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Pre-Service Teachers' Perceptions of, and Experiences with, Technology-Enhanced Transformative Learning towards Education for Sustainable Development

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Abstract: Teacher education for sustainable development (ESD) is faced with continuing unsustainability trends, which require deep and enduring social transformation. Transformative learning is a possible solution to facilitating reflection on the cognitive and socio-emotional processes underpinning students' learning towards sustainability. The purpose of this paper is to investigate students' perceptions of, and experiences with, technology-enhanced self-directed learning and design thinking as possible moderators of transformative learning in order to advance the concept and practice of teacher ESD. These perceptions and experiences are represented by 225 pedagogical and non-pedagogical students from the University of Ljubljana, asked to respond anonymously to three online questionnaires in May and June 2021. Findings indicate that strengthening the transformative aspect of ESD in pre-service teachers requires the consideration of critical reflection, self-awareness, risk propensity, holistic view and openness to diversity, and social support. Moreover, self-directed learning was found to be a moderator for transformative learning among pre-service science teachers, while design thinking was evenly developed among transformative learning for both low- and high-ability students, no matter the study programme. The conditioning factors and explanatory arguments for these results are also discussed.

Keywords: teacher education for sustainable development (ESD); transformative learning; self-directed learning; design thinking; online learning; pre-service teachers



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1. Introduction

Every education system, from primary school to university studies, faces the challenge of equipping students with competitive knowledge and higher-order thinking, which are skills needed for the 21st century [1], while having to design new learning spaces for ESD to overcome planetary boundaries [2,3]. Higher education needs special attention because its complex environment is directly related to the labour market, industry, society, and sustainable development [1]. Thus, ESD “must play a central role in our unavoidable commitment to build a sustainable future for the good of our society and the planet” [4]. Changing priorities and emerging technologies seem to be the driving change in pedagogy and higher-education practices [5]. In the last two decades, higher education institutions have made significant advancements in knowledge and digital skills, supported by rapidly changing information-communication technology (ICT), but they do not seem to have catalysed the necessary change to address today's complex challenges [6], especially societal changes towards sustainable development [3].

By merging physical space and cyberspace, we can use the Internet of Things, Big Data, artificial intelligence, 3D technologies, and robotics to solve various social challenges and balance economic development with environmental sustainability [7]. In this way, a new kind of intelligence can reach every corner of society and people could find their daily life more comfortable and sustainable [7]. The realisation of such a human-centred society,

referred to as Society 5.0, requires highly-skilled, self-directed learners who are trained and educated in different educational settings [8]. Thus, the need for pedagogical changes cannot be overlooked [8,9], especially the inner dimensions of individuals, e.g., values, beliefs, worldviews, mindfulness, self-awareness, compassion, empathy, and consciousness [6,10,11]. Moreover, despite the prominence of sustainability as a concept, societies' trajectories remain deeply unsustainable [12]. Sustainable development and education about it are concepts used daily [2,13]. In this context, the 2030 Agenda for Sustainable Development aims to achieve sustainable development in a balanced, integrated, and indivisible manner in three dimensions: (1) economic, (2) social, and (3) environmental, as proposed by the United Nations (UN) [14]. It is to be implemented through seventeen sustainable development goals (SDGs). Thus, teacher education for ESD can be implemented and advanced through SDG4 with six indicators that monitor and measure progress in the education vertical, from initial education to life-long learning. The SDG4, according to its target 4.4, aims to promote ESD by increasing the number of people with relevant skills for labour market competitiveness including Society 5.0 ICT skills, while SDG4 indicator 4.7, aims to promote ESD by acquiring knowledge and specific and transversal skills in learners of all age groups through cognitive and non-cognitive pedagogies [15]. To achieve this, several authors [3,4,6,16,17] have argued that ESD should involve more transformative learning "to encourage tomorrow's leaders to be committed to developing a sustainable behaviour in their relationships, inside every organization, at institutional and public-management level" [16].

Many teachers and educators face this challenge in their fields since most lessons are delivered through rote or assimilative learning, where students acquire new information that can easily fit into their pre-existing knowledge structures, as in the field of sciences and mathematics, while teacher education and economics are very familiar with active approaches [17–20]. Despite various active learning approaches being included in teacher education curricula, a lack of developed competencies for ESD has been identified [21]. Thus, to make a pedagogical change that enables the transition from traditional to transformative learning, several authors suggest introducing innovative ICT-enhanced pedagogies based on metacognitive strategies [2,22–25], which establish self-directed learning as a foundation of transformative learning, as argued by [26].

The approach that should be used for developing transformative learning in pre-service teachers is still under debate since transformative learning might lead to the direction of ESD [6,16,25,27,28], where societal changes are needed [29,30]. While rote learning might help identify SDGs, active learning methods are needed to develop students' self-awareness and evaluation of the merit of each goal and indicator [16]. Transformative learning approaches in teacher ESD are seldom, but some efforts have been made toward the creation and standardization of new learning spaces which bridge learning with action and social transformation [25]. A common teaching challenge in pre-service teacher education is designing curricula and running courses that help students unlearn common-sense beliefs, make a paradigm shift while revising and not only augmenting previous knowledge [17]. Thus, pre-service teachers could be aware of how and why their assumptions have come to constrain the way they perceive, understand, feel, act and, finally, they will be able to make important choices and act upon these new understandings [31] toward sustainable development.

To bridge the gap between ESD and transformative learning, educators or instructors must create learning environments that encourage intellectual openness and enhance extrarational processes and social critique [25,32]. Here, technology-enhanced teacher–student, teacher–society, student–student, and student–society interactions are proposed as interactions in traditional and virtual classrooms that can be synchronous or asynchronous [33]. It may be that the use of various student-centred approaches to active online learning, such as self-directed learning and design thinking, develops both cognitive and affective structures for transformative learning in pre-service teachers [8,34].

1.1. Transformative Learning, Self-Directed Learning, and Design Thinking in Teacher Education

Mezirow defines transformative learning as “learning that transforms problematic frames of reference—sets of fixed assumptions and expectations (habits of mind, meaning perspectives, mindsets)—to make them more inclusive, discriminating, open, reflective, and emotionally able to change” [35]. Transformative learning goes beyond knowledge acquisition and the way we learn and integrate knowledge into our lives and worldviews [31]. There are different strands of transformative learning but all share an emphasis on experience, critical reflection, and dialogue in the learning process [36]. The transformational learning experience can be facilitated when teachers or educators expose learners to other perspectives within the context of a trusting environment and encourage them to move beyond the safety of their worldviews [37,38] (pp. 284–328). Educators should also become more socially responsible, independent, and rational, with a deeper self-awareness, more open perspectives, and a wider worldview [39].

For pre-service teachers’ education, authors [17,40,41] have highlighted four perspectives in transformative learning to improve pedagogical abilities: (1) consciousness-raising, (2) critical reflection, (3) personal growth and change, and (4) individuation. When applying transformative learning theory to teachers’ development, transformation displays enactment in the learner, which can be seen as pre-service teachers’ ability to reintegrate into their life their new perspective [17]. Thus, learning and enactment of new perspectives can occur by transforming meaning perspectives [42]. Social support in new collaborative spaces and self-directed learning are crucial factors for dealing with various sustainability challenges [25]. By providing conflicting perspectives in sustainability, pre-service teachers may be motivated to examine their perspectives [20]. These new collaborative spaces should also enable creative engagement in a series of interpretive acts that involve generating, experimenting, collaborating, reflecting, and acting on novel ideas [19]. Both creativity and transformative learning can change the way of thinking, knowing, and shifting perspectives, and creativity could serve as a catalyst for transforming the ways in which a teacher and students acquire knowledge in the reflective process of learning [19]. Reflective learning can be seen as an active self-directed process, in which students determine the information or skills they need and acquire them [43]. Thus, it may bring students into a cycle of responsibility [44].

Self-directed learning is essential in 21st-century educational institutions, especially in the field of higher education and in teacher education [45,46]. Moreover, it can be seen as a possibility where a learner acts equally in the roles of transmitter and recipient of learning measures [47,48]. Self-directed learning has gained visibility in these last decades, especially when active student engagement was enabled through active learning [45]. Although student-centred learning has been highly promoted and practised in pre-service teacher education, especially when work is organised in different workshops and learning projects, we are questioning the ability of self-directed learning to prepare future teachers for the collective changes they face in real life. Some issues have arisen concerning the efficacy of active learning approaches since Kirschner, Sweller, and Clark [49] have argued that any active learning with minimal guidance leads to working memory overload. Apart from this, when epistemological beliefs are presented to students out of the context of the particular discipline, they tend to feel a deep state of disconcertedness and they lean on grades as the measure of achievement [45]. Such top-down examination reinforces disempowerment [50], including the study programmes that employ self-directed learning [51].

Moreover, ESD can be jeopardised due to emergencies in education, such as COVID-19. Thus, Servant-Miklos and Noordegraaf-Eelens [45] have argued that self-directed learning might not be able to prepare students for addressing societal challenges, which is why an alternative rationale for higher education is urgently needed. Thus, the bridge between learning and action is a core element of social transformation, as argued by [25]. Several authors have found this perspective in design thinking, which requires a metacognitive approach to cope with design, societal, or environmental challenges [8,52–57].

Design thinking has many perspectives, but the mainstream one has been established by Stanford University researchers [58], which involves: (1) empathy, (2) problem definition, (3) ideation, (4) prototype, and (5) solutions testing and finalising with product elaboration, communication, and identification of new or potential users and functionality for product performance improvement. As argued by [8], design thinking “shows values such as practicality, ingenuity, empathy, and appropriateness, as well as values rooted in humanity, e.g., subjectivity, imagination, commitment, and justice, as human-centred design is socially situated in values and sense making”, also argued by [59–61]. A design thinker as a transformative learner is able to draw from multiple perspectives and see beyond others, imagining novel solutions that are better than the existing alternatives. Moreover, they should be able to explore constraints [62] and create and share team knowledge in interdisciplinary interactions [63]. Benson and Dresdow [63] have provided a rationale for design thinking as an approach for transformative learning since design thinking: (1) supports focusing on the values and questions people really care about, (2) is multidimensional and goes beyond disciplines, (3) is able to produce explicit purposes for multiple stakeholders and learning outcomes that address these purposes, (4) enables interdisciplinary reflective conversations to create transformation space where multiple opportunities for different members of the educational community can be enriched, (5) encourages risk-taking, exploration, and creative trade-offs, and (6) enhances social critique which helps strengthen the relationship between curriculum, learning experiences, and the needs of students, business, and society. Moreover, Dorst [55] suggests the use of abduction in combination with a disorienting dilemma in the design thinking process, wherein students only know the value which users need, while the subject matter together with conceptualisation are unknown, and this challenges what students believe [55] and increases motivation since it sets students up for failure. Since the design thinkers tend to learn from failure, which increases their motivation [64], it could also increase their self-awareness when they realise that their current knowledge is insufficient to solve a problem, thus, triggering transformative learning [32].

