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Transdisciplinary knowledge integration – PART I: Theoretical foundations and an organizational structure

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ABSTRACT

Transdisciplinary processes deal with transdisciplinary problems that are (i) complex, (ii) societally relevant, (iii) ill-defined, and (iv) real-world problems which often show a high degree of ambiguity resulting in contested perceptions and evaluations among and between scientists and practitioners. Therefore, they are susceptible to multiple trade-offs. Transdisciplinary processes construct socially robust orientations (SoROs) particularly for sustainable transitioning. The integration of science and practice knowledge on equal footing (1) is considered the core of transdisciplinary processes. Yet other forms of knowledge integration contribute essentially to construct SoROs. Individuals may (2) use different modes of thought; (3) refer to various cultures with diverse value and belief systems; and (4) problems are perceived and prioritized based on roles and interests. Coping with transdisciplinary problems, (5) purposeful differentiation and integration and (6) an integration of evolutionary evolving codes of representing knowledge are necessary. Finally, (7) what systems to integrate requires consensus-building among participating scientists and practitioners. This paper is Part I of a two-part publication. It provides a conceptualization of the different types of knowledge integration. Part II analyzes tasks, challenges, and barriers related to different types of knowledge integration in five transdisciplinary processes which developed SoROs for sensitive subsystems of Germany affected by the irresponsible use of digital data.

1. Introduction

1.1. What knowledge integration for transdisciplinary problems?

The objective of integrating or co-producing knowledge from science and practice about technology and other domains of society has gained increasing attention in scientific research, technology, and society (STS; see Callon, 1999) and especially in the emerging sustainability science. The "social engagement-oriented concept" of transdisciplinarity (Lawrence et al., 2022, p.46) is presented in this paper (Häberli and Grossenbacher-Mansuy, 1998; Scholz et al., 2000a; Scholz et al., 2000b; Scholz and Tietje, 1996). The term "transdisciplinary" was coined about a half-century ago (Jantsch, 1970, 1972; Mahan Jr., 1970; Piaget, 1972). For a long time, transdisciplinary processes took place primarily in the areas of environmental and urban development. But for some time now, business and management sciences (Schaltegger et al., 2013), engineering (Wognum et al., 2019), and medical and public health and health sciences (Ciesielski et al., 2017) as well as other science domains have been utilizing transdisciplinary approaches. Today, "research practice, funding agencies and global science organizations suggest that

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research aimed at addressing sustainability challenges is most effective when 'co-produced' by academics and non-academics" (Norström et al., 2020, p. 182).

Transdisciplinary processes, conceived as a knowledge-integration-based collaboration of science and practice on an equal footing, have become part of the research agenda and the goals of numerous funding programs related to sustainable transitions. However, relatively few papers have described (i) what actually happens in transdisciplinary processes, (ii) what knowledge integration between science and practice means, and (iii) what other types of knowledge integration can be distinguished. Many papers are written under the heading of transdisciplinary sustainability research. Most of these, however, address only what we understand as "participatory research" (Scholz et al., 2006). In such projects, the control surrounding the process and the manner and time in which practitioners are involved in it are controlled by scientists (Karrasch et al., 2022). Additionally, the participation of practitioners is often sporadic and ill-defined with respect to the roles, rights, and obligations of both practitioners and scientists in the process. By contrast, in this paper we deal with transdisciplinary processes in which the practitioners are involved from the initial stage of problem definition to the completion of the transdisciplinary process, ideally as co-leaders. This provides a "science with society view" rather than a science for society stance" (Scholz and Stauffacher, 2009). Of note, similar to "participatory research," transdisciplinary processes that rely solely on ideas about science–practice interactions (Jaeger and Scheringer, 2018; Mahan Jr., 1970; Mittelstrass, 1996, 2011; Piaget, 1972; Zscheischler et al., 2017) and not on equal-footing based science–-practice collaboration are not considered in the present work.

This paper is Part I of a two-part publication. It addresses the epistemological and epistemic-cognitive aspects of knowledge integration from science and practice in transdisciplinary processes. Importantly, the paper deals with issues from a general as well as from a specific, exemplary, or application-driven perspective. Part II (Scholz et al., 2024) analyzes and illustrates the theoretical, methodological, and organizational challenges of knowledge integration in five transdisciplinary processes related to a two-year, large-scale transdisciplinary project that included 63 practitioners and 57 scientists as project leaders, members of the steering board, expert groups, and seven

Box 1
The DiDaT project – improving the responsible use of digital data in Germany as a best-practice case of a transdisciplinary process.

(The DiDaT process is described in more detail in Part II.)

Why was DiDaT initiated? The DiDaT (*Di*gital *Da*ta as Subject of a Transdisciplinary process) focuses on unintended (negative) side effects of the digital transformation. The guiding question of DiDaT emerged from the concerns of a European Expert Round Table (ERT), which concluded that Europe and Germany were among the losers in regard to the digital transformation, as the ownership, economic value, access, and use of digital data were not well understood and managed (Scholz et al., 2018). The fundamental transformation to a globally interconnected, digital data-based system, for example, did not take place for quite some time in Germany. For instance, the overall mindset of the German automotive industry focused on the optimization of mechanics by digital data. Whereas in 2020, the length of the cables in a Mercedes S class amounted to about eight kilometers (Deppe, 2017), that of the Tesla Y's cables was only 150 m (Hennsler, 2019). The stock market value of Mercedes was about US$ 30 billion, while that of Tesla was around US$ 200 billion. The economic value of future transportation will be widely skimmed off by Google Maps and Google Earth, as well as similar databases and the digital twin of transport systems. The economic value of mechanical combustion machine production will become low. For this reason, mobility in Germany was selected as one of seven critical vulnerability spaces (see column 5 in Fig. 3) for which a transdisciplinary process was initiated.

