significant opportunity for the analysis, synthesis, and resolution of problems, thus effecting contextual transformations [13].

Building upon prior research, this study considers four dimensions of complex thinking, as elucidated below.

The first dimension pertains to systems thinking, which guides problem-solving by interpreting data from various scientific domains. It involves determining the significance of elements within a system through an analysis of the entire structure [18], along with the capacity to consider the systemic consequences of policies and actions [19]. Systems thinking aims to delineate the constituent parts of a whole, and its complexity emerges from the pursuit of the most comprehensive comprehension of a given situation.

Numerous countries have conducted studies exploring systems thinking within the context of complex thinking. For instance, in Saudi Arabia, a study involving 120 secondary school students aged 16 to 18 investigated the connection between systems thinking skills, epistemological beliefs, and mathematical beliefs. The findings revealed a positive correlation and notable gender-based differences. Specifically, males outperformed females in subscales related to systems thinking skills in holistic system perception and systemic synthesis, while females excelled in the subscale of systemic analysis [20]. In Colombia, research addressed the complex issue of high dropout rates in education, recognizing it as a multifaceted phenomenon inadequately aligned with students' realities and educational policies. A conceptual model grounded in systems thinking was employed, highlighting variables such as work and family commitments, students' financial circumstances, and the role of educators as recurrent factors among participants [21].

A systems-based approach serves as a valuable framework for scrutinizing the behavior of an entity by examining interrelationships. In contrast to the analytical approach, the systemic approach encompasses the entirety of elements within the system under investigation, including their interactions and interdependencies.

The next dimension revolves around scientific thinking, which advocates for the resolution of real-world problems and inquiries using objective, dependable, and credible methods, along with data analysis to determine accuracy. It encompasses a range of cognitive processes and reasoning strategies, including inductive and deductive reasoning, problem-solving, and the development and testing of hypotheses [22]. The scientific thinking method is a powerful weapon for observing, analyzing, and solving problems [23], where scientific understanding locates the need for external validity measurements [24]. Scientific thinking requires orderly, detailed, and analytical processes in any of its parts.

Studies of scientific thinking have been the subject of interest from various disciplines. In the field of teaching scientific thinking skills, classroom-based action research was conducted with teachers to measure the impact of retrieval practices on the teaching and learning of concepts, locating best practices for teaching basic skills [25]. In the field of medicine, a systematic and scientific methodology for the study of complex things is located in China, as the mode of thinking in modern medicine is gradually changing from analytical and reductive thinking to holistic and systematic thinking [26]. Scientific thinking promotes the generation of new knowledge, which provides opportunities for improving the quality of life and the possibility of responding to the challenges and needs of society.

The third facet pertains to critical thinking, which empowers individuals to assess the validity of their own and others' reasoning, allowing them to form judgments about a given situation or problem and recognize flawed arguments. Critical thinking entails a mentally disciplined approach that involves actively and adeptly conceptualizing, employing, scrutinizing, amalgamating, and/or appraising information derived from observation, personal experience, reflection, reasoning, or communication to serve as a compass for belief and action [27,28]. Critical thinking hinges on the capacity to scrutinize the coherence of reasoning and appraise logical consistency in both tangible and conceptual phenomena.

Research on critical thinking has been located in complex systems and high cognitive abilities. For example, the mediating role of metacognitive awareness in the relationship between self-regulation and critical thinking was realized, locating a significant interrelationship between them, where metacognitive awareness was located as a partial mediating variable between self-regulation and critical thinking [29]. A different research investigation examined how a research community perceives critical thinking, which is manifested as cognitive presence in the context of practical inquiry. This concept was put into practice using established coding methods. The findings of the study revealed that critical thinking is primarily viewed as a means to validate existing knowledge structures and as a problem-solving approach within the practical inquiry model [30]. Critical thinking promotes high capacities to seek new knowledge and to self-manage, in turn, one's own learning.

The fourth dimension is located in innovative thinking. The cultivation of innovative thinking relies on several key skills, including the capacity to understand the context (interpret), the capacity to generate new ideas (create), the ability to work collaboratively with others (collaborate), the ability to contemplate and represent what could be in the current situation (reflect), and the ability to assess and appraise (evaluate) [31]. Innovative thinking supports problem-solving and the creation of solutions to complex problems and phenomena [32]. Innovative thinking promotes generating ideas and solutions, especially in complex situations where new methods must be integrated to address problems or procedures.

Innovative thinking is a driving force in social, technological, and economic development. A study was conducted to identify whether innovative thinking in managers influences the competitiveness of small and medium enterprises (SMEs) in the industrial sector in Colombia, and a model for developing innovative thinking in leaders was promoted [33]. Conversely, in China, an examination was carried out to assess the effectiveness of educational technology training in contemporary universities using big data. They introduced a fuzzy evaluation method that relies on various factors to assess the comprehensive university education system, which operates at multiple levels. This endeavor was prompted by the acknowledgment that global economic shifts and the influence of technological advancements have heightened the importance of fostering industry-education collaboration for the purposes of innovation and entrepreneurship [34]. Innovative thinking promotes development through new services, solutions, products, or processes and, in the realm of complexity, requires locating new ways to address changing problems and situations.

2.2. National culture

Undoubtedly, one of the most universally recognized works on culture, especially concerning National Culture, is that of Geert Hofstede [8], which involved obtaining data in 50 countries with a rigorous research design and which sought to find out if there were differences in the culture of the workers of the countries studied, that influence their work behavior in a significant way. Their results have been so relevant that many researchers have taken up their concepts and measures.