Transformative learning, supported by self-directed approaches to learning and design thinking, can also improve pre-service teacher education and help educators be better prepared to support student learning when they enter the field [17,46,65,66]. Moreover, such framed learning activities might develop pre-service teachers’ critical consciousness and increase reflection of social conditions, since pre-service teachers are more likely to resist critical education practices that challenge their notions of the self, society, and their interaction [65]. It seems that transformative learning results of pre-service teachers, achieved through design thinking and self-directed learning and supported by active learning methods, can enable teachers to cope with the biggest challenge in the classroom today—learner variability [17,65].

1.2. Teacher Education at the University of Ljubljana

Teacher education at the Faculty of Education of the University of Ljubljana (UL) is recognised worldwide with its quality of pedagogical work and research, while several networks in international projects and the mobility of staff and students further strengthen the role and position in the Slovenian academic space with its central position in the development of competences of ESD [67]. The Faculty of Education UL offers study programmes in pre-school and primary school education and some programmes for two-subject teachers in lower secondary school, e.g., a science, mathematics, and technology teacher. Primary teacher education aims to educate and train students for teaching in primary school grades 1–5, while a two-subject teacher education aims to train and educate future two-subject teachers for teaching two subjects in grades 6–9 in lower secondary schools. Pre-service teachers combine different study areas, such as chemistry–biology, mathematics–physics, mathematics–technology, chemistry–physics, biology–home economics [67]. Pre-service teachers of two-subject study programmes for teacher education acquire: (1) the fundamental professional knowledge from two subject areas, important for education in each

subject area, (2) specialist didactic knowledge from the two selected subject areas of education together with practical pedagogical training, and (3) the fundamental professional knowledge from the areas of pedagogy, psychology, philosophy, and sociology, relevant for working in education [67].

In recent years, an extensive effort has been made towards introducing ICT-supported teaching and learning to provide a solution to contemporary issues in 21st-century education, including establishing conditions for implementing SDGs in university teaching. Through various projects during the last decade, a lot was invested in ICT equipment and training to follow the trends of effective educational technology in teacher education and provide the most effective learning experience possible. There is active ICT-enhanced learning for primary and two-subject teachers' programmes, especially in learning projects, laboratory work, and other hands-on learning workshops [68]. In 2017, the University of Ljubljana launched two projects to improve the use of ICT in the pedagogical process, co-funded by the European Union (European Social Funds). The first one, called Digital University of Ljubljana, targeted all twenty-six faculties as members of UL, with all study programmes. The second project, called ICT in pedagogical study programmes at the University of Ljubljana, targeted only nine faculties of UL to deliver pedagogical study programmes. The second project aimed to train students and future primary and secondary school teachers to use ICT in the learning process. In addition, the role of ICT is recognised as crucial in enabling creativity and innovation in education, training, and learning in general [69]. Some of the project outputs were quantified as follows: (1) sixty-five pilot updates of study subjects intended for the training of future teachers in primary and secondary schools in different subject areas; (2) organization of four international expert conferences to deepen knowledge about the possibilities of using ICT in different content areas, share best practices and experiences between teachers and colleagues, and present partial results of the project; (3) organization of ten workshops on the use of ICT in the pedagogical process (e.g., language systems, interactive learning materials, collaborative learning environments, didactic games, Moodle, accessibility of virtual and augmented reality technologies in teaching, creative laboratory in the pedagogical process, development of multimedia learning materials (basic video production, tools and procedures for video editing); (4) individual consulting (120 h) to support higher education teachers and associates; (5) according to the needs expressed by teachers and associates developing supporting instructional materials and video tutorials (fifty-three instructional materials/video tutorials) available on the project website; (6) creation of professional bases for the didactic use of ICT in the educational process in six content areas e.g., languages, social sciences and humanities, mathematics–computer science–engineering, natural sciences, arts, and interdisciplinary [69]. As a spin-off of the described projects, a Centre for Digital University of Ljubljana was established in 2020 to support the use of ICT in the pedagogical process at all twenty-six faculties of the University of Ljubljana proved to be very useful when the COVID-19 pandemic broke out.

For effective and high-quality technology-enhanced teaching and learning, there is a need for further studies and more insights, for example, to study how technology-enhanced active learning can advance the concept and practise of teacher education ESD.

Studies on pre-service teacher ESD do not focus on the efficacy of self-directed learning as the basis of transformative learning, considering that self-directed learning is not able to adequately prepare pre-service teachers to address societal challenges, as argued by [25]. Moreover, an alternative to effective transformative learning in higher education can be found in the design thinking approach [8,20], but we are lacking evidence for design-based transformative learning in pre-service teachers in online education.

1.3. Research Objectives

We hypothesise that a lack of confidence in one's self-directed and design thinking capabilities will not matter if training content is delivered through a less active learning approach, while the effect of active learning on learner confidence will depend on the

level of self-directedness in learning and on the level of design thinking, such that pre-service teacher study programmes with more active learning modalities will result in lower transformative learning for those who feel less competent in their self-directed learning and design thinking.

Our study investigated how students from teacher education and architecture study programmes perceive and experience transformative learning on ESD and how it is influenced by their online self-directed learning and design thinking. The following research questions (RQs) guided this quantitative study:

RQ1: *How do students across pedagogical and non-pedagogical study programmes perceive online self-directed learning?*

RQ2: *What is the level of design thinking in students across online pedagogical and non-pedagogical study programmes?*

RQ3: *Which abilities for transformative learning in pre-service teachers are useful in giving concreteness to teacher ESD?*

Hypotheses (H) created against the theoretical background are:

Hypothesis 1 (H1). *Self-directed learning will moderate the effect of the teacher education study programme on transformative learning.*

Hypothesis 2 (H2). *Design thinking will moderate the effect of the teacher education study programme on transformative learning.*

Hypothesis 3 (H3). *Pre-service teachers have higher social skills, self-awareness, and critical thinking and reflection skills than their non-pedagogical counterparts.*

2. Materials and Methods

Technology-enhanced learning can expand opportunities in many areas of learning [33]. For example, it can be very sensitive to transformative learning because the nature and direction of synchronous and asynchronous online learning can affect the modelling of the cognitive system [32,33]. For effective learning, sensory memory, working memory, and long-term memory must be activated before new information is conveyed. Thus, if the instructor or organiser fails in designing the tasks, too much information can interfere with both knowledge and skill acquisition [54]. Consequently, this may lead to outcome bias. Therefore, research design plays a crucial role in valid results [70].

The present empirical study was carried out through a quantitative approach. In particular, a survey was conducted to understand the transformative learning in pre-service teacher online education needed for education and training for sustainable development.

2.1. Online Teaching and Learning Context

Online teaching and learning were used in both pedagogical and non-pedagogical study programmes after the COVID-19 pandemic started in March 2020, and the proportion of synchronous learning was similar for all. The teachers who delivered the online courses had varying levels of ICT skills and had taught entirely online for three semesters since the pandemic outbreak (Table 1). Teachers of architecture study programmes were found to be advanced ICT users at the University of Ljubljana [71].

Table 1. Description of the study process at the University of Ljubljana related to ICT use prior to and during the COVID-19 pandemic.

Study Process in Academic Years 2017 and 2018	Study Process in the Academic Year 2019/20	Study Process in the Academic Year 2020/21
Higher education teachers and associates implemented face-to-face teaching at the Faculty of Education UL during the whole academic year, thereby using the support of ICT in their teaching. In the state-of-the-art report at the Faculty of Education UL, Radovan et al. state that “Most of the educators do a lot of research into the possibilities offered by ICT. They show interest, participate in several projects related to innovative didactic approaches supported by ICT. Innovative didactic approaches are more widely used by the pedagogues in comparison to colleagues from other faculties, so they are also more critical of the use of ICT and use it where it is considered pedagogical process added value” [71]. Higher education teachers and associates implemented face-to-face teaching at the Faculty of Architecture UL during the whole academic year, thereby using the support of ICT. The state-of-the-art report of the Faculty of Architecture UL states as follows: “Most of the educators in relation to other members of the UL more often use ICT to find general information, study procedures, entertainment, and social networks. They often use ICT in specific introductory presentations, presentations of the results, provide different kinds of feedback, motivate students, support the research work with students, implement problem- and project-based learning, check students’ prior knowledge, as well as in the assessment of students’ knowledge. More often than associates from other UL faculties, they use the online collaboration environment, lecture recordings, tools for capturing/processing/storing and publishing images in video” [71].	Winter semester (1 October 2019–17 January 2020). Higher education teachers and associates implemented face-to-face teaching on all faculties of the University of Ljubljana, thereby using the support of ICT in their teaching similarly to previous years. Summer semester (17 February 2020–29 May 2020). The teaching started face-to-face in all faculties of the University of Ljubljana. It shifted to online teaching according to the request by the authorities of the University of Ljubljana on 12 March 2020 [72]. In order to support distance learning, the University of Ljubljana provided, to all higher education teachers and associates, MS Teams and Zoom licences. The Centre Digital UL [73] provided the training and support to educators in distance teaching also. Between 3 May 2020 and 29 May 2020, the recommendation was to combine online teaching with face-to-face hands-on activities in smaller groups of students wherever possible [74].	Winter semester (1 October 2020–18 January 2021) and Summer semester (15 February 2021–28 May 2021). For the whole academic year, all faculties of the University of Ljubljana recommended combining online teaching with face-to-face and hands-on activities in smaller student groups wherever possible. Furthermore, the Ministry of Education and Sports of the Republic of Slovenia [75] and the University of Ljubljana addressed the issue [76]. In order to support distance learning, the University of Ljubljana provided MS Teams and Zoom licences to all higher education teachers and associates. The Centre Digital UL [73] provided the training and support to educators in distance teaching also.

