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U-shaped learning: a new model for transdisciplinary education

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Over the past two decades, transdisciplinarity has been cited increasingly by policymakers and university actors as a means to reshape learning and research processes to improve society's potential to tackle grand societal challenges. Most recently, the Earth-Humanity Charter calls for the co-creation of a worldwide network of thousands of transdisciplinary hubs that will be active at local, national, and global levels, with a function to address the existential challenges facing humanity in the 21st century. To date, the majority of research published on transdisciplinarity focuses on the transdisciplinary research process. The transdisciplinary learning process i.e., how researchers, students, academic and extra-academic actors can develop their capacity for transdisciplinarity, is under-researched. As a result, many practitioners find themselves designing transdisciplinary learning experiences without an evidence base regarding the learning process, the learning gains of those involved or learning design principles. Based on the results of a literature review of transdisciplinarity, this article proposes that transdisciplinary practice requires two capacities: knowledge integration and actionable knowledge (closing the knowledge-action gap). These capacities are supported by the development (or presence) of intra-personal, interpersonal and cognitive competencies. The results suggest that a U-shaped model of transdisciplinary learning is evident in practice. This conceptual model also potentially enables the measurement of learning gains in transdisciplinary education.

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Introduction

To many, transdisciplinarity is a complex word used to describe a very simple idea: to solve societal problems, you need multiple viewpoints, multiple actors and varied expertise (Klein, 2014; Gibbs, 2015; Vienni Baptista & Rojas-Castro, 2020). Within academia, transdisciplinarity has emerged as a movement to address complex challenges (Gibbs, 2015; Fam et al., 2018) to bring about greater 'response-ability' (Sterling, 2004, p. 50) and to "overcome the mismatch between knowledge production in academia, on the one hand, and knowledge requests for solving societal problems" (Hoffmann-Riem, Biber-Klemm, Grossenbacher-Mansuy, Hirsch Hadorn, Joye, Wiesmann & Zemp, 2008, p. 3). This is increasingly reflected in European policy (European Commission, 2019, 2020).

From an educational perspective, transdisciplinarity is a normative and societally-oriented educational approach that prioritises solving societal problems through the integration of knowledge and the equal participation of societal actors in the knowledge-creation process (Hirsch Hadorn et al., (2008)). Universities are motivated to do transdisciplinarity to develop transdisciplinary research capabilities (LERU, 2016). Transdisciplinary learning is seen as necessary to develop the skills of future researchers and experts to foster their ability to build effective partnerships with many different actors for addressing complex societal and environmental challenges (Sterling, 2004; Kueffer et al., 2012). Transdisciplinarity is predominantly associated with environmental science and sustainability education across all disciplines (Dlouha et al., (2013); Fam et al., 2018; Gaard et al., 2017; Macagno et al., 2024) and is perceived as a new paradigm that can systematise sustainability education (Wallen et al., 2022).

Within transdisciplinarity, learning is viewed as collective and collaborative across all disciplines (e.g., arts, natural sciences and social sciences) with actors in public and private spheres (Fam et al., 2018). In transdisciplinary learning, students collaborate and interact to understand where their knowledge sits in relation to the knowledge of others thereby creating both 'distributed intelligence' and 'collective intelligence' (Gibbs, 2017).

This article uses the term extra-academic actor to describe those who are connected to transdisciplinary work on challenges but who are external to the academy (O'Sullivan, 2023). Extra-academic actors may have lived experience of a complex societal issue e.g. flooding in a city; professional experience of the complex societal issue e.g. engineers; extra-academic research expertise of the complex societal issue e.g. private consultancy firms; or those with a political interest e.g. local, regional or global political groups, activist or otherwise. This term is used, as opposed to more commonly used terms, such as societal actor or external stakeholder, for several reasons. Academic actors and extra-academic actors are all actors in society. The word external suggests that some actors are on the outside while others are on the inside; in grand societal challenges, everyone is a stakeholder. Knowledge produced outside the university is of no greater or lesser importance than knowledge produced within the university.

As a mode of learning, transdisciplinarity is in its infancy, without a clear pedagogy or principles. The aim of this paper is to examine the literature on transdisciplinarity to ask how transdisciplinarity is conceptualised; what competencies practitioners and transdisciplinarity scholars ascribe to transdisciplinary learning; and what curricula are designed with the aim of developing these. It presents a conceptual model of transdisciplinary learning called U-shaped learning, which creates a visualisation of transdisciplinary learning as the development of two key capacities: knowledge integration and actionable knowledge. The development of these capacities is dependent on the presence or cultivation of a range of competencies: intrapersonal, interpersonal and cognitive.

Aims of the study

Within transdisciplinarity, learning takes place through collective and collaborative interactions across disciplines (e.g. arts, natural sciences, and social sciences) and with extra-academic actors i.e. actors external to the higher education institution (Fam, Neuhauser and Gibbs 2018; O'Sullivan, 2023). While existing literature explores transdisciplinarity as a concept and research process, there is a lack of research on the transdisciplinary learning process i.e., how researchers, students, academic and extra-academic actors can develop transdisciplinary capacities. Transdisciplinary learning necessitates the mobilisation of constellations of actors who create actionable knowledge at a porous boundary between university and society, this mobilisation and engagement requires a suite of competencies in all actors. Yet we have insufficient knowledge about what these competencies are and how they are developed. This disables the design, monitoring and realisation of transdisciplinary activities. This article seeks to address this gap by proposing a model of the transdisciplinary learning process as U-shaped learning that is based on the results of a literature review of transdisciplinary learning in higher education. The literature review was framed by the following questions:

- How is transdisciplinarity conceptualised in the literature?
- What competencies do researchers and educators see as foundational for building transdisciplinary capacities?
- What learning processes are proposed to develop these competencies?