From birth, people learn symbols, heroes, rituals, and values, which vary contextually for any individual or group of individuals. This learning is continuous and constitutes culture, shaping values that affect people's behavior [35].

Hofstede's theory posits that individuals' mental programming occurs on three distinct levels: universal, collective, and individual. Most people share the universal level; the collective is characteristic of specific groups, and the individual level shapes each person's unique personality. Consequently, culture can be defined as "the collective programming of the mind" [8, p. 13]. Hofstede's perspective suggests that individuals acquire patterns of thought, emotions, and behaviors from an early age, forming a mental program that

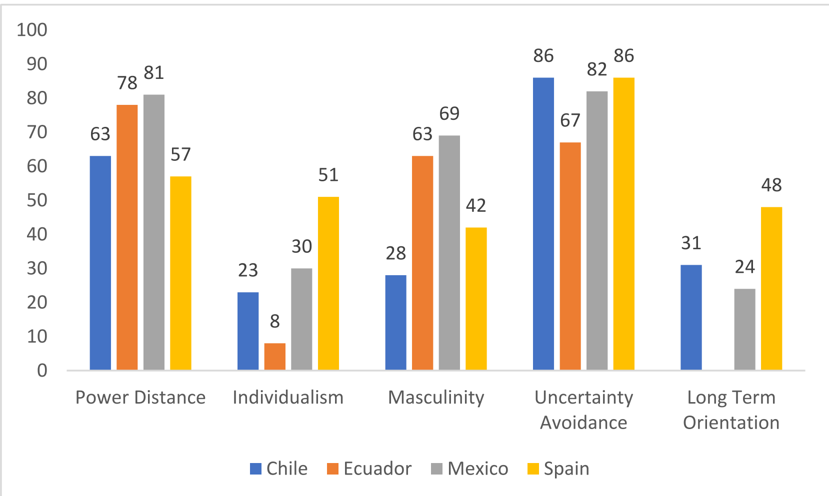

Fig. 1. Scores of the national culture dimensions by country (Hofstede Insights, 2023: https://www.hofstede-insights.com/).

evolves within various settings such as their home, neighborhood, school, workplace, and community.

Hofstede [35] introduced four cultural dimensions at the national level. The first one is Uncertainty Avoidance (UA). It measures the comfort level in situations with incomplete information, with indicators like job stability, rule orientation, and stress. Cultures with low UA tend to have less workplace stress, fewer formal rules, and a more conducive environment for generating and appreciating innovation in both products and processes. Next, Power Distance (PD) reflects a cultural group's approach to power and authority. High PD cultures exhibit a tendency for employees to defer to their superiors without questioning their decisions, and authority figures, including teachers, are highly respected. A third dimension, Masculinity-Femininity (MF), relates to the degree to which a society values traditionally masculine traits such as competitiveness and assertiveness versus feminine qualities like empathy and nurturing. High-masculinity cultures prioritize career success and competitive achievements, while feminine cultures emphasize collaboration and nurturing, with attention to less fortunate individuals. Finally, Individualism-Collectivism (IC) characterizes the extent of individuality within a culture. High IC cultures are more individualistic, with individuals prioritizing their own interests over group interests. Conversely, low IC cultures tend to foster cohesiveness, with individuals valuing the interests of the group over their own.

In later studies, Hofstede introduced a fifth dimension called Confucian Dynamism, which is particularly relevant to Southeast Asian cultures and pertains to their long-term orientation and values. More recently, a dimension called Indulgence was added, referring to the extent to which a society allows free gratification of basic human needs.

While regions may exhibit some consistency in these dimensions among member countries, there can be exceptions. This study focuses on the analysis of three Latin American countries and one European nation. Fig. 1 presents the values of these countries' national-culture dimensions.

The graph in Fig. 1 clearly indicates that the dimension with the most substantial variation among the countries is individualism, followed closely by masculinity. Furthermore, the disparities between Ecuador and Spain are notably pronounced. It's worth noting that the long-term orientation dimension will not be factored into this study due to the absence of measures for Ecuador.

In 1991, the GLOBE project was introduced, which stands for Global Leadership and Organizational Behavior Effectiveness [36]. This project significantly enriched Hofstede's research for several compelling reasons. Firstly, it represented a more recent study capable of capturing contemporary shifts in cultural trends. Secondly, it was more comprehensive and intricate in scope. Lastly, it introduced distinct metrics that expanded upon the achievements of earlier studies. The GLOBE project encompassed 62 different world cultures, involved 170 researchers, and engaged 17,300 middle managers within 951 organizations. This extensive effort allowed for the testing of 27 hypotheses. The outcomes facilitated the categorization of cultures into 10 groups and the identification of 9 distinct cultural dimensions. It is possible to see that many of them emanate as ramifications of those raised by Hofstede and that it is possible to justify their separation. Additionally, the GLOBE project captured not only the current state of culture but also the state desired by its members, giving an extremely interesting twist to Hofstede's work.

3. Methodology

Ethical approval

Privacy issues related to the collection, curation, and publication of student data were validated with Tecnologico de Monterrey's Data Owners and the Data Security and Information Management Departments. Data collection followed an informed consent protocol to address ethical factors in the research presentation of the objectives, questions, process, and data collection through online surveys. Provided that this study was not experimental, the physical and emotional well-being of the participants was never at risk.