2.2. Sample

Participants for this study ($n = 296$) were recruited via an online classroom, Moodle, where a link to questionnaires in Google Forms was provided. Exclusion criteria included cases of missing data, those who completed the study in under fifteen minutes, and those who failed an instructed response attention check. Three instructed-response attention check items were included in the survey to detect inattentive respondents and improve data quality [70]. There were 225 participants who successfully completed the study and met all inclusion criteria. Participants were undergraduate students from pre-service teacher education, and students from the Faculty of Architecture were included as a control group, all at the University of Ljubljana, Slovenia, during the academic year 2020–2021. The sample included more female ($n = 201$, 89.33%) than male participants ($n = 24$, 10.67%). The distribution of students among different study programmes was as follows: 49 pre-service two-subject science teachers, e.g., biology–chemistry, biology–home economics,

chemistry–home economics, chemistry–physics; 55 pre-service two-subject technology teachers, e.g., technology–mathematics and technology–physics; 54 pre-service primary school teachers, and 67 architecture students were taken as a reference group. The chosen pedagogical study programmes were derived from SDG4, according to its target 4.7, which aims to promote ESD. Acquiring knowledge and specific and transversal skills is especially important in pre-service teachers through cognitive and non-cognitive pedagogies [15] to be able to transfer the competencies in their future pedagogical work. Primary school pre-service teachers should be able to enhance transformative learning in students in the early stages of education (ages 6–11), which continues in lower secondary school (ages 11–15), where two-subject science and technology teachers play a crucial role in ESD, as argued by [1,68].

For this article, a shortened annotation of pedagogical students is as follows: Pre-service science teachers, pre-service technology teachers, and primary school pre-service teachers. The authors selected the architecture study programmes as an example of a non-pedagogical study programme, where self-directed learning and design thinking are well-articulated and developed in students towards sustainable development goals and thoroughly used in teaching practice as an active learning approach [8]. Moreover, gender distribution is very similar to that of pre-service teacher education.

At the end of the educational work with the students, they were informed about the purpose of the study and were given instructions on how to fill in the questionnaires. As this was a voluntary activity, students were free to withdraw from the study at any time and were not incentivised to obtain responses.

The final sample of this study consisted of 225 students with a mean age of 21.08 years ($SD = 4.64$).

2.3. Instruments

2.3.1. Self-Directed Learning

In our previous studies, we have successfully used Williamson's questionnaire of self-directed learning, which was proven as valid and reliable in detecting the skills required for undergraduate architecture students [77]. Considering the above characteristics of ESD, Williamson's survey seems the most appropriate in detecting the skills required for pre-service teachers [77].

The self-directed learning 60-item questionnaire was adapted with themes of sustainable development and used to survey students' perception of their ability in online self-directed learning. The questionnaire, with five subscales, is well-explained in our previous study [8]. These subscales are as follows: (1) *Awareness*, (2) *Learning strategies*, (3) *Learning activities*, (4) *Evaluation*, and (5) *Interpersonal skills*.

Williamson's original response scale as a 5-point Likert scale ranges from 5 (always) to 1 (never). The Cronbach's alpha tests show whether the scales are reliable, considering the acceptable values suggested by [78], which should be greater than 0.70.

2.3.2. Design Thinking

Forty-five items were included to assess participants' design thinking. We deliberately chose adapted the Avsec and Jagiełło-Kowalczyk [8] metacognitive design thinking scale with 13 subscales, which is based on Dosi et al.'s [64] questionnaire. A 6-point Likert scale, ranging from 6 (strongly agree) to 1 (strongly disagree), used for self-assessment of design thinking as a very complex and multi-faceted skill proved accurate enough, as students were forced to avoid a central tendency or neutral position in the scale, as already argued by [79–81]. For the purpose of this study, we have chosen only constructs which support a model for developing effective design thinking processes "to overcome existing shortcomings while improving interpersonal skills, creativity and digital skills, make pedagogical changes, and enhance redesign of learning outcomes towards sustainable development," as argued by [8]. Moreover, the questionnaire can be suitable, given the nature of ESD towards SDGs' achievement in different learning spaces.

The adapted design thinking questionnaire's items used in the present study were divided into the following 13 constructs, well-described in the study by Dossi et al. [64] and explained in our recent study [8]. These constructs are as follows: (1) *Embracing risk*, (2) *Human centeredness*, (3) *Empathy*, (4) *Mindfulness and awareness of the process*, (5) *Problem reframing*, (6) *Team knowledge*, (7) *Multi-/inter-/cross-disciplinary collaboration*, (8) *Open to different perspectives/diversity*, (9) *Learning-oriented*, (10) *Experimentation*, (11) *Abductive thinking*, (12) *Envisioning new things*, and (13) *Creative confidence*.

2.3.3. Transformative Learning

The authors of the present study have measured transformative learning and its phases using an adapted form of subscales from several valid and reliable surveys, e.g., Stuckey et al. [32], Cox [82], Madsen and Cook [83], and the LAS [84]. Romano [85] suggests using a combination of surveys since such a composite allows “defining transformative learning on several dimensions, considering the individual and the social dimension of change and both the internal and the behavioural dimension of transformation”.

When developing the survey for transformative learning measurement, we had to focus on different transformative learning outcomes, such as acting differently, having a deeper self-awareness, more open perspectives, and experiencing a deep shift in world-views, as suggested by [32]. Moreover, all outcomes cover the processes developed in transformative learning on three levels: (1) cognitive (critical reflection, action, experiences, disorienting dilemma), (2) extrarational (emotional, imaginal, creative), and (3) social support (social action, empowerment). These three levels are well-documented and explained in the studies by [32,82–84,86] and successfully cover all ten phases of transformative learning, as proposed by [38].

Original questionnaires by the aforementioned authors have either a 4-point or a 5-point Likert scale, while we used a 6-point Likert scale. We have chosen this scale because the ultimate purpose of the instrument was to track the development of metacognitive awareness for purposes of either self-assessment or research. A 6-point Likert scale used for the self-assessment of transformative learning as a very complex and multi-faceted process proved accurate enough, as students were forced to avoid a central tendency or neutral position in the scale, as already argued by [79–81].

The newly generated 31-item instrument for transformative learning measurement used in the present study was divided into the following 8 constructs:

1. *Attitudes toward uncertainty*. Three items were used from the Cox (2017) survey, aiming to explore a level at which participants are comfortable with uncertainty and suspending their judgement, to “view a solution as an imprecise and often inconclusive concept, to engage in a process where the outcome, the amount of knowledge, and the time needed for achieving the result are unknown” [8]. A learner's perception of uncertainty serves as a disruptive experience, whereby the learner experiences a gap between expectation and observation. Thus, uncertainty might encourage deeper reflection [82].
2. *Criticality and reflection*. Five items were used from the Cox survey [82]. Criticality, or critical reflection, centres on the identification, critique, and reformulation of underlying beliefs or assumptions [31]. Criticality may be prompted by a sense of uncertainty or doubt regarding beliefs, which places a thought back into motion through a learner's re-examination of a belief [82].
3. *Social support*. Four items were used from the Cox survey [82]. Social support can be seen through discourse or through experiencing other learners' perspectives as a means to frame and re-frame one's own understanding [38]. Using teamwork and social interactions, learners develop the necessary openness and confidence to deal with learning by experiencing, reflecting on, and exploring uncertainty [87], both on a cognitive and an affective level [88].
4. *Considering and making changes in thought and action*. Four items were reworded from the Madsen and Cook survey [83], based on the LAS [84]. Acting differently refers

to the consideration of past actions or behaviours, which results in a new set of expectations guiding further action [37]. Transformative learning outcomes represent the results of a reconstructive process, which is propelled at least in part by the learner [82].

5. *Awareness of the benefits of change and prediction of future behaviour.* Four reworded items were used from Madsen and Cook [83]. Having a deeper self-awareness might help learners bring the unconscious to consciousness [32]. Thus, their capacity for transformative learning enhances the transformation of sociocultural reality by acting upon it [38,82].
6. *Holistic view and openness to diversity.* Four items were reworded from the Stuckey et al. survey [32] and Cox survey [82]. Transformative learning outcomes, such as an increased holistic view and openness, considering many factors, e.g., socio-economic patterns, relationships, interdependencies, including people's needs, organizational constraints, and regulatory impact. Diversity can be seen for the purpose of the present study as "working together in different teams and integrating various perspectives" [8]. Changes, as a consequence of transformative learning, can be seen as not only what we know but also how we know [89].
7. *Beyond rational/extrarational.* Four items were used, reworded from the surveys of [32,82–84], involving emotional level, creative confidence, desire to make a difference, and optimism. The development of extra-rational processes in students could play a central role in empowering and motivating students towards ESD by stimulating emotions, creativity, social dialogue, and imaginative learning, as claimed by [32]. In addition, this ability can be a driver that moves students forward even when they are unable to see a final image or have failed at a task [8]. It could be that students with a strong transformative learning ability "have a desire to develop the skills, structures, and processes to generate value from valuable insights, and they are determined to convince someone of their idea and justify it if they find it valuable" [8], which is also confirmed by [64]. Since creativity and transformative learning embody strong cognitive and affective dimensions [90], a learner with greater creative confidence will make the transformation of knowledge, skills, and attitudes easier [19].
8. *Disorienting dilemma.* Three items were used and reworded from the Stuckey survey [32]. The disorienting dilemma is an important phase of Mezirow's transformative learning [38] and it leads to a sense of deep uncertainty, spurring critical reflection of assumptions [82] and increasing the motivation to learn [20]. It can trigger events occurring in a specific domain that initiates a transformative learning process [82].

The transformative learning items were subjected first to Exploratory Factor Analysis (EFA), using IBM SPSS statistical software (v.25), confirming eight constructs. Evidence of construct validity was provided with EFA. Kaiser–Meyer–Olkin (KMO) sampling adequacy of the transformative learning measurement was 0.91, and Bartlett's test of sphericity was significant ($p = 0.00 < 0.05$). When Principle Component Analysis (PCA) was carried out, the total variance of transformative learning factors was 72.9%; this means that at least 50% of the variance could be explained by common factors and considered reasonable [91]. The communalities h^2 (variance of the variables) on the transformative learning questionnaire were greater than 0.5, indicating that the extracted factors explained a more significant proportion of the variance in a single item [78]. Therefore, measures are acceptable and valid for further analysis as they are all above a cut-off of 0.3 [78].