Answering these questions will help universities and civic organisations understand how and what students learn in transdisciplinary education and how transdisciplinary groups—comprising academic and extra-academic actors—can be prepared for and supported in engagement with transdisciplinary work. Additionally, it focuses the attention of scholars on making explicit how integrative and actionable knowledge capacities are developed in educational programmes.

Methods

Procedure. The first phase of the literature review comprised a snowball search that began with a focus on key texts from recognised scholars who have published on transdisciplinarity, for example, Eric Jantsch, Basarab Nicolescu, Susan McGregor, Julie Klein, Christian Pohl, Gertrude Hirsh-Hadorn, Paul Gibbs and Dena Fam among others. This first phase sought to establish how transdisciplinarity has been and is conceptualised in the literature.

The second phase of the literature review built on the first phase and comprised a focused search to surface curricula and teaching models that are self-described as transdisciplinary. Several search terms and combinations thereof were trialled and the terms "transdisc*" and "curriculum" and "design" yielded the most relevant results. These terms were used within article title, abstract and keywords in Scopus and Web of Science with a date range between 1970 and 2023. 283 articles were returned from Scopus and 87 from Web of Science. Each abstract was reviewed to narrow inclusion to literature that presented instances of educational practice informed by the literature on transdisciplinarity i.e. they demonstrated an understanding of the term, its history and origins and key principles. As integration is not fully developed within educational practice, the absence of integration was not an exclusion criterion. Publications were further narrowed to those that addressed how transdisciplinary curricula were designed and what transdisciplinary curricula were designed. The list was limited to educational programmes for students in higher education institutions. The results included

conference proceedings, book chapters and journal articles. These results were filtered by the author by reading through abstracts. This reduced the number of relevant articles to approximately 100. The dataset was complemented by articles listed by the Swiss Academies of Arts and Sciences' Network for Transdisciplinary Research (td-net) annual report *A Tour d'horizon of literature related to transdisciplinarity*. Td-net produces a list annually of all publications that contribute to the field of transdisciplinary education and research. This network is the centre of the contemporary European tradition of transdisciplinarity and is closely connected to environmental science researchers at ETH Zurich.

Results

As a field, contemporary writing on transdisciplinarity is diffuse, ever-increasing and comprises multiple definitions, aspirations, normative stances and practices. To some it is a theory, to others a pedagogy, to more a research method, a way of doing, or a different way of seeing the world (Max-Neef, 2005). The reality is that what can appear a simple problem-solving disposition to some is to others a complex epistemological paradigm with ambitions to transform how we perceive, create and use knowledge (Nicolescu, 1994, 2007, 2010, 2014). For the past decade, the term has enjoyed a growing popularity within the higher education sector. Transdisciplinarity has been cited within literature as a means to reorient education in the face of global challenges, for example, climate change (Sterling, 2004; Cincera et al., 2018; Fam et al., 2018). In recent years, the use of transdisciplinarity has become more widespread and what it is used to convey, more diverse. It can mean being "very interdisciplinary or involving stakeholders or full post-normal science" (Scholz, 2020).

How is transdisciplinarity conceptualised in the literature? Discourse on transdisciplinarity has been active for fifty years and the intellectual agenda is not set within or by a single discipline (Gibbons et al., 1994). The term transdisciplinarity emerged from the work of Eric Jantsch (1970), the OECD Seminar on Interdisciplinarity in Universities in Nice in September 1970 and the resulting book *Interdisciplinarity: Problems of Teaching and Research in Higher Education* (Apostel et al., 1972). At that time, a call for interdisciplinarity and transdisciplinarity in universities was initiated as a call for sectoral reform. The seminar and resultant publication did not seek to eliminate any of the disciplines but to teach them in the context of their dynamic relationship with other disciplines and in terms of societal problems. At the conference, transdisciplinarity was defined as "a common system of axioms for a set of disciplines" (Klein, 2004, p. 515). Two distinct though overlapping transdisciplinary capacities emerged from the 1972 publication that demonstrate an early split in emphasis within transdisciplinarity. From one perspective, transdisciplinarity supposes epistemological restructuring: this perspective emphasises a capacity for integration. This is synonymous with the contributions of Jean Piaget to the 1970 OECD conference. The second perspective emphasises actionable knowledge, or the capacity to create knowledge that enables action. This supposes political restructuring of the university to produce purposive knowledge to solve societal problems. This is synonymous with the work of Jantsch, in particular, as it pertains to the system of a university. These two capacities can be traced through the differing transdisciplinarity perspectives, but elements of both are present in contemporary (twenty-first century) transdisciplinary approaches.

Knowledge integration. While the concept of integration is central to transdisciplinarity, it can be conceptualised at different levels: integration of knowledge at an epistemological level (for example, Western, indigenous, multi-disciplinary etc.) and integration of knowledge gained from lived experiences (of self and others) into academic discourse.

In *Interdisciplinarity: Problems of Teaching and Research in Higher Education*, Jean Piaget (1972) explored the epistemology of interdisciplinary relationships and transdisciplinarity. He defined the meaning of knowledge in terms of its method of construction and described his search for underlying transformational systems that would convey interconnectedness rather than causality (Piaget, 1972). This ambition was to capture reality as a whole (unity of knowledge). Piaget used the concept of interaction between disciplines to distinguish between multi-, inter- and transdisciplinarity. Multidisciplinarity, he wrote, "occurs when the solution to a problem makes it necessary to obtain information from two or more sciences or sectors of knowledge without the disciplines drawn on thereby being changed or enriched" (Piaget, 1972, p. 133). Interdisciplinarity comprised "actual interactions, to a certain reciprocity of exchanges resulting in mutual enrichment" (ibid). He referred to transdisciplinarity as a "higher stage" "which would not only cover interactions or reciprocities between specialised research projects, but would place these relationships within a total system without any firm boundaries between disciplines. While this is still a dream, it does not seem to be unattainable…" (ibid p.135). Full transdisciplinarity would be a "general theory of systems or structures including operative structures, regulatory structures and probabilist systems, and linking these various possibilities by means of regulated and definite transformations" (ibid p. 136).