An online survey instrument was administered to a total of 684 university students hailing from four distinct countries: Chile, Ecuador, Mexico, and Spain. It is pertinent to note that the participating universities in Latin America were private, while those in Spain were public institutions. The students encompassed a variety of academic disciplines, including both STEM and non-STEM fields. The instrument employed, known as the eComplexity instrument, had been methodically validated through theoretical, statistical, and expert assessment [37,38]. The primary objective of this instrument was to gauge students' perceptions of their complex thinking competencies, specifically in terms of critical, scientific, innovative, and systemic thinking, using a set of 25 items. The instrument aimed to assess the various dimensions that constitute complex thinking. To analyze differences among the countries and explore potential connections with cultural dimensions, a multiple analysis of variance was conducted.

The survey responses were drawn from a convenience sample comprising participants from Chile (61 individuals, including 46 males and 15 females), Ecuador (141 individuals, including 90 males and 51 females), Mexico (350 individuals, including 176 males, 171 females, and 3 without specified gender), and Spain (132 individuals, including 101 males, 30 females, and 1 without specified gender). The data was processed using IBM-SPSS version 27.

To assess the suitability of using parametric or nonparametric tests for each dimension, a homogeneity of variance test was applied. Depending on the outcomes for each dimension, either a least-squares determination (LSD) or a Tamhane post-hoc analysis was employed to evaluate mean differences. Furthermore, straightforward boxplots were generated to visually inspect the data distribution for each dimension.4. Results.

This section is organized in three subsections: First, the analysis of variance of the overall results presents differences by country of the four components of complex thinking. Then another subsection illustrated the distributions with boxplots. Finally, another subsection is dedicated to gender differences.

3.1. Analysis of variance (ANOVA) of the complex thinking components by country

The aggregated homogeneity test results reveal that significance is observed only in the case of the scientific thinking component, indicating that the homogeneity condition is not met, necessitating the use of the Tamhane test. For all other dimensions, the least-squares determination test was deemed appropriate. Interestingly, the results yielded by both methods were identical for the scientific thinking component.

Table 1 summarizes the outcomes of the tests for homogeneity of variances.

In conducting multiple comparisons, a clear distinction emerges, grouping the first three dimensions into two categories: Spain and Chile exhibit no significant differences from each other, while a similar pattern is observed between Mexico and Ecuador. However, the variation between these two groups is notably more pronounced. Notably, the behavior concerning the fourth dimension, systemic thinking, differs substantially. Both Chile and Spain exhibit significant differences from every other country, including each other.

The overall ANOVA test demonstrates a significant difference between groups across all dimensions, as depicted in Table 2.

3.2. Boxplots of the components of complex thinking by country

Figs. 2–5 present graphical representations of the means using simple boxplots categorized by dimension. A visual inspection of these boxplots reveals that both Chile and Spain exhibit lower means compared to Ecuador and Mexico. Interestingly, Spain consistently has the lowest mean across all dimensions except for innovative thinking.

Additionally, it is apparent that Chile and Ecuador display a broader distribution, indicating greater variance, specifically in the scientific and innovative thinking dimensions. Notably, Chile exhibits a lower outlier frequency in all cases.

In the case of Spain, it's observable that approximately 50 % of the sample values are distributed very closely around the mean, suggesting a relatively tight clustering of data points.

It can be observed in Fig. 2 that Ecuador and Mexico have higher values than Chile and Spain. Even though Ecuador and Mexico have similar starting points, Mexico has many outliers at the bottom. All distributions seem somewhat skewed, but the case of Spain is in the opposite direction of the others. Ecuador and Chile seem to have wider distributions than Mexico and Spain (not considering the outliers).

It is observed in Fig. 3 that the behavior of the boxplots is quite similar to that of the scientific thinking dimension. The differences are mainly two: On the one hand, Ecuador shows a narrower distribution for the bulk of the data and a great number of outliers at the bottom. On the other hand, Mexico has a greater maximum value than Ecuador this time. The behavior for Spain is almost identical for both dimensions.

Once again, the distributions look very similar to the ones corresponding to scientific and critical thinking. This time, however, they all show outliers, particularly Spain, while the main shaded area seems to shrink a bit more.

For the last plot, the same pattern remains, clearly distinguishing how Ecuador and Mexico have higher mean values than Chile and Spain. The distribution for Spain has compacted even further compared to the previous charts.

3.3. Gender differences

When comparing the means between male and female students, a notable difference was observed, with female students consistently exhibiting significantly lower values than their male counterparts. However, a deeper exploration was done, breaking down these gender differences by country and dimension. The results are shown in Table 3. Non-significant results have been highlighted in bold font.

From Table 3 it can be observed that the group behavior is still happening to a certain extent. Ecuador and Mexico have significant

Table 1
Results of homogeneity of variances tests.

		Levene statistic	df1	df2	Sig.
Scientific	Based on mean	4.273	3	680	0.005
	Based on median	3.595	3	680	0.013
	Based on median and with adjusted df	3.595	3	656.384	0.013
	Based on trimmed mean	4.097	3	680	0.007
Critical	Based on median	0.479	3	680	0.697
	Based on median and with adjusted df	0.467	3	658.560	0.705
	Based on trimmed mean	0.467	3	680	0.705
	Based on trimmed mean	0.496	3	680	0.685
Innovative	Based on mean	1.650	3	680	0.177
	Based on median	1.571	3	680	0.195
	Based on median and with adjusted df	1.571	3	657.023	0.195
	Based on trimmed mean	1.358	3	680	0.255
Systemic	Based on mean	1.338	3	680	0.261
	Based on median	1.238	3	680	0.295
	Based on median and with adjusted df	1.238	3	670.821	0.295
	Based on trimmed mean	1.403	3	680	0.241

Table 2
Overall analysis of variance for each dimension.