In addition, we calculated the factor loadings using Oblimin rotation, where the pattern matrix revealed that all the survey items had significant loadings greater than the threshold of 0.5 (0.7) [78]. Finally, a pattern matrix was used to assess the EFA convergent validity and the Confirmatory Factor Analysis (CFA). The CFA was carried out using the IBM SPSS Amos (v.24) software programme.

The result of CFA of the transformative learning model indicated good fit (minimum discrepancy per degree of freedom (CMIN/df) = $684.2/398 = 1.719$, the index of

comparative adjustment (CFI) = 0.956, the Tucker–Lewis index (TLI) = 0.931). However, previous studies demonstrated that the Chi-Square test is sensitive to sample size and model complexity [92,93]. Therefore, more parsimonious models are preferred to complicated models [92]. The parsimonious fit measure indexes used in this study were: the parsimony comparative fit index (PCFI) = 0.81; parsimonious normed fit index (PNFI) = 0.78; and parsimonious goodness of fit index (PGFI) = 0.71. Overall, according to Hair et al. [93] these model fit indexes indicated that the model in this research was acceptable. The root mean square error of approximation (RMSEA) value was less than the threshold value of 0.08 (0.048). Thus, there was a good fit in each construct [94]. The probability of close fit (PCLOSE) was greater than 0.05 (0.15), which indicates a good model fit [95]. All the model-fit indices met a satisfactory range for a good model fit. All the CR values were above 0.9, which surpassed the suggested threshold value of 0.7 [93], establishing the constructs' composite reliability (CR). Second, the convergent validity in this study verified the following: (1) whether the average variance extracted (AVE) values were greater than 0.5 [96]; and (2) whether the factor loadings of all the items were significant and greater than 0.5. If all the conditions were met, acceptable construct validity was indicated [93].

The AVE values ranged from 0.56 to 0.64, indicating suitable convergent validity. We found that the CR values ranged from 0.78 to 0.88, which suggested internal consistency, and that the other indicators of the model's construct validity were good. Cronbach's alpha estimates ranged from 0.77 to 0.90, indicating appropriate internal consistency (Table 2). All the Cronbach's alpha values were higher than 0.60, presenting an acceptable level of reliability [78].

Table 2. Summary for measurement model of the transformative learning questionnaire.

Subscale	AVE	SQRT(AVE)	CR	Cronbach's Alpha
<i>Attitudes toward uncertainty</i>	0.60	0.77	0.81	0.82
<i>Criticality and reflection</i>	0.56	0.75	0.86	0.87
<i>Social support</i>	0.62	0.79	0.87	0.84
<i>Considering and making changes in thought and action</i>	0.64	0.80	0.78	0.83
<i>Awareness of the benefits of change and prediction of future behaviour</i>	0.58	0.76	0.85	0.84
<i>Holistic view and openness to diversity</i>	0.56	0.75	0.83	0.81
<i>Beyond rational/extrarational</i>	0.64	0.80	0.88	0.90
<i>Disorienting dilemma</i>	0.58	0.76	0.80	0.77

Note. AVE = average variance extracted. SQRT(AVE) = square root of the average variance extracted. CR = composite reliabilities.

It is necessary to determine the square root of every AVE value to establish discriminant validity. The square root of the AVE of each construct should be greater than the correlation of that construct with any other constructs [78]. Thus, it is first necessary to obtain a component correlation matrix to observe the correlation of each construct with the other constructs.

Table 3 shows the factor correlation matrix, with very low correlations among the eight factors, i.e., the correlations did not exceed 0.43 (the upper limit was 0.7). The factors were distinct and uncorrelated, which indicates high discriminant validity of those factors [78]. In addition, we calculated the factor loadings using Oblimin rotation, where the pattern matrix revealed that all the survey items had significant loadings greater than the threshold of 0.5 (0.7). This provided evidence for high validity; thus, high concurrent and predictive validity of the results were verified [97].

The transformative learning measurement demonstrated adequate validity and reliability for the dataset used in this study.

Table 3. Factor correlation matrix.

Component	1	2	3	4	5	6	7	8
1	1.00	0.21	0.27	−0.43	0.30	0.32	0.24	0.39
2		1.00	0.13	−0.19	0.35	0.29	0.12	0.14
3			1.00	−0.23	0.09	0.23	0.05	0.19
4				1.00	−0.23	−0.36	−0.29	−0.39
5					1.00	0.28	0.22	0.17
6						1.00	0.25	0.34
7							1.00	0.24
8								1.00

Note. PCA extraction method and rotation using Oblimin with Kaiser Normalisation.

2.4. Procedure and Data Analysis

All three questionnaires were distributed online to the pre-service teachers and architecture students' email addresses, with a link to the questionnaires. Students participated in the study during online distance learning sessions at the end of the semester in May and June 2021 throughout a study day. A high response rate was achieved because students participating in the study spent time responding to the questionnaires during their pedagogical work. Ethical considerations were taken into account during data collection and analysis, as well as privacy protection.

The data were analysed using SPSS Statistics, a software package commonly used for statistical analysis in the social sciences. A descriptive analysis of the data was carried out to describe and summarise the characteristics of a sample, expressed by the mean and standard deviations. Due to the violation of normality of the distributions and the nature of ordinal variables, the nonparametric test, Kruskal–Wallis, was used to detect statistically significant differences between the different groups of students. An ϵ^2 was used as a measure of effect size, as proposed by [98]. Cronbach's alpha coefficient was used to estimate the reliability of the scales and subscales of the questionnaires used in this study.

For a nuanced investigation of whether self-directed learning and design thinking would moderate the effect of pre-service teachers' education, overall trends were examined, with participants divided into "higher" and "lower" self-directed learning and design thinking groups, using a median split. After reviewing these mean trends, we conducted a 2×4 factorial analysis of variance (ANOVA), which included condition and self-directed learning (design thinking) (lower vs. higher) as independent variables, and transformative learning as the dependent variable. For a more nuanced investigation, we examined a full range of self-directed learning (design thinking) as a continuous variable. To facilitate a multiple regression analysis, we created dummy variables for pre-service teachers' education, where the architecture education group was the reference group.

2.5. Ethical Considerations

The Head of the Department of Physics and Technology at the Faculty of Education, University of Ljubljana, asked students to participate in the research. The students were informed about the purpose of this research, which aimed to improve teaching and learning in teacher education for ESD, especially when it came to ICT-supported teaching in remote and online environments. The concept of SDGs was introduced to students in various courses of their studies, with particular attention to SDG4, as the ESD is an integral part of this goal.

Participation in this study was completely voluntary, and students were given an informed consent form, which also explained the necessary precautions to protect the privacy of participating students. Students were also informed of the time it would take them to complete the survey and the importance of answering as they thought and not as they thought others expected them to. It was also pointed out that responses will be analysed and presented in groups. Their identity would not be revealed under any circumstances.

As we collected personal data, e.g., gender, age, year of study, course of study, students were asked for informed consent to proceed with the survey. Students were also given the opportunity to be informed about data collection, analysis, and storage details in this study, which complied with the General Data Protection Regulation (GDPR) of the University of Ljubljana. Upon enrollment, all students at the University of Ljubljana were informed that the authorised person at the University of Ljubljana is responsible for protecting personal data, monitoring and supervision counselling, and education at the University of Ljubljana as per the GDPR.

3. Results

Prior to hypothesis testing, data were cleaned and coded, and each scale and corresponding subscales were tested for internal consistency. As suggested by [78], all scales/subscales demonstrated sufficient internal consistency for basic research via Cronbach's alpha scores above 0.70.

3.1. Perceived Ability for Self-Directed Learning

Means (*M*), standard deviations (*SD*), and differences in the subscales across the pedagogical and non-pedagogical students can be found in Table 4.

Table 4. Comparative inferential analysis. Students' mean scores on self-directed learning, and differences in the questionnaire subscales depending on the study programme of the participants.

Subscale	Non-Pedagogical Study Programme		Pre-Service Science Teachers		Pre-Service Technology Teachers		Pre-Service Primary School Teachers		Test Kruskal–Wallis		Effect Size
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	Value <i>H</i>	Sig. <i>p</i>	ϵ^2
<i>Awareness</i>	4.01	0.38	4.09	0.48	4.26	0.50	4.15	0.48	12.89 **	0.005	0.06
<i>Learning strategies</i>	3.79	0.48	3.89	0.54	4.13	0.54	3.99	0.47	16.83 ***	0.000	0.08
<i>Learning activities</i>	3.87	0.49	3.61	0.62	3.95	0.52	3.85	0.62	10.21 *	0.017	0.05
<i>Evaluation</i>	4.02	0.54	3.91	0.58	4.00	0.54	3.93	0.65	1.59	0.661	0.01
<i>Interpersonal skills</i>	3.76	0.46	4.01	0.53	4.20	0.58	4.16	0.53	27.65 ***	0.000	0.12
Total score	3.89	0.38	3.90	0.46	4.11	0.47	4.01	0.50			

Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The reliability of the self-directed learning questionnaire was very high both in the total scale and in the subscales measured by Cronbach's α (0.96; from 0.82 to 0.87, respectively). Therefore, the self-directed learning questionnaire proved to be a reliable and valid data collection instrument suitable for use in teacher education [78].

The test for normality, Shapiro–Wilk, revealed a violation of normality assumption across the study programmes ($p < 0.05$), suggesting the use of non-parametric tests. Students' self-evaluated mean scores of the subscale items are shown in Table 4 and contrasted (using Kruskal–Wallis test) based on the study programme group as the differentiating factor.

In the case of the study programme variable, we have significant differences in the subscales of self-directed learning that appear in Table 4, although it must also be stated that an effect size of ϵ^2 is moderate, as calculated and interpreted by [98].

After Bonferroni-adjusted significance tests for pairwise comparison, we found significant differences at subscales of (1) *Awareness* between pre-service technology teachers and the control group ($H = 41.669$, $p = 0.003$, relatively strong effect size $\epsilon^2 = 0.19$), (2) *Learning strategies* between pre-service technology teachers and the control group ($H = 47.447$, $p = 0.000$, relatively strong effect size $\epsilon^2 = 0.22$) and between pre-service technology teachers and pre-service science teachers ($H = 33.837$, $p = 0.048$, moderate effect size $\epsilon^2 = 0.15$), (3) *Learning activities* between pre-service technology teachers and pre-service science teachers ($H = 38.837$, $p = 0.018$, relatively strong effect size $\epsilon^2 = 0.18$), and at (4) *Interpersonal skills* between pre-service technology teachers and the control group ($H = 58.332$, $p = 0.000$, relatively strong effect size $\epsilon^2 = 0.26$) and between pre-service primary school teachers and control group ($H = 45.562$, $p = 0.000$, relatively strong effect size $\epsilon^2 = 0.21$).