Historically and philosophically, therefore, we can draw from the content and influence of Piaget's work that there is a distinction between the integrative ambitions of interdisciplinarity and transdisciplinarity. This is continued in the work of Nicolescu (2007), now a prominent figure in international discourse on transdisciplinarity. Nicolescu critiqued both Piaget and Jantsch for "falling into the trap" of proposing transdisciplinarity as a "hyperdiscipline" or a "science of sciences" (Nicolescu, 2014, p. 19). In the 1980s, Nicolescu developed a methodology of transdisciplinarity in a series of articles published in the French review *3rd Millennium* by merging what he described as the soft sciences and hard sciences through bringing the excluded 'subject' (human beings) into the domain of knowledge (De Alvarenga, 2008). Nicolescu's methodology of transdisciplinarity was published in his first book in France *Nous, la particule et le monde* (1985). Nicolescu's three pillars of a transdisciplinary methodology are:

- Ontology – multiple Levels of Reality
- The Logic of the Included Middle
- Epistemology – knowledge as an emergent complexity

To Nicolescu, Reality [uppercase 'R'] is what resists our experience or resists representation or description even through mathematical formulation. Levels of Reality refer to sets of systems: those that are invariant under certain sets of general laws, for example, natural systems, and those that are variant under certain sets of general laws, for example, social systems (Nicolescu, 2010). Nicolescu describes the Included Middle as a space of interaction between the multiple Levels of Reality (natural systems and social systems) and Reality as a whole, the complex system. This is a zone of non-resistance, the Hidden Third, which Nicolescu describes as an interaction term. This space is where the integrative process can take place. Gibbs and McGregor (2023, p. 3) explain it further as a space where "people (A) temporarily stop resisting each others' contradictory ideas (non-A) and start listening to each other until something new

emerges". In this space, we don't just know, we can imagine and create, we can transform and be transformed. To Nicolescu (2010), this was vital to education and learning. This short synopsis reveals a constituent part of the ambition of transdisciplinarity that is underplayed in contemporary accounts of transdisciplinarity but that is acknowledged, nonetheless (Klein, 2014; Lang et al., 2012; Pohl & Hirsch Hadorn, 2007; Scholz, 2020; Scholz et al., 2006).

In what might be termed a more Eurocentric model of transdisciplinarity, the integration of knowledge from extra-academic actors is seen as central to transdisciplinarity (Pohl & Hirsch Hadorn, 2007). Extra-academic actors include practitioners, scientific domain experts or those with lived experience of a challenge. Practitioners are considered experts because they work with real-world challenges. Scientists are considered experts because they develop evidence-based assumptions of dynamics underlying real-world systems (Scholz et al., 2015). The goal is to create knowledge that is "solution-oriented, socially robust and transferable to both scientific and societal practice" (Lang et al., 2012). Integration also takes place in the process that brings together individuals from different fields to work together over an extended period. This process has as its key outcome the development of new overarching conceptual and methodological frameworks that enable action in response to a challenge or complex problem. This process supports mutual learning between and among science and society (Scholz, 2020).

The placing of self in relation to others is emphasized in American and European conceptualisations of transdisciplinarity but articulated in terms of the interpersonal and intrapersonal competencies seen as necessary for collaboration and joint problem-solving (see, for example, Misra et al., 2015). For other practitioners, a similar ambition is expressed as connecting to the interiority of each individual—the integration within the self of all parts of the self. For example, Collado-Ruano, Madroñero-Morillo & Álvarez-González (2019, p. 180) define the transdisciplinary perspective as "the unification of our human dimensions, including our cognitive, affective, emotional, volitional, motivational, spiritual, religious, and behavioral levels of the whole personality or at a transpersonal level". They contend the spiritual and emotional universe of each individual is something unique that can not be standardized with educational curricula or pedagogical models. For this reason, they state the importance of training transdisciplinary educators to integrate a multidimensional approach in the learning–teaching processes. In other words, transdisciplinary educators need to reevaluate the role of intuition, of the imaginary, of sensitivity, and of the body in the transmission of knowledge.

While in a more Eurocentric model, the emphasis is on integration of disciplines and extra-academic knowledge (Hoffmann, Pohl & Hering, 2017), elsewhere practitioners emphasise the integration of different epistemologies i.e. indigenous conceptualisations of knowledge (Robson-Williams et al. 2023; Kassam, 2021). In Ecuador, for example, transdisciplinarity is seen as an act of unifying scientific knowledge (an ecology of knowledge) and indigenous spiritual wisdom (Collado-Ruano et al., 2019). This has been described as bio-literacy pedagogy and emerged as a direct response to government policy derived from the ancestral philosophy of Good Living. Good Living is based on Quechua's ancestral worldview of Sumak Kawsa, a philosophical and political proposal that sees humans as integral and interdependent with natural and social environments; there is no division between subject and object. Part of this is an emphasis on the mystic (a thread in common with Nicolescu) but also action to establish communal relations and to "act upon oneself and others": the "politics of relation of otherness" (ibid, p. 188). The following section traces the development of the action-oriented strand of transdisciplinarity.

Actionable knowledge (problem-solving).