		Sum of squares	df	Mean square	F	Sig.
Scientific	Between groups	33.272	3	11.091	25.136	0.000
	Within groups	300.039	680	0.441		
	Total	333.311	683			
Critical	Between groups	21.223	3	7.074	23.795	0.000
	Within groups	202.169	680	0.297		
	Total	223.393	683			
Innovative	Between groups	18.320	3	6.107	15.644	0.000
	Within groups	265.44	680	0.39		
	Total	283.761	683			
Systemic	Between groups	23.475	3	7.825	31.084	0.000
	Within groups	171.177	680	0.252		
	Total	194.652	683			

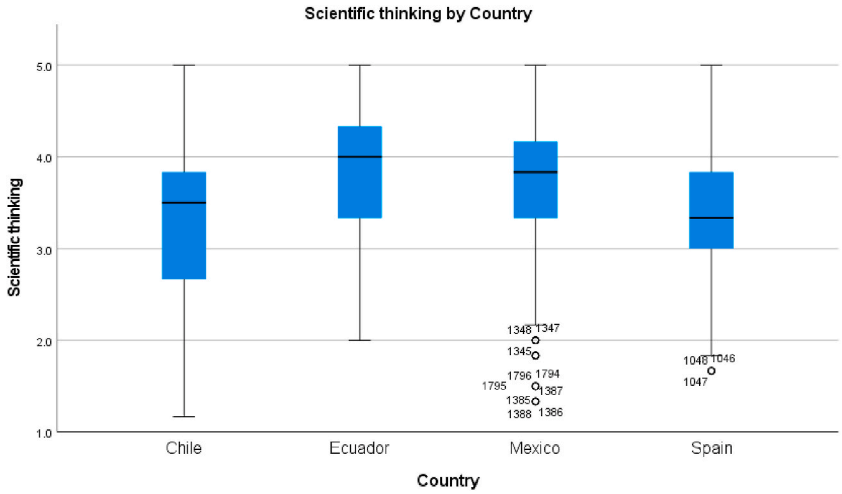

Fig. 2. Boxplot of scientific thinking by country.

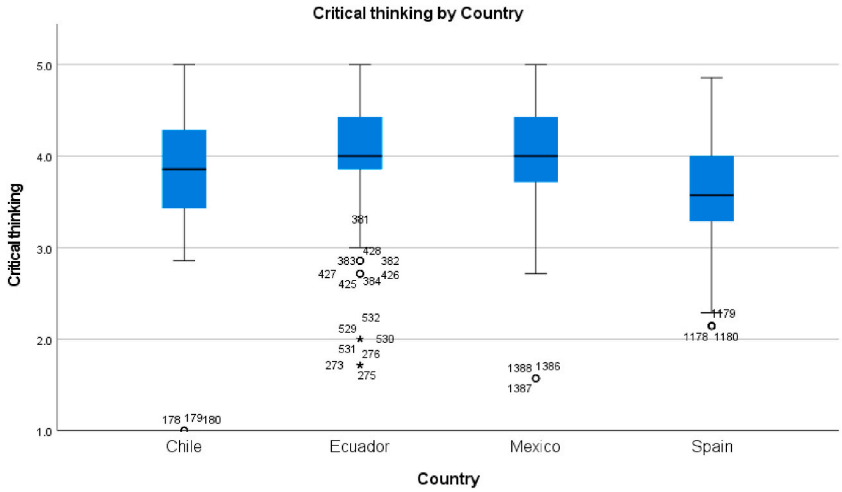

Fig. 3. Boxplot of critical thinking by country.

gender differences in scientific and innovative thinking but not in systemic and critical thinking. Interestingly, the differences in means are negative in the case of Mexico, indicating that women have higher scores in all dimensions than men. This is the only country where that happens. Spain and Chile coincide in significant differences in systemic thinking and not significant in scientific, clearly

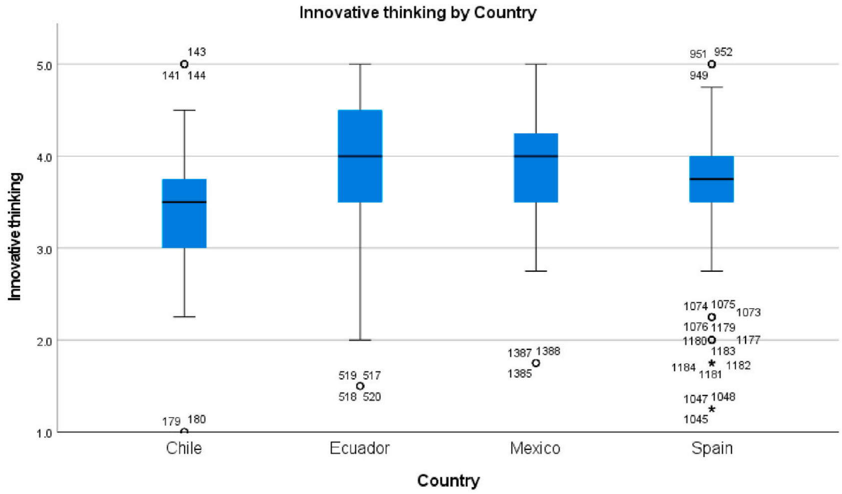

Fig. 4. Boxplot of innovative thinking by country.