Since the items of the self-directed learning questionnaire were focused on the subjects of ESD, it was found that pre-service technology teachers had the most developed competencies of ESD, while architecture students as non-pedagogical students had difficulties in some of the subscales of self-directed learning. This indicates a proper development of initial design and technology education towards ESD using the self-directed learning approach in the implementation of the SDGs, while other pedagogical study programmes and architectural education still seem to have an insufficient implementation of ESD. Figure 1 shows the students' average scores on each subscale of self-directed learning across the groups of students or study programmes.

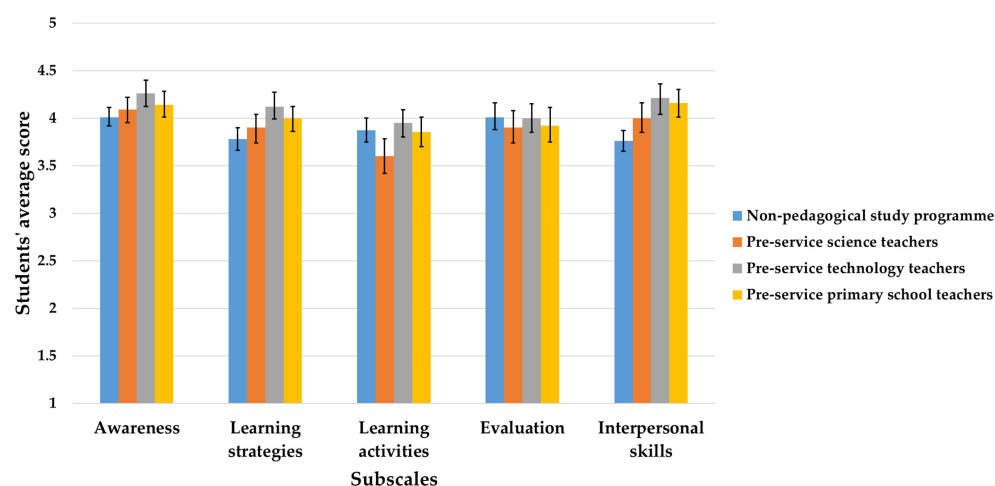


Figure 1. Students' self-directed learning scores on questionnaire subscales with 95% confidence intervals.

The differences between different constructs of self-directed learning were calculated to find whether the constructs are evenly developed in students or some constructs are underdeveloped against others. It might be helpful to provide more insights into the model of self-directed learning as a dynamic, non-linear, and cyclic multi-step process [47]. The resulting mean values of participants were compared. The differences observed between these items are significant, with $p < 0.001$ (Friedman test: Chi-square value = 89.22; $p = 0.000$; small effect size: Kendall's $W = 0.099$). These significant differences also indicate that the majority of students have the required level of self-awareness, are able to use basic learning strategies and approaches, assess and monitor their knowledge and skill acquisition, and have been involved in creating collaborative learning spaces and resources.

Wilcoxon's rank test revealed the most underdeveloped subscale of *Learning activities*, the most developed *Awareness* and *Interpersonal skills* ($p < 0.001$), while *Learning strategies* and *Evaluation* can be treated as similar and moderately developed ($p > 0.05$).

3.2. Perceived Ability for Design Thinking

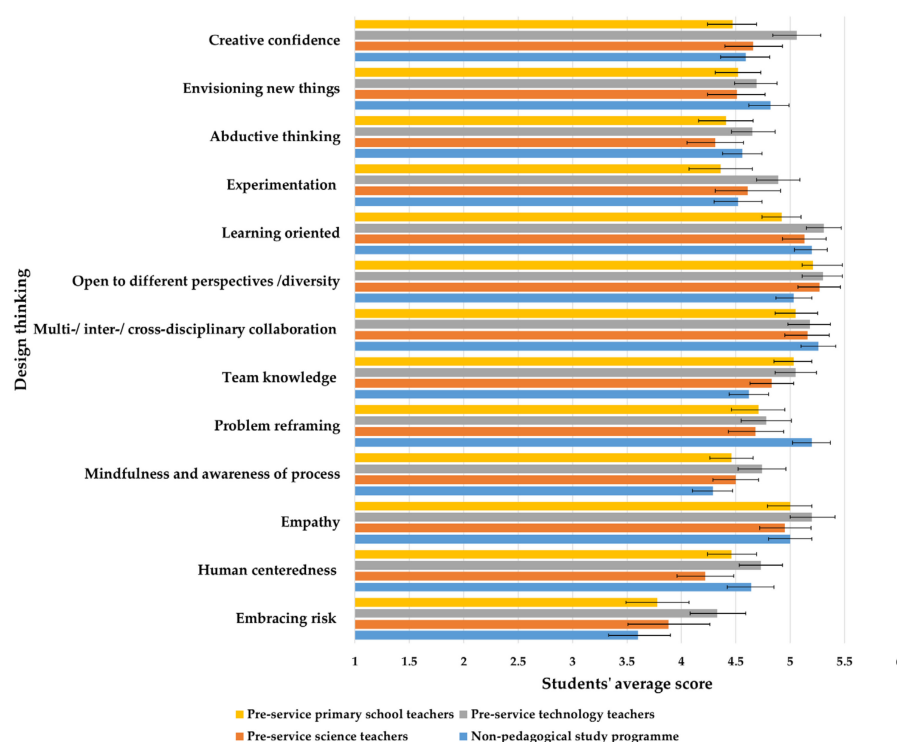
Students' design thinking ability was assessed on a 6-point Likert scale against 13 subscales of the questionnaire. Means (M), standard deviations (SD), and differences in the subscales across the pedagogical and non-pedagogical students can be found in Table 5.

The reliability of the design thinking questionnaire was very high both in the total scale and in the subscales measured by Cronbach's α (0.96; from 0.75 to 0.88, respectively). Therefore, the design thinking questionnaire proved to be a reliable and valid data collection instrument suitable for use in teacher education settings [78].

Figure 2 shows students' average scores expressed with a mean, where an equal distance was assumed between ordinal values on the scale. Students, in general, have evaluated themselves as above the average on all subscales of design thinking.

Table 5. Comparative inferential analysis. Students' mean scores on design thinking, and differences in the questionnaire subscales depending on the study programme of the participants.

Subscale	Non-Pedagogical Study Programme		Pre-Service Science Teachers		Pre-Service Technology Teachers		Pre-Service Primary School Teachers		Test Kruskal–Wallis		Effect Size ϵ^2
	M	SD	M	SD	M	SD	M	SD	Value H	Sig. p	
Embracing risk	3.61	1.14	3.89	1.30	4.34	0.93	3.79	1.06	12.53 **	0.006	0.06
Human centeredness	4.64	0.89	4.22	0.91	4.73	0.74	4.47	0.84	10.29 *	0.016	0.05
Empathy	5.00	0.84	4.96	0.81	5.21	0.75	5.00	0.75	3.15	0.371	0.02
Mindfulness and awareness of process	4.29	0.75	4.50	0.72	4.75	0.80	4.46	0.72	11.98 **	0.007	0.06
Problem reframing	5.20	0.72	4.69	0.89	4.78	0.86	4.71	0.90	15.57 ***	0.000	0.07
Team knowledge	4.62	0.71	4.83	0.69	5.05	0.71	5.03	0.65	16.83 ***	0.000	0.08
Multi-/inter-/cross-disciplinary collaboration	5.26	0.65	5.16	0.71	5.18	0.72	5.06	0.71	3.03	0.391	0.02
Open to different perspectives/diversity	5.04	0.67	5.27	0.69	5.30	0.67	5.21	0.66	7.66	0.054	0.04
Learning oriented	5.19	0.63	5.13	0.70	5.32	0.59	4.93	0.67	10.56 *	0.014	0.05
Experimentation	4.53	0.93	4.61	1.03	4.89	0.74	4.36	1.04	8.25 *	0.041	0.04
Abductive thinking	4.56	0.74	4.31	0.91	4.66	0.73	4.41	0.91	4.51	0.212	0.02
Envisioning new things	4.81	0.75	4.51	0.93	4.69	0.71	4.52	0.77	6.423	0.093	0.03
Creative confidence	4.59	0.92	4.66	0.93	5.07	0.82	4.47	0.82	14.97 **	0.002	0.07
Total score	4.78	0.53	4.74	0.54	4.98	0.55	4.72	0.61			

Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.**Figure 2.** Students' perceived ability for design thinking on 13 subscales with 95% confidence intervals.

A mean value of 5 was exceeded on subscales of (a) *Empathy*, (b) *Multi-/inter-/cross-disciplinary collaborative teams*, (c) *Open to different perspectives/diversity*, and (d) *Learning-oriented*, while it seems that *Embracing risk* is just above the average, as one less developed.

The test for normality, Shapiro–Wilk, revealed a violation of normality assumption across the study programmes ($p < 0.05$), suggesting the use of non-parametric tests.

Students' mean scores on the subscale items are contrasted (using Kruskal–Wallis) based on the study programme as the differentiating factor. In the case of the study programme variable, we have significant differences in the subscales of design thinking

that appear in Table 5, although it must also be stated that an effect size of ϵ^2 is weak to moderate, as calculated and interpreted by [98].