> "There is not a single system of science, there are as many systems as there are purposes." Eric Jantsch (1972, p. 99)

What is missing from Nicolescu's methodology, but is emphasised in Eric Jantsch's (1970) work is action. Argyris (1996) describes actionable knowledge as knowledge required to implement the external validity (relevance) of that knowledge in the world. Although emerging from the discipline of management and business (Sexton & Lu, 2009), the term actionable knowledge has been adopted and used within environmental science (e.g. Mach et al., 2020) to describe knowledge co-production that is problem-driven and brings knowledge producers and decision-makers together. Jantsch (1970) argued that universities and knowledge should be organised for a purpose and the university should take an active role in societal planning and service to society. He contended that universities needed to be designed for "flexible change in accordance with the dynamically evolving situation" (Jantsch, 1972. p. 99) and his approach has been described as problem-solving (Klein, 2014). Jantsch shifted the analysis from the elements within a system to how they interact and saw purpose as leading to a mutual enhancement of epistemologies. He saw knowledge as developing the ability to judge complex, dynamically changing situations.

Another methodology seen as connected to this actionable principle of transdisciplinarity is postnormal science (PNS) (Funtowicz & Ravetz, 2008). Funtowicz and Ravetz describe normal science as apt in policy-relevant fields of science when "simple puzzle-solving is effective" (Funtowicz & Ravetz in Hirsch Hadorn et al., (2008), p. 362). PNS is needed when high levels of one or both of the following is present: systems uncertainties and decision stakes. Scientific input in these circumstances especially to the policy process needs an extended peer community. This extended peer community is all those with a stake in the dialogue. PNS has parallels with early work identifying "wicked problems" which are "difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize" (Rittel & Webber, 1973) and complements transdisciplinarity in creating a new understanding of science (Funtowicz & Ravetz, 2008) which is expressed by Gibbons et al. (1994) as a shift from Mode 1 to Mode 2 science. Gibbons et al. (1994) argued that Mode 2 seeks to expand the use of science from just describing and explaining phenomena (Mode 1), to also clarifying societal goals (target knowledge) and how to get to those goals (transformation knowledge) (Mode 2). In simple terms, Mode 2 is focused on the use of knowledge to society. It is an outgrowth of and stands next to Mode 1, rather than replacing it. Networks of people and how they interact in "socially organised forms" are central aspects to Mode 2 (Gibbons et al., 1994, p. 17). The distinction between the Mode 2 approach and the contemporary transdisciplinary approach is that Mode 2 does not query the epistemological foundations of academic knowledge to the same extent as transdisciplinarity. Within transdisciplinarity, what comprises knowledge that is deemed valid to be part of academic discourse is queried.

What we can establish from the history of the emergence of transdisciplinarity is that in transdisciplinary practice, methodology and theory take shape from the problem formulation. This is highly specific and local and is based on a common theoretical understanding and epistemological interpenetration. In simplest terms, in transdisciplinarity the problem comes first. If there are multiple actors with relevant knowledge necessary to create societal action to respond to societal problems (that are created by all actors), impact upon all actors and about which all actors may have relevant insights and knowledge, then the participation of all actors is necessary.

A contemporary European tradition of transdisciplinarity. In 1991, the Swiss National Science Foundation (NSF) made a call for transdisciplinary research as part of the Swiss Environmental Priority Programme. Transdisciplinary research comprised joint problem definitions and evaluation of research outcomes by practitioners and scientists (Scholz, 2020). This "problem first" approach captures the focus of a discourse of transdisciplinarity that co-joins the two transdisciplinary capacities (knowledge integration and actionable knowledge). This European tradition is a discourse of trans-sector, problem-oriented research that is values-driven, aligned with sustainability and involves the participation of extra-academic actors (Klein, 2014; Augsburg, 2014). Process-oriented and practice-oriented, this is a science with as opposed to for society (Scholz & Steiner, 2015).

This approach was further solidified when in 2000, the Zurich 2000 conference brought together the heads of NSF and ETH Zurich with industry and civil organisations under the banner *Transdisciplinarity: Joint problem-solving among science, technology, and society: An effective way for managing complexity*. The conference yielded a wealth of material on how to do transdisciplinarity and proposed a definition of transdisciplinarity as aspiring "to the efficient use of knowledge by relating different epistemics (i.e. ways of knowing) when dealing with a complex, societally relevant real-world problem" (Scholz & Steiner, 2015). Researchers acknowledged that transdisciplinarity has its own distinct theoretical structures, research methods and modes of practice and these are individual to the problem at hand and therefore may not be transferable (Pohl, Krütli & Stauffacher, 2017). This European tradition seeks to (Pohl & Hirsch Hadorn, 2008):

a. grasp the relevant complexity of a problem,
b. take into account the diversity of life-world and scientific perceptions of problems,
c. link abstract and case-specific knowledge, and
d. develop knowledge and practices that promote what is perceived to be the common good (p. 36).

In 1997, Swiss researchers produced a report *Research on sustainability and global change – visions in science policy*. The stated aim was for science to produce and communicate knowledge of three types: Systems knowledge about structures, processes, variabilities, etc.; Target knowledge about the targets of future development and scenarios; Transformation knowledge about the transition from the current to a future target situation (ProClim, 1997). Swiss researchers proposed that these types of knowledge must be submitted for public debate. Thus knowledge is produced within a team structure and communicated in dialogue with broader sections of society. Transdisciplinarity is comprised of democratic discourse and this means that it is dependent on a team that possesses the competencies needed for this type of work. A key point referenced in OECD policy (OECD, 2020) is that prior experience with transdisciplinarity is key to developing capacities and to successful transdisciplinary research teams. The orientation towards conceptualising transdisciplinarity in terms of competency development harmonises with a body of literature on transdisciplinarity that can be traced back arguably to Nicolescu's *Manifesto of transdisciplinarity* (2002) and *The charter of transdisciplinarity* (1994) both of which are heavily normative and promote the idea of a transdisciplinary individual and the need for integral education of the human being.