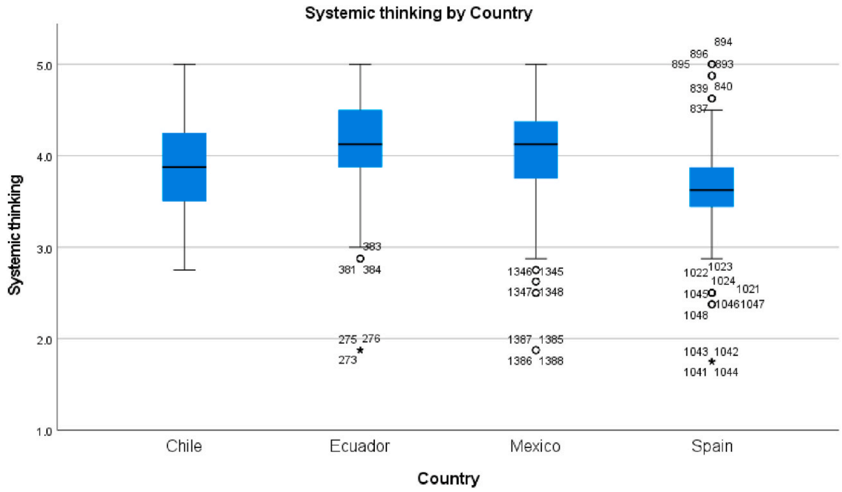

Fig. 5. Boxplot of systemic thinking by country.

contradicting the other group's results. Nonetheless, there are no more coincidences between those two countries. In the Spanish sample, critical and innovative thinking have no significant differences based on gender, contrary to what happens in Chile, where those differences seem to be strongly supported.

The overall scores for all the components of complex thinking by country and gender are presented in Fig. 6.

4. Discussion

The cultivation of reasoning abilities for handling complexity, encompassing various types of thinking such as critical, innovative, scientific, and systemic, unveils notable disparities in diverse cultural settings. Fig. 1 illustrates differences in scores among two sets of countries: Chile and Spain, on the one hand, exhibit lower averages in general, and Ecuador and Mexico, on the other, whose scores are higher. It's noteworthy that Spain consistently records the lowest scores across all dimensions except for innovative thinking. Scholars such as [13] emphasize complex thinking as a form of integrative thinking involving advanced cognitive skills. Likewise [15–17] underscore the significance of cultural influences in education, contributing to both academic and social development. In the context of the cultural dimension of power distance, there appears to be a conspicuous and direct correlation with all facets of complex thinking.

From a cultural dimension perspective, it becomes imperative to design educational programs centered around complex reasoning. Differences in uncertainty avoidance display an inverse relationship, and participants from various countries tend to score lower on power distance and individualism. However, their connection with complex thinking dimensions is less prominent and exhibits less negative correlation [8,9]. emphasize that individuals' minds are shaped by three distinct levels: universal, collective, and individual, wherein culture is defined as the acquisition of patterns of thinking, emotions, and behavior that develop within diverse contexts such

Table 3
Gender differences by country and dimension.

Country	Sex		Sistemic	Scientific	Critical	Innovative
Chile	Female	Mean	3.782609	3.23188406	3.673913	3.336957
		N	46	46	46	46
		Std. Deviation	0.4491	0.78132387	0.587599	0.630735
	Male	Mean	4.241667	3.53333333	4.12381	3.916667
		N	15	15	15	15
		Std. Deviation	0.468819	0.83855507	0.536881	0.698638
	Difference		0.459058	0.30144928	0.449896	0.57971
	p-value		0.001	**0.204**	0.01	0.004
	test		LSD	LSD	LSD	LSD
Ecuador	Female	Mean	4.0806	3.7389	3.9952	3.853
		N	90	90	90	90
		Std. Deviation	0.58219	0.77171	0.64617	0.7734
	Male	Mean	4.2623	4.085	4.1793	4.162
		N	51	51	51	51
		Std. Deviation	0.42371	0.57963	0.457	0.5334
	Difference		0.1817	0.3461	0.1841	0.309
	p-value		**0.102**	0.009	**0.074**	0.018
	test		Tahmane	Tahmane	LSD	Tahmane
Mexico	Female	Mean	4.113636	3.88068182	4.084416	4.011364
		N	176	176	176	176
		Std. Deviation	0.541538	0.62510894	0.569645	0.582984
	Male	Mean	4.080409	3.69493177	4.001671	3.888889
		N	171	171	171	171
		Std. Deviation	0.454677	0.62466748	0.461739	0.561059
	Difference		−0.03323	−0.18575	−0.08274	−0.12247
	p-value		**0.052**	0.006	**0.145**	0.012
	test		LSD	LSD	Tamhane	LSD
Spain	Female	Mean	3.607673	3.28547855	3.585573	3.636139
		N	101	101	101	101
		Std. Deviation	0.468718	0.58182502	0.524698	0.64858
	Male	Mean	3.8	3.52777778	3.752381	3.8
		N	30	30	30	30
		Std. Deviation	0.431267	0.66822137	0.512934	0.518619
	Difference		0.192327	0.24229923	0.166808	0.163861
	p-value		0.048	**0.055**	**0.13**	**0.208**
	test		LSD	LSD	LSD	LSD