After Bonferroni-adjusted significance tests for pairwise comparison, we found significant differences at subscales of (1) *Embracing risk* between pre-service technology teachers and the control group ($H = 40.141$, $p = 0.004$, relatively strong effect size $\epsilon^2 = 0.18$), (2) *Human centeredness* between pre-service technology teachers and pre-service science teachers ($H = 34.669$, $p = 0.036$, moderate effect size $\epsilon^2 = 0.15$) and between pre-service science teachers and pre-service primary school teachers ($H = 32.643$, $p = 0.043$, moderate effect size $\epsilon^2 = 0.14$), (3) *Mindfulness and awareness of process* between pre-service technology teachers and the control group ($H = 39.591$, $p = 0.004$, relatively strong effect size $\epsilon^2 = 0.18$), (4) *Problem reframing* between pre-service technology teachers and the control group ($H = 32.761$, $p = 0.032$, moderate effect size $\epsilon^2 = 0.14$), between pre-service science teachers and the control group ($H = 39.121$, $p = 0.008$, relatively strong effect size $\epsilon^2 = 0.17$), and between pre-service primary school teachers and the control group ($H = 38.667$, $p = 0.006$, moderate effect size $\epsilon^2 = 0.15$), (5) *Team knowledge* between pre-service technology teachers and the control group ($H = 44.715$, $p = 0.001$, relatively strong effect size $\epsilon^2 = 0.20$) and between pre-service primary school teachers and the control group ($H = 35.428$, $p = 0.017$, relatively strong effect size $\epsilon^2 = 0.17$), (6) *Learning-oriented* between pre-service technology teachers and pre-service primary school teachers ($H = 39.461$, $p = 0.009$, relatively strong effect size $\epsilon^2 = 0.18$), (7) *Experimentation* between pre-service technology teachers and pre-service primary school teachers ($H = 33.957$, $p = 0.037$, moderate effect size $\epsilon^2 = 0.15$), and (8) *Creative confidence* between pre-service technology teachers and pre-service primary school teachers ($H = 45.651$, $p = 0.001$, relatively strong effect size $\epsilon^2 = 0.20$) and between pre-service technology teachers and the control group ($H = 34.183$, $p = 0.023$, moderate effect size $\epsilon^2 = 0.15$). Epsilon square effect size was calculated and interpreted, as proposed by [98].

3.3. Perceived Ability for Transformative Learning

Students' transformative learning ability was assessed on a 6-point Likert scale against 8 subscales of the questionnaire. Means (M), standard deviations (SD), and differences in the subscales across the pedagogical and non-pedagogical students can be found in Table 6.

Table 6. Comparative inferential analysis. Students' mean scores on transformative learning, and differences in the questionnaire subscales depending on the study programme of the participants.

Subscale	Non-Pedagogical Study Programme		Pre-Service Science Teachers		Pre-Service Technology Teachers		Pre-Service Primary School Teachers		Test Kruskal–Wallis		Effect Size ϵ^2
	M	SD	M	SD	M	SD	M	SD	Value H	Sig. p	
Attitudes towards uncertainty	3.72	0.74	3.92	0.75	4.57	0.77	3.96	0.97	30.77 ***	0.000	0.14
Criticality and reflection	4.92	0.87	4.86	0.89	5.15	0.62	4.45	0.90	18.11 ***	0.000	0.09
Social support	4.98	0.71	5.15	0.75	5.33	0.79	5.17	0.65	10.77 *	0.013	0.05
Considering and making changes in thought and action	4.82	0.62	4.57	0.82	4.83	0.69	4.63	0.71	4.86	0.183	0.02
Awareness of the benefits of change and prediction of future behaviour	4.55	0.64	4.85	0.57	5.00	0.71	4.73	0.65	18.11 ***	0.000	0.09
Holistic view and openness to diversity	4.94	0.60	5.02	0.62	5.14	0.62	4.95	0.61	5.01	0.171	0.02
Beyond rational/ extrarational	4.79	0.72	4.73	0.72	5.05	0.68	4.62	0.74	12.99 **	0.005	0.06
Disorienting dilemma	4.85	0.89	4.67	0.85	4.94	0.76	4.50	0.80	10.81 *	0.013	0.05
Total score	4.69	0.56	4.70	0.56	4.99	0.57	4.63	0.62			

Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The reliability of the transformative learning questionnaire was very high both in the total scale and in the subscales measured by Cronbach's α (0.95, from 0.77 to 0.90, respectively).

Therefore, the transformative learning questionnaire proved to be a reliable and valid data collection instrument suitable for use in teacher education settings [66].

The test for normality, Shapiro–Wilk, revealed the violation of normality assumption across the study programmes ($p < 0.05$), suggesting the use of non-parametric tests.

Students' mean scores on the subscale items are contrasted (using Kruskal–Wallis) based on the study programme as the differentiating factor. In the case of the study programme variable, we have significant differences in the subscales of design thinking that appear in Table 2, although it must also be stated that an effect size of ϵ^2 is weak to relatively strong, calculated and interpreted as proposed by [98].

After Bonferroni-adjusted significance tests for pairwise comparison, we found significant differences at subscales of (1) *Attitudes towards uncertainty* between pre-service technology teachers and the control group ($H = 63.383$, $p = 0.000$, relatively strong effect size $\epsilon^2 = 0.28$), between pre-service technology teachers and pre-service science teachers ($H = 47.715$, $p = 0.001$, relatively strong effect size $\epsilon^2 = 0.21$), and between pre-service technology teachers and pre-service primary school teachers ($H = 46.456$, $p = 0.001$, relatively strong effect size $\epsilon^2 = 0.20$), (2) *Criticality and reflection* between pre-service technology teachers and pre-service primary school teachers ($H = 50.911$, $p = 0.000$, relatively strong effect size $\epsilon^2 = 0.22$) and between pre-service primary school teachers and the control group ($H = 35.961$, $p = 0.014$, relatively strong effect size $\epsilon^2 = 0.16$), (3) *Social support* between pre-service technology teachers and the control group ($H = 38.715$, $p = 0.006$, relatively strong effect size $\epsilon^2 = 0.17$), (4) *Awareness of the benefits of change and prediction of future behaviour* between pre-service technology teachers and the control group ($H = 48.874$, $p = 0.000$, relatively strong effect size $\epsilon^2 = 0.22$) and between pre-service technology teachers and pre-service primary school teachers ($H = 33.321$, $p = 0.046$, moderate effect size $\epsilon^2 = 0.15$), (5) *Beyond rational/extrarational* between pre-service technology teachers and pre-service primary school teachers ($H = 42.667$, $p = 0.004$, relatively strong effect size $\epsilon^2 = 0.19$), and (6) *Disorienting dilemma* between pre-service technology teachers and pre-service primary school teachers ($H = 35.981$, $p = 0.022$, relatively strong effect size $\epsilon^2 = 0.16$) and between pre-service primary school teachers and the control group ($H = 32.441$, $p = 0.036$, moderate effect size $\epsilon^2 = 0.14$).

Students, in general, have evaluated themselves as above the average on all subscales of transformative learning (Figure 3). A mean value of 5 was exceeded on subscales of *Social support* and *Holistic view and openness to diversity*, while it seems that *Attitudes towards uncertainty* is just above the average, as one less developed.

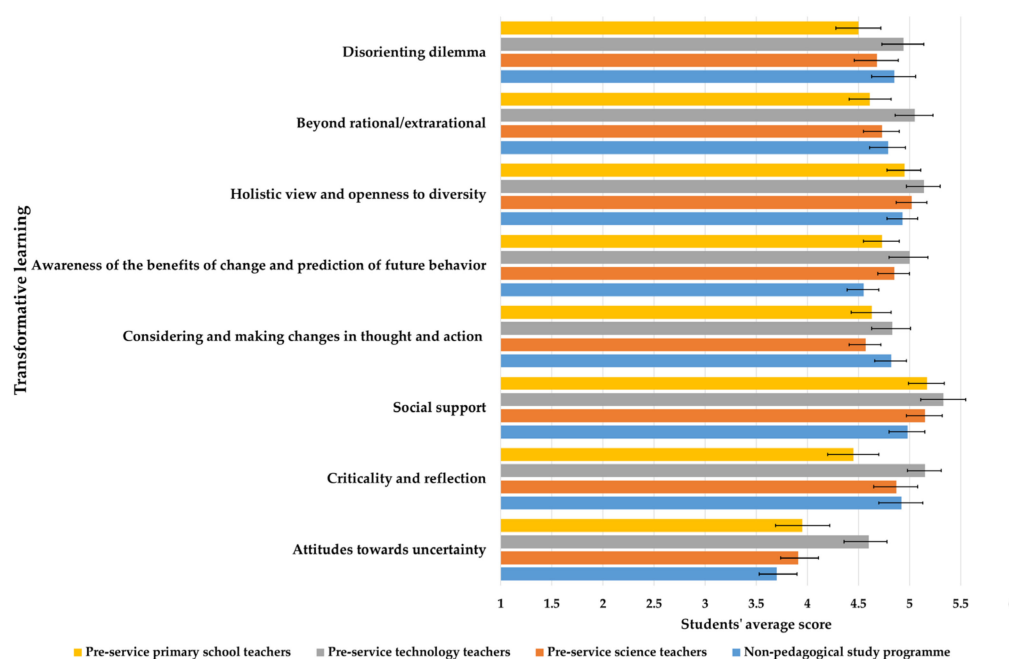


Figure 3. Students' perceived ability for transformative learning on 8 subscales with 95% confidence intervals.

3.4. Relationships between Self-Directed Learning, Design Thinking, Transformative Learning, and Pre-Service Teacher Education

This study's hypothesis predicted that self-directed learning and design thinking would moderate the effect of pre-service teacher education on transformative learning. First, we conducted a median split of self-directed learning and design thinking to divide participants into "higher" and "lower" self-directed learning and design thinking groups. This enabled the visualization of the transformative learning reported by those lower vs. higher in self-directed learning and design thinking, per study programme condition (Figure 4).

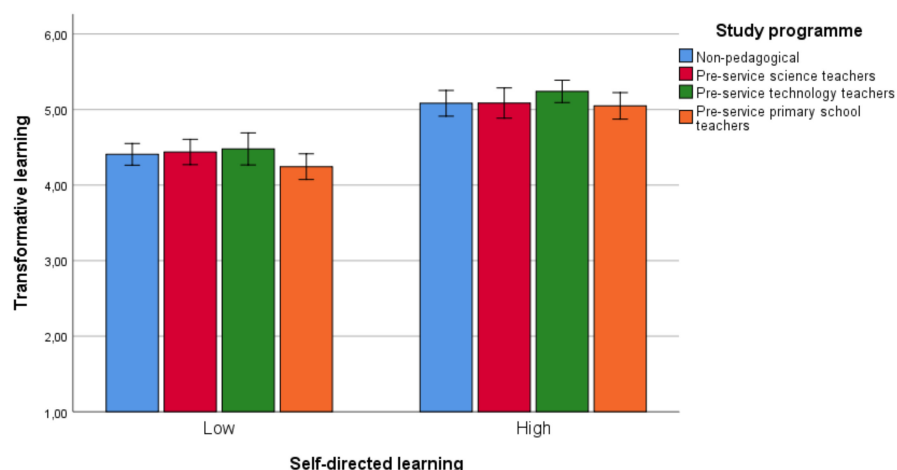


Figure 4. Relationship between self-directed learning, transformative learning, and study programme, with 95% confidence intervals.