What capacities and competencies do researchers and educators seek to develop in learning programs? Across the literature, educators describe the goals of the transdisciplinary learning process as enabling learners to effectively integrate perspectives and connect to real-world action to problem solve. The literature demonstrates that practitioners envisage transdisciplinary practice as requiring two capacities: knowledge integration and actionable knowledge (closing the knowledge-action gap). These capacities are supported by the development (or presence) of intrapersonal, interpersonal and cognitive competencies. Transdisciplinary practice therefore requires individuals to possess the inter- and intra-personal and cognitive competencies to work with diverse groups of people, with diverse sources of information in response to diverse multi-faceted problems or challenges (Augsburg, 2014; Misra et al., 2015). The U-shaped image (see Fig. 1) captures the breadth of this work: to be able to integrate knowledge from other disciplines and domains and to be able to create opportunities to action knowledge, individuals

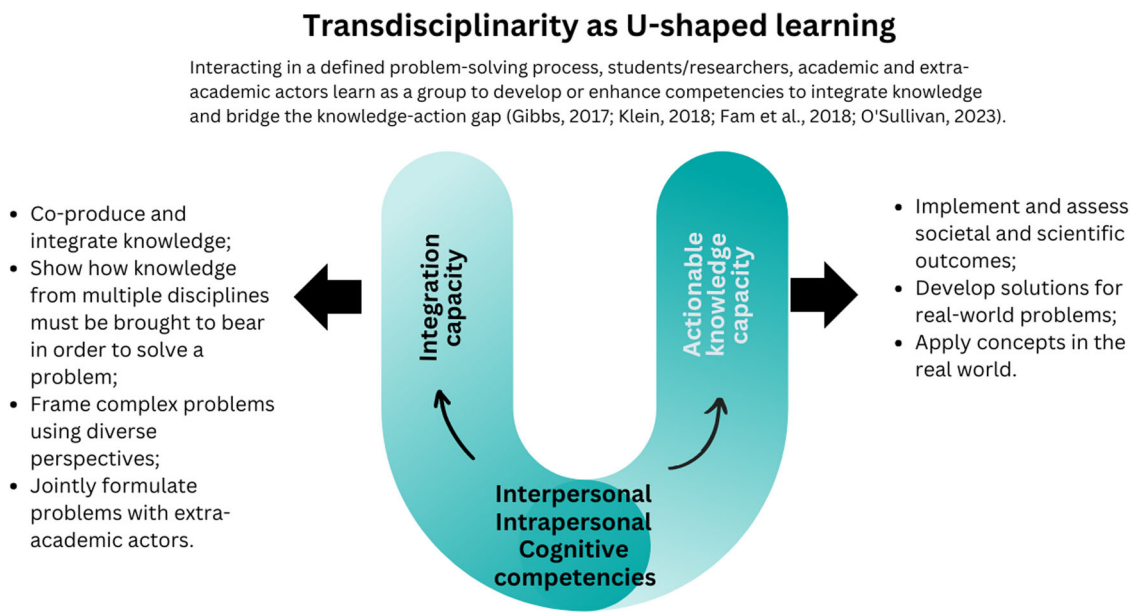

Fig. 1 The U-shaped model of transdisciplinary learning develops two capacities: integration capacity and actionable knowledge capacity. These are supported by the presence or cultivation of a range of competencies.

and teams need a broad set of intrapersonal, interpersonal and cognitive competencies.

Within policy, competencies such as empathy, open-mindedness, sensitivity, social skills, facilitation, knowledge brokerage and the ability to build trust are considered important competencies for transdisciplinary research (OECD, 2020). The National Research Council (2014, p. 98) report on team science identifies the following competencies as necessary for transdisciplinarity: team knowledge (e.g., task understanding, shared mental models, role knowledge); team skills (e.g., communication, assertiveness, situation assessment) and team attitudes (e.g., team orientation, trust, cohesion). Boix Mansilla et al. (2016) list the attributes that need to be present or cultivated on an individual and group level as: competency for deliberation and learning from each other and development of meaningful social relations with group members (ibid). In practice, the intrapersonal and interpersonal are connected in more recent work on transdisciplinarity which uses the term 'capabilities' rather than competencies to included value and beliefs: Misra et al. (2015) locate themselves within the science of team science and describe transdisciplinarity as an orientation composed of "values, attitudes, and beliefs and conceptual skills and behaviors" (ibid p. 6). To them, successful collaboration in transdisciplinarity can be seen at three levels of orientation: intrapersonal, interpersonal, and intellectual orientation. Hawkins (2017) describes how important academic humility and self-reflection are for transdisciplinary work including "a willingness to forgo the personal power-base often associated with traditional monodisciplinary hierarchical structures" (Hawkins, 2017, p. 66).

Within the domain of research practice, certain transdisciplinary approaches have emphasised the central role of the emotional or affective in transdisciplinarity. Cognitive emotion is the term Boix Mansilla et al. (2016) use to describe factors central to successful inter- and transdisciplinary research and inter- and transdisciplinary collaborations. These have three interconnected dimensions: cognitive, emotional, and interactional (Boix Mansilla et al., 2016). Engaging with a network means taking part in relationship and identity work (Vassilev et al., (2014)). Transdisciplinarity learning, according to Gibbs (2017), is social in its nature, a community of learners that is defined by flexibility, adaptability, reflexivity, participation, dialogue and collaboration. The traits of transdisciplinary learning are seen to be flexibility, adaptability, and reflexivity as well as participation, dialogue, and collaboration (Gibbs, 2017) in a manner that bridges cognition, skills, and dispositions (Klein in Fam et al., 2018). This is iterative and transformative. Augsburg's (2014) proposition is that transdisciplinarity is a process of becoming rather than being and across the literature, learning is seen as a process, which is outlined in the next section.