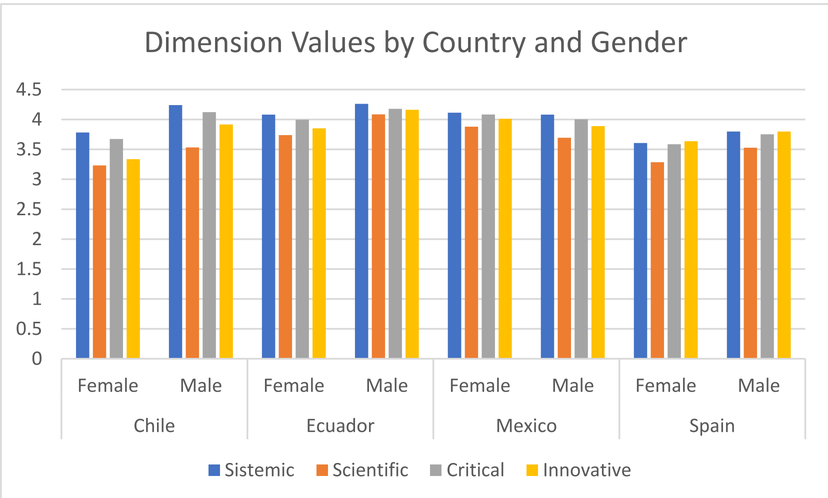

Fig. 6. Values of complex thinking components by country and gender.

as home, community, school, work, and society. Integrating various cultural dimensions into complex reasoning training necessitates a deliberate effort within the curricula of educational programs.

Regarding power distance, a clear and direct association with all complex thinking components emerges. Ecuador and Mexico consistently achieve higher scores compared to Chile and Spain, which may seem counterintuitive, especially considering the higher education levels in the latter set and the consistency that exists across universities. Nonetheless, these countries exhibit lower scores in the power distance dimension. One plausible interpretation is that acknowledging hierarchies and structures as intrinsic may offer a framework for handling complexity. In terms of masculinity, a parallel pattern is evident, with Chile scoring the lowest. This implies that the competitive nature of this dimension may encourage more comprehensive evaluation and discourage simplistic solutions. However, individualism appears to demonstrate a less evident and less negative connection with complex thinking dimensions. High levels of individualism might potentially impede complex thinking, particularly in its systemic dimension, which demands a holistic outlook. Uncertainty avoidance also showcases a negative relationship, albeit less pronounced, possibly because complex thinking precisely serves as a means to navigate uncertainty.

As for gender comparisons, the country with the most dimensions being significantly different between sexes is Chile, and the one with the least is Spain. These two countries showed a similar behavior in all cultural dimensions except individualism. Chile is the least individualistic of all, and Spain has the highest score. In the Chilean case, three out of four components of complex thinking are significant. The one exception is scientific thinking. In the case of Spain, three out of four components are not significant. The exception, however, is barely so. It is significant at the $p < 0.05$ level, but not so considering $p < 0.01$. In fact, the value is 0.048. Thus, it is easy to believe that the trend is not to have any differences at all. It is unclear how the individualism dimension can affect gender differences. A possible explanation is that the lack of teamwork does not allow for a discrimination structure. Every individual is evaluated based on their own merits without competing with the interests of the larger group. That way, men and women are performing on an even floor.

Additionally, systemic thinking differences are significant in Chile, exhibiting a higher level of uncertainty avoidance and a lower level of masculinity and power distance. This is counterintuitive compared to Ref. [20], wherein a highly masculine and hierarchical country like Saudi Arabia, systemic thinking is higher in males than females, deserving further exploration.

It was surprising that both Ecuador and Mexico had significant differences in scientific and innovative thinking but in opposite directions. The case of Mexico shows higher scores for females in all components of complex thinking. Even when these differences are small, they are significant in the two categories previously mentioned. There must be contextual factors that impact this result that are not controlled in this study, making that observation inconclusive and worth exploring in future research.

5. Conclusions and limitations

It appears that cultural distinctions have the potential, to some degree, to outweigh the beneficial impacts of specific institutional endeavors aimed at achieving high-quality and standardized higher education for the entire population.

The fact that Chile and Spain have lower scores is counterintuitive, considering the quality of the educational systems. Yet, this behavior seems to be correlated with the values of their national culture dimensions. One might anticipate that these initiatives would contribute to narrowing the digital and educational divide. However, the unexpected findings observed in the cases of Spain and Chile, as well as among female students, emphasize the necessity of implementing targeted measures to mitigate the adverse effects of certain cultural idiosyncrasies.

There are clear patterns that show that gender differences occur based on cultural coincidences between countries. The similarities between the previously defined groups are present to a great extent. While it's not possible to draw definitive conclusions at this stage, and the cultural aspect warrants additional investigation, it is crucial, even at this preliminary phase, to develop educational environments that take into account the unique characteristics of various student groups. This study constitutes a solid first step in identifying the relationship of Hofstede's cultural dimensions with the development of complex thinking components as a driver of success in the STEM disciplines. It is clear that some patterns were found. Nonetheless, further exploration is needed, as well as triangulation of methods to corroborate these results quantitatively.

A notable constraint in this research is the uneven distribution of participants across countries, with varying numbers, although the overall sample size remains substantial. Additionally, there is a possibility that results may vary greatly from private to public universities. Since this was a convenience sample, there may be confounding effects that require further control and exploration. Another limitation is the selection of countries, given that the generalizability of the findings is restricted. The selected Latin American countries can be considered to have medium to high leadership in the region. Other circumstances showing less development are not included and would be worth reviewing.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Guillermo Rodríguez-Abitia: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **María Soledad Ramírez-Montoya:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Sandra Martínez-Pérez:** Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Edgar Omar López-Caudana:** Data curation, Funding acquisition, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank the financial support from Tecnologico de Monterrey through the "Challenge-Based Research Funding Program 2022". Project ID #I005 - IFE001 - C2-T3 - T. Also, the technical support of Writing Lab, Institute for the Future of Education, Tecnologico de Monterrey, Mexico, in the production of this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e20894.