As shown in Figure 4, those higher on self-directed learning reported similar levels of transformative learning across the four study programmes, with a modest trend toward greater transformative learning reported by pre-service technology teachers. For those lower on self-directed learning, the trends looked similar.

After reviewing these mean trends, we conducted a 2×4 factorial analysis of variance (ANOVA), which included condition (study programme) and self-directed learning (lower vs. higher) as independent variables and transformative learning as the dependent variable (Table 7).

Table 7. Transformative learning by self-directed learning (lower vs. higher) and different study programmes.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig. <i>p</i>	Partial η^2
Corrected Model	32.50 ^a	7	4.65	22.32	0.000	0.42
Intercept	4777.55	1	4777.55	2,2961.90	0.000	0.99
Self-directed learning	27.62	1	27.62	132.74	0.000	0.38
Group	1.17	3	0.39	1.87	0.135	0.03
Self-directed learning * Group	0.21	3	0.07	0.34	0.797	0.01
Error	45.15	217	0.21			
Total	5157.81	225				

^a Adjusted $R^2 = 0.40$.

Results indicated a significant main effect for self-directed learning, $F(1, 217) = 132.74$, $p < 0.001$, while a non-significant interaction term was detected, $F(3, 217) = 0.34$, $p > 0.05$.

For a more nuanced investigation, we examined the full range of self-directed learning, as a continuous variable. To facilitate a multiple regression analysis, we created dummy variables for the study programme, with the non-pedagogical study programme as the

reference group. We conducted a multiple linear regression (Table 8), regressing transformative learning onto self-directed learning, dummy condition variables, and interaction terms, which explained a significant 61% of the variance in transformative learning, $F(7, 217) = 50.81$, $p < 0.001$. We calculated the explained variances using R^2 from the model, where $R^2 = 0.02$ signifies a small impact, $R^2 = 0.13$ a medium effect size, and $R^2 = 0.26$ a large effect size [78].

Table 8. The interactive effect of self-directed learning and pre-service teachers' study programme on transformative learning.

	Unstandardized Coefficients		<i>t</i>	Sig. <i>p</i>
	β	Std. Error β		
Constant	0.10	0.46	0.23	0.822
Pre-service science teachers	1.53	0.65	2.36	0.019
Pre-service technology teachers	0.89	0.64	1.40	0.162
Pre-service primary school teachers	0.59	0.62	0.97	0.336
Self-directed learning	1.18	0.19	9.98	0.000
Pre-service science teachers * Self-directed learning	−0.39	0.17	−2.37	0.019
Pre-service technology teachers * Self-directed learning	−0.21	0.16	−1.30	0.196
Pre-service primary school teachers * Self-directed learning	−0.20	0.16	−1.28	0.202

Note. Adjusted $R^2 = 0.61$.

As detailed in Table 8, self-directed learning, pre-service science teachers, and the interaction between the two were significant predictors in the model. Thus, our hypothesis was partially supported: self-directed learning moderated some but not all effects of pre-service teacher education on transformative learning. As expected, the biggest differences among the conditions were at the high end of self-directed learning. Pre-service science teachers high in self-directed learning reacted with the least confidence about being capable of transformative learning, whereas other pre-service teachers appeared to react evenly at both ends of self-directed learning, lower and higher.

Figure 5 shows the transformative learning ability reported by students with low and high design thinking ability according to the study programme.

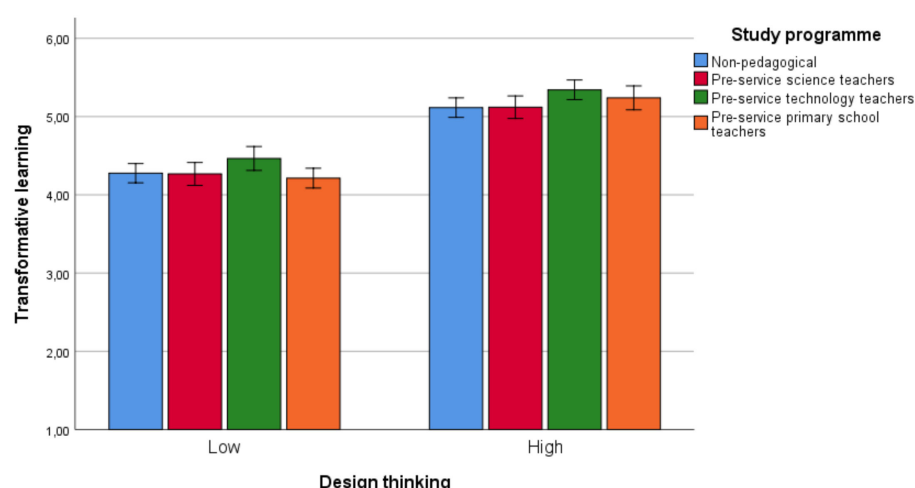


Figure 5. Relationship between design thinking, transformative learning, and study programme, with 95% confidence intervals.

As shown in Figure 5, those higher on design thinking reported similar levels of transformative learning across the four study programmes, with a modest trend toward greater transformative learning reported by pre-service technology teachers. For those lower on design thinking, the trends looked similar.

After reviewing these mean trends, we conducted a 2×4 factorial analysis of variance (ANOVA), which included condition (study programme) and design thinking (lower vs. higher) as independent variables and transformative learning as the dependent variable (Table 9).

Table 9. Transformative learning by design thinking (lower vs. higher) and different study programmes.

Source	Type III Sum of Squares	df	Mean Square	F	Sig. p	Partial η^2
Corrected Model	48.87 ^a	7	6.98	52.63	0.000	0.63
Intercept	4923.31	1	4923.31	3,7117.36	0.000	0.99
Design thinking	1.63	3	0.54	4.09	0.007	0.05
Group	43.96	1	43.96	331.38	0.000	0.60
Design thinking * Group	0.30	3	0.10	0.76	0.519	0.01
Error	28.78	217	0.13			
Total	5157.81	225				

^a Adjusted $R^2 = 0.62$.

Results indicated a significant main effect for design thinking, $F(3, 217) = 4.09, p = 0.007$ and the type of group of students $F(1, 217) = 331.38, p < 0.001$, while a non-significant interaction term was detected, $F(3, 217) = 0.76, p > 0.05$.

We also conducted a multiple linear regression (Table 10), regressing transformative learning onto design thinking, dummy condition variables, and interaction terms, which explained a significant 93% of the variance in transformative learning, $F(7, 217) = 469.35, p < 0.001$.

Table 10. The interactive effect of design thinking and pre-service teachers' study programme on transformative learning.

	Unstandardized Coefficients		t	Sig. p
	β	Std. Error β		
Constant	−0.07	0.16	−0.44	0.661
Pre-service science teachers	0.08	0.25	0.31	0.759
Pre-service technology teachers	0.03	0.25	0.13	0.895
Pre-service primary school teachers	0.12	0.23	0.51	0.609
Design thinking	1.00	0.03	29.27	0.000
Pre-service science teachers * Design thinking	−0.01	0.05	−0.12	0.908
Pre-service technology teachers * Design thinking	0.01	0.05	0.29	0.773
Pre-service primary school teachers * Design thinking	−0.02	0.05	−0.52	0.606

Note. Adjusted $R^2 = 0.93$.

As detailed in Table 10, only design thinking was a significant predictor in the model. Thus, our hypothesis was not supported: design thinking did not moderate the effects of pre-service teacher education on transformative learning. According to the reference group, it seems that design thinking is a direct predictor of student transformative learning, not the student's study major.

4. Discussion

The ESD can be organised for a range of courses, and some courses involve more active and didactically optimised delivery methods and approaches than others. This study explores the circumstances wherein different pedagogical programmes of study reduce or increase individuals' confidence in their ability to engage in transformative learning for sustainable development.

4.1. Undergraduate Students' Characteristics of Self-Directed Learning, Design Thinking, and Transformative Learning Experience

Regarding the results obtained, we can argue that students in both pedagogical and non-pedagogical programmes engaged in this study have an above-average level of (1) reflective process control, (2) reflective process knowledge, and (3) reflective process monitoring, which confirms the findings by [8]. Although self-directed learning is generally well-developed, we ranked constructs from the most developed (*Awareness, Interpersonal skills*) to the least developed (*Learning activities*). It seems that students need more scaffold learning [99], especially when ICT-enhanced learning is engaged towards ESD, as argued by [45]. Moreover, less guidance in active learning can lead to working memory overload and students feeling tired and less motivated, especially when failing during active ICT-supported learning [49].

We also contrasted average scores across the study programmes and found differences in four subscales of self-directed learning. Pre-service technology teachers significantly outperformed the control group as non-pedagogical students in *Awareness, Learning strategies*, and *Interpersonal skills*, where a relatively strong effect size was detected. Smaller differences were found between pedagogical study programmes; thus, we can point to better self-directed learning in pre-service teachers except for *Evaluation*, where no differences were found. Pre-service teachers performed significantly better on feedback-seeking, experimentalism, interactions, diversity of contents, use of ICT, decision-making items, as a part of the *Learning strategies* subscale, and on integrative thinking, collaboration, communication, emotional intelligence, negotiation, social awareness, conflict resolution, and mediation items, as a part of the *Interpersonal skills* subscale. These results are aligned with the findings by [4,8,17] and [46].

Some highlights can be made on pre-service technology teachers, which outperformed all others on all scales. We need to mention that pre-service technology teachers were the only ones out of all the study participants to have taken an extensive creativity course named Creative Technical Workshop (60 periods), and they are fully engaged in design thinking, a relatively new approach to learning in teacher education, where more guidance/scaffolding is offered. Since we showed, in our previous study, that design thinking may enhance self-directed learning [8], it seems that activities conducted in this programme's utilised design thinking as well as a student-centred method based on socio-constructivists theory, and students showed significant progress in self-directed learning, also by didactical and goal-oriented use of ICT [9]. Moreover, they use failure as a trigger for the use of meta-cognitive design thinking as an innovative approach to teaching and learning, which can be seen as a means of improving the quality of education towards sustainability, as argued by [8,32,64,99].