What learning processes are proposed to develop transdisciplinary capacities? Within the literature, transdisciplinary curricula are referred to in terms of the process of learning rather than the content. Transdisciplinary curricula articulate a variety of problem-solving processes, for example, problem identification, problem definition, clarification of aims and problem analysis including context and development of strategies to address the problem. Much of the literature on transdisciplinary learning uses the languages of skills, attitudes and competencies to describe the desired learning process (Gibbs, 2017). Mutual learning is seen as an important component of models as is the development of competencies: collaboration, communication, reflexivity, team development and project management. McGregor, Volckmann (2011) identified transdisciplinary learning processes as comprising three emergent themes: (a) transdisciplinary learning (compared to disciplinary learning), (b) the transdisciplinary learning cycle, and (c) transdisciplinary habits of mind. Crosby et al. (2018) contend that in transdisciplinary learning students develop skills (critical listening, thinking and reflective practice) and competencies (observation and system mapping) in three phases: (1) joint problem formulation, (2) co-production and integration of knowledge and (3) the implementation and assessment of societal and scientific outcomes from the process.

Programmes and modules vary in their design specifics but the two capacities of transdisciplinarity – knowledge integration and actionable knowledge – are present and co-joined in the majority. This literature review suggests that, in practice, the motivation to integrate is driven not by grand epistemological ambitions but by a desire to solve complex problems i.e. use knowledge to support action. Bammer et al. (2023) describe the desired outcome of a university-wide framework for transdisciplinary problem-solving as developing in students "expertise in finding, managing and integrating different knowledge and experience, as well as shepherding change that takes into account the systemic and context-specific nature of the problem" (ibid, p. 1). Analytical and integrative methodologies to cope with complexity are demonstrated in learning outcomes e.g. systems thinking and engagement with extra-academic actors (Krasny et al., 2009; Miller et al., 2008).

Actionable knowledge is evident in the focus on shared problem definition, focus on a grand societal challenge and collaboration with extra-academic actors (Nurius et al., 2017; McGregor, Volckmann (2011)). Greenhalgh-Spencer, Frias and Ertas (2017, p. 75) describe the transdisciplinary curriculum as beginning with "a problem to be solved or a project to be developed". More commonly, the curriculum uses a real-world societal problem or challenge as the starting point but the interaction between students, academics and extra-academic actors in a defined problem-solving process forms the curriculum. ETH Zurich (Pearce et al., 2018) cite Meeth's definition of transdisciplinary learning as their starting point: "Whereas interdisciplinary programs start with the discipline, transdisciplinary programs start with the issue or problem and, through the processes of problem-solving, bring to bear the knowledge of these disciplines that contributes to a solution or resolution" (Meeth, 1978, p. 173). For example, the Tackling Environmental Problems (TEP) course at the Department of Environmental Systems Science (D-USYS) at the Swiss Federal Institute of Technology in Zurich (ETH Zürich) places complex real-world problem-solving at the centre of learning. Each year, students work with affected stakeholders on a specific case study connected to sustainable development in Switzerland (Pearce, 2021). Learning goals were designed to develop what the course organisers describe as transferable skills in students. However, the case study does not explicate the role that disciplinary content plays and how different disciplines are integrated.

The ETH Zurich example has similarities with work by Crosby, Fam, and Mellick Lopes (2018) who outline a Living Lab at the Transdisciplinary Living Lab (TDLL) at the University of Technology Sydney (UTS). Like Pearce above, they describe transdisciplinarity as an iterative learning process. In the case of TDLL, this centres around an on-campus food waste management system. The course has an explicit learning cycle designed around Jahn's concept of an 'ideal transdisciplinary process' (Jahn et al., 2012).

While there was a clear gap in the literature regarding how transdisciplinary programmes or modules are created institutionally from the perspective of process, staffing and disciplinary contributions, there are many examples within the literature on the structure and final design of transdisciplinary learning

experiences (Gibbs, 2017; Fam et al., 2018). However, the literature review demonstrated that the educational practice of transdisciplinarity has not evolved considerably since Klein (2008) produced a comprehensive overview of transdisciplinary curriculum models. Models are teamwork-based either within university environments or in workplaces through work placements. Fam et al. (2018, p. 90) outline curriculum approaches that identify the commonalities of inter- and transdisciplinary teaching and learning approaches for example: team-orientation, project-based, addressing complex problems and collaboration with extra-academic actors (businesses or public bodies). Models include case study methods (including formative scenario analysis, modelling systems dynamics, integrated risk model, future workshops and life-cycle assessment), stakeholder workshops, seminars and fieldwork based around a real-world challenge that combines interdisciplinary approaches with transdisciplinarity i.e. collaborating with extra-academic actors. These learning experiences may be supported by thematic modules e.g. ecosystems, values, social transformation in addition to disciplinary content.

Discussion

This article sought to examine the existing literature on transdisciplinarity – both its conceptual history and its educational practice—to understand how transdisciplinarity is conceptualised, how it is articulated by academics who teach transdisciplinary courses and how those courses are designed to support transdisciplinary learning. The review demonstrates that both within its conceptual history and in its articulation by academics, transdisciplinarity is conceived of as the development of two capacities: knowledge integration and actionable knowledge. The former includes knowledge from different disciplines, epistemologies, cultures, communities and individuals across society. The literature on transdisciplinary education focuses on the learning process—a combination of curriculum and pedagogy—which is expressed in curricular language in terms of competence development. On the whole, the transdisciplinary curriculum comprises a problem-oriented methodology and the content for this is seldom explicated. Likewise, while knowledge integration—between disciplines as well as extra-academic actors—is seen as a necessary part of transdisciplinarity, both the process of integration and the place of disciplinary knowledge are seldom explicated.