References

[1] S. Tobón, A.C. Núñez, La gestión del conocimiento desde el pensamiento complejo: un compromiso ético con el desarrollo humano, Rev. EAN (Esc. Adm. Negocios) 58 (2006) 27–39.
[2] UNESCO, Descifrar el código: la educación de las niñas y las mujeres en ciencias, tecnología, ingeniería y matemáticas (STEM), UNESCO, París, 2019.
[3] I.M. Greca, J. Ortiz-Revilla, I. Arriassecq, Diseño y evaluación de una secuencia de enseñanza-aprendizaje STEAM para Educación Primaria, Rev. Eureka sobre Enseñanza Divulg. Ciencias 18 (1) (2021) 1802.
[4] M.T. Wang, J.L. Degol, Gender gap in science, technology, engineering, and mathematics (STEM): current knowledge, implications for practice, policy, and future directions, Educ. Psychol. Rev. 29 (1) (2017) 119–140, https://doi.org/10.1007/s10648-015-9355-x.
[5] A. García-Holgado, S. Verdugo-Castro, C. González, M.C. Sánchez-Gómez, F.J. García-Peñalvo, European proposals to work in the gender gap in STEM: a systematic analysis, IEEE Revista Iberoamericana de Tecnologías del Aprendizaje 15 (3) (2020) 215–224.
[6] D. Fonseca, A. García-Holgado, F.J. García-Peñalvo, E. Jurado, R. Olivella, D. Amo, G. Maffeo, O. Yigit, Y. Keskin, G. Sevinç, K. Quass, C. Hofmann, Towards the improvement of diversity gaps through the compilation of projects, best practices and STEAM spaces, in: M.L. Sein-Echaluce Lacleta, A. Fidalgo-Blanco, F. J. García-Peñalvo (Eds.), Innovaciones docentes en tiempos de pandemia. Actas del VI Congreso Internacional sobre Aprendizaje, Innovación y Cooperación, CINAIC 2021 (20-22 de Octubre de 2021), Servicio de Publicaciones Universidad de Zaragoza, España, 2021, pp. 38–43, https://doi.org/10.26754/CINAIC.2021.0007.
[7] J. Sulik, B. Bahrami, O. Deroy, The diversity gap: when diversity matters for knowledge, Perspect. Psychol. Sci. 17 (3) (2022) 752–767, https://doi.org/10.1177/17456916211006070.
[8] G. Hofstede, Culture's Consequences: International Differences in Work-Related Values, SAGE Publications, Beverly Hills, USA, 1984.
[9] G. Hofstede, Cultures and Organizations: Software of the Mind, McGraw-Hill Book Company, London, UK, 1991.
[10] T.R. Kelley, E. Sung, Examining elementary school students' transfer of learning through engineering design using think-aloud protocol analysis, J. Technol. Educ. 28 (2) (2017) 83–108.
[11] Y. Li, A.H. Schoenfeld, A.A. diSessa, A.C. Graesser, L.C. Benson, L.D. English, R.A. Duschl, Design and design thinking in STEM education, Journal for STEM Education Research 2 (2019) 93–104, https://doi.org/10.1007/s41979-019-00020-z.
[12] G. Rodríguez-Abitia, M.S. Ramírez-Montoya, S. Martínez-Pérez, E.O. López-Caudana, Cultural differences in complexity reasoning in higher education, in: F. J. García-Peñalvo, A. García-Holgado (Eds.), Proceedings TEEM 2022: Tenth International Conference on Technological Ecosystems for Enhancing Multiculturality. TEEM 2022. Lecture Notes in Educational Technology, Springer, Singapore, 2023, https://doi.org/10.1007/978-981-99-0942-1_45.
[13] M.S. Ramírez-Montoya, I.M. Castillo-Martínez, J. Sanabria-Z, J. Miranda, Complex thinking in the framework of education 4.0 and open innovation—a systematic literature review, Journal of Open Innovation: Technology, Market, and Complexity 8 (1) (2022) 4, https://doi.org/10.3390/joitmc8010004.
[14] S. McCoy, E. Loiacono, G. Rodríguez-Abitia, Diferencias Culturales en la Evaluación de Sitios Web: comparación entre Usuarios Estadounidenses y Mexicanos, Rev. Latinoam. Caribe Asociacio′n Sist. Informacio′n 6 (1) (2013), https://doi.org/10.17705/1relc.00027.
[15] O.B. Savinskaya, Gender equality in preschool STEM programs as a factor determining Russia's successful technological development, Russ. Educ. Soc. 59 (4) (2017) 206–216, https://doi.org/10.1080/10609393.2017.1399758.
[16] A. Reinking, B. Martin, The gender gap in STEM Fields: theories, movements, and ideas to engage girls in STEM, J. N. Approaches Educ. Res. 7 (2) (2018) 148–153, https://doi.org/10.7821/naer.2018.7.271.
[17] L. Archer, J. Moote, E. MacLeod, B. Francis, J. DeWitt, ASPIRES 2: Young People's Science and Career Aspirations, Age 10-19, UCL Institute of Education, London, UK, 2020, https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2021.v18.i1.1802.
[18] A.M. Jaaron, C.J. Backhouse, Operationalisation of service innovation: a systems thinking approach, Serv. Ind. J. 38 (9–10) (2018) 561–583, https://doi.org/10.1080/02642069.2017.1411480.
[19] K. Barquet, L. Järnberg, I.L. Alva, N. Weitz, Exploring mechanisms for systemic thinking in decision-making through three country applications of SDG synergies, Sustain. Sci. 17 (4) (2022) 1557–1572, https://doi.org/10.1007/s11625-021-01045-3.
[20] E.A. Khaled, Systemic thinking skills: relationship to epistemological beliefs and mathematical beliefs, Eur. J. Educ. Res. 11 (3) (2022) 1887–1896, https://doi.org/10.12973/eu-jer.11.3.1887.
[21] A. Guzmán Rincón, S. Barragán Moreno, F. Cala-Vitery, N. Segovia-García, Dropout in rural higher education: analysis of causes from systemic thinking, [Deserción en la Educación Superior Rural: Análisis de Causas desde el Pensamiento Sistémico] Qualitative Research in Education 11 (2) (2022) 118–150, https://doi.org/10.17583/qre.10048.
[22] S.A. Suryansyah, W. Kastolani, L. Somantri, Scientific thinking skills in solving global warming problems, IOP Conf. Ser. Earth Environ. Sci. 683 (2021), 012025.