As shown in Figure 2, students' design thinking was above the average, expressed with self-assessment scores on 13 subscales. Results from a non-parametric test show over-performance of pre-service technology teachers on most scales. Such a result was expected, since pre-service technology teachers used design thinking in their learning projects in several subjects, and they have absorbed the course of creative thinking, while other groups have not. Here, we also confirm findings by [19], where creativity was found to be a driver towards effective transformative learning founded on self-directed learning, where creative and collaborative learning spaces created in the courses of pre-service technology teachers can bridge transformative learning and ESD, since the success of self-directed learning depends on both students and educators, interactively, as argued by [25,43]. Moreover, at *Embracing risk, Mindfulness and awareness of process, Team knowledge*, and *Open to diversity*, it was found that pre-service teachers outperformed non-pedagogical students, which points to enhancing transformative learning through failure, disorienting dilemmas, and collaborative cross-disciplinary learning projects, where their realisation is under risk or the results are unknown [25,32,55,56]. Involving these opportunities in design thinking, students became more aware, act differently, are more open to diversity, and make informed decisions after reflection, as argued by [56,59,63], and indirectly promote

self-directed learning and transformative learning, as argued by [20,27]. Moreover, the translation of cognitive and affective empathy in design thinking into conative (inclination for action) might have been realised, as stated by [8,60].

The most critical subscale of *Problem reframing* was discovered in pre-service teachers. It seems that learning and developing skills for the reformulation of the initial problem in a meaningful and holistic way points to fewer opportunities given to pre-service teachers, while architecture students practise on real-world cases and get motivated and interested to better understand a given problem. It seems they want to ensure that there is no, or less, risk for failure when learning by doing, which is in line with the findings by [8,55,64]. As Dorst [55] has argued, the key elements of design practise is that paradoxes and design thinkers must oppose conflict and satisfy potentially conflicting considerations. When designers meet novel situations or problems, they start searching for a central paradox, and, when the nature of that paradox is satisfactorily established, then they start working toward the solution [55]. This paradigm in architecture and design education can be transferred, developed, and applied to pre-service teachers' courses to improve pre-service teachers' design and transformative learning [32,41]. This is carried out since dealing with conflicting values was found as a success factor of transformative learning [18,25].

The pre-service teacher transformative learning experience was especially highlighted at *Social support* since teacher education programmes focus on collaborative teamwork, many social interactions with teachers and pupils in schools and other social institutions. Thus, learners develop the openness and confidence necessary to deal with learning by experiencing, reflecting on, and exploring uncertainty, as argued by [87], and pre-service teachers can make progress both on a cognitive and affective level, as argued by [88]. Moreover, pre-service teachers also developed a higher level of awareness of the benefits of changes when acting differently, which might help them predict future behaviour. Deeper self-awareness can, thus, boost transformative learning by bringing the unconsciousness to consciousness and acting upon social-cultural reality, as argued by [32,41], in which pre-service teachers are engaged during internships in schools and other educational institutions where social-emotional communication can be enhanced as an important success factor for transformative learning, confirming arguments by [25,40].

Pre-service teachers have outperformed non-pedagogical students in a less developed category of *Attitudes towards uncertainty*. It seems that pre-service teachers learned and trained in study programs wherein didactical strategies, methods, and approaches to learning differ depending on the study situation, thus, having a better perception of the gap in what they want to learn and what they have actually learned. Feeling uncertainty might encourage deeper reflection, as argued by [82], and help change the belief system in a positive manner, as argued by [18].

As an overview, we have found that pre-service teachers have significantly outperformed their non-pedagogical counterparts in *Interpersonal skills*, *Team knowledge*, and *Social support*, which points to more developed skills for collaboration, communication, and interactions, in line with the findings by [25].

4.2. The Effect of Teacher Education Study Programmes on Transformative Learning in Self-Directed Learning and Design Thinking

ESD can be implemented in many disciplines, and some study programmes involve more advanced teaching/learning methods than others. Since the education of sustainable development focuses on three domains, (1) cognitive, (2) emotional, and (3) conative (inclination for action), where sustainability competencies are complemented by strong disciplinary skills, transformative learning is proposed where different views on the same challenges are required for innovative conceptualisations and creative approaches, as argued by [100].

This study also examines the circumstances under which the study programme reduces the confidence individuals have in learning in a transformative way. Results suggest that the students' belief that they would be successful in transformative learning depends on the study programme under certain circumstances, namely, when their self-directed

learning is high and the programme is science education. While our hypothesis expected that self-directed learning moderates the relationship between the study programme and transformative learning, the results did not follow a perfectly predictable pattern. Although we expected that the strongest relationship between self-directed learning and transformative learning would exist for pre-service technology teachers, self-directed learning mattered for pre-service science teachers. It seems that high-ability self-directed pre-service teachers need more support at transformative learning towards sustainable development, as self-directed learning was not able to address challenges in the socio-constructivist approach, confirming the findings by [45]. Pre-service science teachers might have had a more realistic view of the challenges associated with the issues on sustainability and so they reacted with the least confidence in their transformative learning ability.

The second hypothesis explored whether design thinking would moderate the effect of teacher education study programmes on transformative learning. Results obtained from analysis do not support this hypothesis, meaning that both low- and high-ability pre-service teachers in design thinking advance evenly in transformative learning, according to the reference group which was experienced in design thinking. We argue that design thinking can be used in higher education, especially in teacher education programmes, as a relatively new approach in transformative learning, which is in line with the findings by [19,20,60].

The third hypothesis examined whether pre-service teachers exhibit higher social skills, self-awareness, and critical thinking and reflection skills than their non-pedagogical colleagues. The results of the analysis support this hypothesis in terms of awareness of the benefits of change and prediction of future behaviour, while the categories of *Social support* and *Critical thinking and reflection* do not. Here we can point out that pre-service technology teachers performed significantly ($p < 0.05$) better than architecture students in the categories *Attitude towards uncertainty*, *Social support*, *Awareness of benefits of change*, and *Prediction of future behaviour*. This result suggests that the didactic and purposeful use of ICT and design thinking in technology-teacher education can enhance the cognitive, emotional, and social critical process of transformative learning. It could be applied to other courses. Thus, we support the findings of [9,32,99,100].

Transformative learning, contextualised within self-directed learning and design thinking, might facilitate the process of sustainability transformation through teacher education, where social, economic, and environmental challenges are addressed through SDGs from unsustainable to sustainable learning outcomes, which confirms the findings by [100].

4.3. Implications and Limitations of the Study and Future Work

The present study involved some shortcomings which may be stated as follows: (1) Since the present study was a one-time empirical investigation, the results should be treated with caution. Students have undergone different forms of education and might have developed different self-directed learning and design thinking skills, so the measurement model of a latent variable is not the same in different groups of students. To improve the accuracy of our predictive models, measurement invariance should be examined in a longitudinal study, especially if the study includes latent variables and multiple samples in a cross-disciplinary survey. (2) A much larger and more diverse sample is needed to support the generalisation of results. Since the majority of the sample represents female students, greater diversity should also be achieved when including subjects with a male majority. The control group of students should be more diverse, both in terms of study major and in terms of different learning experiences with design thinking, self-directed learning, and transformative learning in relation to sustainable development. It seems that the selected architecture students in this study were a highly competent group in the role of the reference group. (3) In this study, only a sociological survey was conducted. A need is identified for qualitative data that includes the perceptions of educators on the topic examined in the study. (4) Measuring students' academic outcomes or cognitive results,

and creativity would have expanded the results' explanatory power. (5) This study's conclusions are bound by and limited to the pre-service teacher education programmes: primary, science, and technology teachers. (6) The relationship between self-directed learning, design thinking, and transformative learning in this study was correlational. To explore a causal rather than correlational relationship, future work should examine whether random assignment to an intervention designed to raise self-directed learning (design thinking) increases transformative learning in a manner that reduces differential reactions to study programmes that vary in ICT-enhanced active learning sophistication.

The practical implications of the analysis are derived based on the above, since the conclusions reached will enable enriching transformative teaching/learning processes, as well as defining strategic lines of pre-service teacher education for both regular and contingency situations towards ESD. Moreover, the results enable us to identify feedback elements on the transformative learning practice of great value for professional work as teachers/educators.

Future research should also endeavour to replicate the findings of this study and unpack the reasons for the exhibited patterns. The inclusion of prior negative experience with various student-centred approaches to learning would be a valuable addition to future work designed to test whether such experiences explain transformative learning beliefs, values, team learning, social-emotional communication, and creative problem-solving.

5. Conclusions

This study sheds light on variables that influence the ability for self-directed learning and design thinking that pre-service teachers need to have to succeed in transformative learning. Transformative learning does not always imply improvement towards ESD. The findings suggest that design thinking ability might improve transformative learning for both low- and high-ability pre-service teachers, while self-directed learning needs special treatment among high-ability pre-service science teachers. In order to reduce the overloading of working memory in high-ability students, which can douse transformative learning, some guidance is needed. Moreover, as self-directed learning is not able to address all social challenges, a complementary solution can be seen in collaborative learning spaces as a key factor in dealing with several sustainability challenges through the perception of consciousness-raising, critical reflection, personal growth, and individuation.

The results also suggest that applying the technology-enhanced meta-cognitive design thinking to teacher education for sustainable development is beneficial for developing preservice teachers' schema of transformative learning, especially with respect to rethinking the disorienting dilemma, developing self-awareness, shaping attitudes toward uncertainty, social support, criticality and reflection.

By assessing pre-service teachers' self-directed learning and design thinking, educational institutions seeking to develop and/or administer their study programmes can get a clear picture of potential barriers to the successful deployment of transformative learning.

If educators continue to ignore the tension between the demands for personalised learning pathways and traditional enrollment, learners will abandon technology-enhanced transformative learning as quickly as they tried it. As a result, transformative learning would become fraught with widespread misuse, misconceptions, and misattributions, limiting its power and impact.

Personalised learning pathways can increase motivation because learners deal with subjects they are interested in and feel responsible for. Moreover, educators should support learners in their ideas about what and how to learn and provide them with technological tools that make this process possible. Minimal guidance would help reduce learners' working memory load. Educators should provide guidance and faster access to a domain's actual contents for novices in the field since they have difficulties identifying meaningful learning objectives. The development of social skills, self-awareness, and the ability to cope with risk and uncertainty helps give concreteness to teacher ESD.

In summary, the results of the present studies also suggest that pre-service teachers' active engagement in technology-enhanced transformative learning can be confounded by unclear guidance and the non-didactical use of ICT. Furthermore, technology-enhanced design thinking with target use of ICT in teacher education programmes supports a pedagogical change from "learning to understand" to "learning to act and transform". Moreover, if we can show which learning process leads to a specific outcome, we can unify the various perspectives on transformative learning towards ESD.

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