Opening the black box on knowledge integration. It is widely acknowledged in transdisciplinary research that knowledge integration is a major challenge of inter- and transdisciplinarity (Bammer, 2005; Bergmann et al., 2005; Klein, 2008; McDonald et al., 2009; Jahn et al., 2012) and there is a growing literature within research practice on integration methodologies. In this regard, educational practice and research lags somewhat behind the depth of research carried out on transdisciplinary research and the methodology of knowledge integration (Hoffmann et al., 2017). More often, within the literature on transdisciplinary education, integration is seen as happening in the classroom i.e. students seek out information from within or outside their discipline to solve a challenge (e.g. Greenhalgh-Spencer et al., 2017). Educators at ETH Zurich, for example, describe the goal of their teaching in inter- and transdisciplinarity as "to link students' work back to the realm of practice" (Neuhauser & Pohl, 2015, p. 113). This is achieved through, for example, undergraduate students working on real-life case studies, meeting stakeholders and learning how to do a stakeholder analysis. However, this can lead to challenges when educators are required to articulate to prospective students, university staff and policymakers, what exactly is learned in transdisciplinary education. When disciplinary learning objectives are not specified, transdisciplinary learning is framed in terms of competency development. This presents challenges to the systematisation of transdisciplinarity within universities. This competence focus can lead to a perception that transdisciplinarity is a means to develop soft skills but does not have the same rigour, longevity or ability to genuinely ameliorate societal problems as disciplines do. Findings suggest that transdisciplinary courses can increase collaboration, problem-solving and engagement (Greenhalgh-Spencer et al., 2017) but how this differentiates it from problem-based learning, project-based learning or workplace-learning is unclear. Within the literature, the line between curriculum and pedagogy is blurred. Transdisciplinary learning was described as learning in a transdisciplinary setting and learning about transdisciplinarity (Pearce, Adler, Senn, Krütli, Stauffacher & Pohl, 2018). It has been argued that transdisciplinary competencies can only meaningfully be developed within a transdisciplinary setting and when the group co-creates their understanding of the process they are engaged in i.e. they are informed about transdisciplinary methodologies and are self-reflective and active in process making (O'Sullivan, 2023).

Nicolescu's methodology directs educators to the importance of interaction in transdisciplinary learning and the creation of spaces for this interaction. There is a need for educators to create learning spaces and processes where diverse, sometimes antagonistic viewpoints (academic and extra-academic) are brought together (Gibbs & McGregor, 2023). Within this learning approach, students draw on different disciplinary knowledge as well as complexity theory and systems thinking to occupy a space defined by non-resistance wherein they engage with a diverse group. Envisaging this as a form of social learning can empower educators to understand that transdisciplinary learning requires that educators design interactional spaces where all learners can interact with different forms of knowledge. The following section expands on this proposal.

Transdisciplinary challenge-based learning: closing the knowledge-action gap. Transdisciplinary challenge-based learning (T-CBL) is increasingly evident as an educational approach that creates the space for transdisciplinary learning. T-CBL can be seen through the lens of social learning theory (Wenger-Trayner, Wenger-Trayner, Cameron, Eryigit-Madzwamuse & Hart, 2019), where learning takes place through interactions with both academic and extra-academic actors. In social learning, students need to engage in dialogue and interactions, share problems and insights and collaboratively construct new knowledge (Vrieling, van den Beemt & de Laat, 2016). Group members need to develop an outward perspective, to a wider network containing expertise (Wenger-Trayner et al., 2019). Through interaction, participants gain new insights and resources that will lead them to changed practice and transformational potential (Wenger-Trayner et al., 2019). Social learning creates value which is defined, among other things, as usefulness.

In T-CBL, learning is active because learning is focused on real-life challenges and the creation of potential solution pathways. Students interact with academic and extra-academic actors to analyse, define and agree the parameters of a problem within a challenge area. Students are then given responsibility to act, which can be further defined as to find, appraise and integrate the expertise they need to develop a solution that is co-created by the group. Through this process, the theory is that students will understand a challenge more deeply because they are exposed to and learn to integrate the perspectives of others but also the focus is on translating knowledge into action. Everyone involved participates in creating a learning network that also draws on the

diversity of social relationships within student, academic and extra-academic networks (Vrieling et al., 2016). Both learning and the networks can be formal or informal (Vaessen, van den Beemt and De Laat, 2014). Social learning theory promises to provide a foundation around which a deeper understanding of transdisciplinary learning can be built. This is necessary as the literature on transdisciplinary education points to a clear practitioner orientation of transdisciplinary education around learning as a competency-developing process or competency-based education (CBE). For example, transdisciplinarity has been called a competence (Segala et al., 2009) and is said to develop competencies (Tejedor et al., 2018). In practice, this can lead to challenges in how transdisciplinary education is perceived by educational science and broader university communities.

Competency-based education. While a full critique of the concept of CBE falls outside of the scope of this article, it is relevant to note the challenges that CBE can bring in practice. The most pressing issue with regards to CBE—and one that perhaps captures reservations about it as an approach—is the difficulty in defining what a competency is and the lack of consensus in the literature. The literature has no clear, widely accepted definition of CBE (Frank et al., 2010). There is a lack of clarity on how competencies differ from so-called soft skills e.g. communication and collaboration; disciplinary skills e.g. systems' thinking; or transversal disciplinary skills e.g. research methods. Norris (1991, p. 331) described competence as "an El Dorado of a word with a wealth of meanings and the appropriate connotations for utilitarian times" that is "shrouded in theoretical confusion". Lozano et al. (2012) see competencies as deriving from a classical economic-utilitarianism view of education that focuses on employability. In a review of the literature on competence as it is used in school education in Germany, Glaesser (2019, p. 80) describes competence as "knowledge but also the capacity (or disposition…) to apply what has been learnt". In the 1990s, the word was associated with a drive towards more practicality in education and training (vocational education) placing a greater emphasis on the assessment of performance rather than knowledge. In its inception, the term "re-emerged as a motif around which an innovation could grow" (Norris, 1991). Barth et al. describe the concept as vague and defines competencies as (2007, p. 417) "dispositions to self-organisation, comprising different psycho-social components, existing in a context-overlapping manner, and realising themselves context-specifically". According to the OECD (2019), the ability to develop competencies is itself something to be learned using a sequenced process of reflection, anticipation and action. CBE is further complicated by the relationship between competency, skill and knowledge. According to the OECD (2019): "Skills are part of a holistic concept of competency, involving the mobilisation of knowledge, skills, attitudes and values to meet complex demands". The generic and catch-all nature of competencies is one of several challenges facing the broader adoption of transdisciplinary education within universities.