[23] Y. Geng, Y. Shi, Y. Liu, Y. Cui, D. Liu, Y. Sun, Y. Zhu, Guiding the transportation development in Xiong'an new area by scientific thinking methods, Paper presented at the Conference Proceedings of the 10th International Symposium on Project Management, China, ISPM 2022 (2022) 1249–1255, https://doi.org/10.52202/065147-0169.

[24] G. Rosenzweig, Scientific thinking about legal truth, Front. Psychol. 13 (2022), https://doi.org/10.3389/fpsyg.2022.918282.

[25] O. Yaşar, J. Maliekal, P. Veronesi, L. Little, M. Meise, I.H. Yeter, Retrieval practices enhance computational and scientific thinking skills, Front. Psychol. 13 (2022), https://doi.org/10.3389/fpsyg.2022.892276.

[26] D. Liu, Exploring innovation with scientific thinking, Chin. Med. Sci. J. 37 (2) (2022) 87–90, https://doi.org/10.24920/004123.

[27] M. Sellars, R. Fakirmohammad, L. Bui, J. Fishetti, S. Niyozov, R. Reynolds, N. Thapliyal, Y.L. Liu-Smith, N. Ali, Conversations on critical thinking: can critical thinking find its way forward as the skill set and mindset of the century? Educ. Sci. 8 (2018) 205.

[28] Z. Straková, I. Cimermanová, Critical thinking development—a necessary step in higher education transformation towards sustainability, Sustainability 10 (10) (2018) 3366, https://doi.org/10.3390/su10103366.

[29] M.Ö. Akcaoğlu, E. Mor, E. Külekçi, The mediating role of metacognitive awareness in the relationship between critical thinking and self-regulation, Think. Skills Creativ. 47 (2023), https://doi.org/10.1016/j.tsc.2022.101187.

[30] É. Kaczkó, A. Ostendorf, Critical thinking in the community of inquiry framework: an analysis of the theoretical model and cognitive presence coding schemes, Comput. Educ. 193 (2023), https://doi.org/10.1016/j.compedu.2022.104662.

[31] C. Wisetsat, P. Nuangchalerm, Enhancing innovative thinking of Thai pre-service teachers through multi-educational innovations, Journal for the Education of Gifted Young Scientists 7 (3) (2019) 409–419, https://doi.org/10.17478/jegys.570748.

[32] M.S. Ramírez-Montoya, Estrategias de innovación para ambientes de aprendizaje, Innovación e investigación educativa. Síntesis, Madrid (2022).

[33] D.L.M. Ocasal, A.L.V. Lugo, L.A.B. Melo, P.P. Miranda, Innovative thinking in the leaders and competitiveness of SMEs in the industrial sector in Colombia, Paper presented at the Procedia Computer Science 210 (C) (2022) 333–338, https://doi.org/10.1016/j.procs.2022.10.160.

[34] D. Liang-Feng, L. Yuan, Design of performance evaluation algorithm for diversified talent training in modern universities considering innovative thinking, 2022, Mobile Inf. Syst. (2022), https://doi.org/10.1155/2022/2374468.

[35] G. Hofstede, Culture's Consequences, Sage Publications, Thousand Oaks, CA, 2001.

[36] R.J. House, P.J. Hanges, S.A. Ruiz-Quintanilla, P.W. Dorfman, M. Javidan, M. Dickson, V. y Gupta (Eds.), Culture, Leadership, and Organizations: the GLOBE Study of 62 Societies, Sage, Thousand Oaks, CA, 2004.

[37] I.M. Castillo-Martínez, M.S. Ramírez-Montoya, Instrumento eComplexity: Medición de la percepción de estudiantes de educación superior acerca de su competencia de razonamiento para la complejidad [eComplexity instrument: Measuring higher education students' perception of their competence in reasoning for complexity, 2022. https://hdl.handle.net/11285/643622.

[38] J.C. Vázquez-Parra, I.M. Castillo-Martínez, M.S. Ramírez-Montoya, A. Millán, Development of the perception of achievement of complex thinking: a disciplinary approach in a Latin American student population, Educ. Sci. 12 (2022), https://doi.org/10.3390/educsci12050289. Art. 289.