Further research

Further evidence is needed on how transdisciplinary curricula are created, how disciplinary knowledge from multiple disciplines is integrated and what pedagogical approaches support and comprise transdisciplinary education. There is also a need for experimentation and evidence-building on competency development in both staff and students in order to support their ability to take part in the transdisciplinary process. For example, rather than engaging staff in staff development programmes, the formation of a transdisciplinary team structures allows staff to develop an awareness of their own competencies and develop competencies while increasing confidence in transdisciplinarity (O'Sullivan, 2023). Further research could explore how the participation of staff in transdisciplinary education permeates the broader institutional culture. For example, Barth & Rieckmann (2012) found that Education for Sustainable Development facilitated the personal competence development of the participating academic staff and changed their teaching practice, but also that it influenced the general organisational development of the university.

Limitations

The findings were limited by a lack of clarity and consistency in definition and use of the term transdisciplinarity within the literature. As a result, the search terms surfaced articles using the term transdisciplinarity to describe work that is not transdisciplinary i.e. it did not meet the definition of the term in the conceptual literature. The key components of transdisciplinary educational practice are that the learning involves the active participation of extra-academic actors; focuses on a societal challenge; and involves multiple disciplines. For example, publications used the term transdisciplinarity to describe disciplinary experiences that connected students to extra-academic actors or developed skills that were broad, so-called T-skills (transferable skills that can be applied across all disciplines) (Lavrinoviča, 2021).

Conversely, there are case studies that are existent which may not use the term transdisciplinarity. This limitation was addressed by taking a snowball approach to the literature search in addition to using databases, however, this ran the risk of limiting the search to the community of authors who are known to each other and who frequently collaborate. The increasing use of the term in global policy will potentially raise awareness and increase visibility of practice within marginalised groups. The findings were also limited to publications in the English language which excludes important practices in different geographical areas.

Conclusion

Within educational practice, the T-shaped professional (Oskam, 2009) has been promoted as a model to describe individuals who possess disciplinary expertise in one area (the vertical column) and the ability to adopt the perspectives of other disciplines (the horizontal column). This article argues that transdisciplinarity should rather be conceived of as a U-shaped model. The literature demonstrates that educational practitioners conceptualise transdisciplinarity as the development of these two capacities: knowledge integration and actionable knowledge. However, the development of these capacities is dependent on the presence or development of intra-personal, interpersonal and cognitive competencies, for example, collaboration, reflexivity, openness, flexibility and communication but also attitudes or dispositions (Augsburg, 2014). The learning process design needs to include both the development of these competencies and clear pathways to developing the capacity to integrate knowledge and act on it.

While there is a consistency in ambition within transdisciplinary teaching practices, there is a clear dearth of literature on the process of designing transdisciplinary learning experiences from the academic perspective i.e. opening the black box on the process of curriculum design and disciplinary content integration. Much of the literature comprises case studies of practice by academic practitioners without input from or evaluation by educational scientists (Klein, 2018; Fam et al., 2018). While this is a rich source of information and practice, the focus is on the final design of programmes and courses rather than how academics worked together and on what principles they designed

programmes or courses. Addressing this disconnection between educational science and educational practice is important if transdisciplinary education is to gain wider acceptance within third-level education.

Transdisciplinary education not only develops U-shaped capacities in students and researchers but also holds the potential to develop these in university teachers, coaches and tutors. This article proposes social learning theory as a potential theoretical avenue for further development of the U-shaped model in practice (Wenger-Trayner et al., 2019). Learning is no longer viewed solely as a student activity but is seen as a process that the entire group participates in: students, academic and extra-academic actors (Gibbs, 2017; Klein, 2018; Fam et al., 2018). As Sterling (2004) argues, driving educational change to support transdisciplinary fields such as sustainability means tackling both educational paradigm and provision. This, he writes, is a double learning challenge. If we remove structural constraints, inter- or transdisciplinary models of education may still run counter to intellectual as well as organisational culture (Charli-Joseph et al., 2016; Dlouha et al., (2013)). Inter- and transdisciplinarity will not be nurtured and systematised by structural changes alone, for example, reorganising disciplinary departments, freeing staff time or creating resource flows for university-wide modules and programmes. If universities are to focus on the development of key competencies, a reorientation of learning processes is needed (Barth et al., 2007).

Given the increased impetus in European and global policy (European Commission, 2019, 2020; Allemand et al., 2024) to promote transdisciplinarity, and growing evidence that knowledge integration and the ability to act on knowledge are crucial skills for successful research focused on tackling societal challenges (Hoffmann et al., 2017), there is a need to inform practice and policy with research into transdisciplinary education. An important step in driving system change is the development of a shared understanding of what the goals of transdisciplinarity are and making explicit the process of transdisciplinary learning. This article proposes a shared model of transdisciplinary learning that both educationalists and educational researchers can employ to design and evaluate transdisciplinary learning processes. This will help consolidate practice and build research with the ultimate goal of creating an evidence-base that university leaders, educationalists, researchers and policymakers can use to work in unison to create system change.

Data sharing

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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Informed consent
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