Which transdisciplinary problem? The European ERT stated (Scholz et al., 2018) that the economic aspects inherent in the interaction of ownership, economic value, access, and use of digital data have been widely ignored in Europe. Most of the digital data by far are controlled by a few global, digital-infrastructure providers with headquarters in the US. Which data are used with which algorithms for what purpose is not under the sovereignty of the German government (Scholz et al., 2021b), even if the European Union (EU) is promoting various legal systems to alter this situation. A major source of the problem is that the data are not stored in EU countries. The challenge of responsible data use calls for fundamental, strategic sustainability management. This addresses all seven features of a transdisciplinary problem as presented in Section 2.1.

Resilience assessment. The DiDaT project provided a vulnerability assessment of unintended side effects (also called unseens) of the current practice of utilizing digital data in Germany (Scholz et al., 2021b) and produced SoROs for five different vulnerability spaces. How these spaces were selected is described in Part II. Fig. 3 illustrates the means, functions, structures, and processes that are involved in the six phases of the template in Fig. 1 to proceed from a concern through the identification of a problem or challenge to a set of SoROs that provide a roadmap for the responsible use of digital data.

Transdisciplinary processes need cases not themes. A real-world case, a biophysical entity of the real world, provides a natural benchmarking for all participants from science and practice. An abstract issue, e.g., "a theory of justice," can be reinterpreted and shifted much more easily. All participants should share the guiding question and have some level of concern (see left side of Fig. 1), but they may follow different interests. The concern was related to the ERT's prediction that Germany and Europe are losers in the digital transformation. Unintended side effects (unseens) of digital data use in Germany were a common concern. Methodologically, the use of digital data in Germany is a real-world case (Scholz and Tietje, 2002). The goal was to develop SoROs for certain domains or subsystems of Germany to better allow the utilization of the innovative potential of digital data and digitalization (Scholz et al., 2021b, p. 5).

Triangulation by differentiation and integration. Fig. 3 presents the sequence of differentiation and integration involved in the workflow organization of the DiDaT project. Based on the guiding question, a first faceting provides a set of vulnerability spaces. For each facet, a transdisciplinary project team identified the unseens. For each unseen, (a) a system model was generated including (b) a causal analysis of why certain threats exist, and (c) a description of goal conflicts among stakeholders was provided. Based on (a), (b), and (c), (d) interventions that might mitigate or eliminate an unseen were identified and assessed, and a SoRO was constructed.

working groups on vulnerability spaces. This project was the "Responsible Use of **Di**gital **Da**ta as Subject of a **T**ransdisciplinary Process (DiDaT)" project (Scholz et al., 2021a). For building the bridge between the reflection of theory of transdisciplinary processes (Part I) and the practice of these processes (Part II, Scholz et al. (2024)), the DiDaT project is briefly described in Box 1. Looking at this box helps to better understand some examples and figures and to prepare for Part II.

The structure of Part I is as follows: Chapter 2 introduces a definition of transdisciplinary problems that call for integrating knowledge from science and practice to identify and realize successful coping. In addition, central characteristics of transdisciplinary processes are described. Chapter 3 provides seven theoretical, epistemological, and cognitive foundations of knowledge integration. The discussion in Chapter 4 focuses on the theoretical and practical challenges and the shortcomings of theoretical approaches, and their validation and the conclusions. Chapter 5 comprises what has been elaborated.

2. What makes a transdisciplinary subject and process?

2.1. The ontology of a transdisciplinary problem

"Transdisciplinarity deals with relevant, complex societal problems and organizes processes of mutual learning between agents from the scientific and the non-scientific world" (Scholz et al., 2000b, p. 478). The societal relevance and concern related to a given problem or challenge by a wide range of stakeholders can be seen as a major driver of transdisciplinary processes. Following more than two decades of experience with transdisciplinary processes, this early definition can be extended and differentiated. In addition to (i) complexity and (ii) societal relevance, (iii) being ill-defined (or wickedness, Brown et al., 2010; Scholz and Tietje, 1996, 2002; Simon, 1973) is a third key feature of a problem that is a subject of transdisciplinary processes and research. An ill-defined problem is understood as a problem for which we have incomplete knowledge about (a) the current state, (b) what barriers must be overcome to attain a target state, and (c) what the target state looks like. In addition, (iv) the real-world nature of a problem is essential for transdisciplinarity. If a problem is abstracted, much of the complexity is not represented. In particular, the complexity makes it difficult to assess the uncertainties. This causes ambiguity (Einhorn and Hogarth, 1986), which is a kind of second-order uncertainty, in the sense that there is uncertainty about the likelihood or probabilities of events and causal relations. Transdisciplinary processes include multiple stakeholders with different interests, values, and preferences who perceive and reconstruct a problem from different perspectives. For these reasons, a transdisciplinary problem definition is usually contested among stakeholders who are concerned by, causing, or regulating a certain problem and who represent science and practice (Balvanera et al., 2017). As a consequence, the mitigation of conflicts is part of transdisciplinary processes starting with the joint definition of the subject to deal with. This complexity and ambiguity results in the need for trade-offs within and between stakeholders such that ambivalence exists in relation to preferences between certain alternatives or prospects. Based on this, we suggest the following definition:

> *transdisciplinary problems are (i) systemically complex, (ii) societally relevant, (iii) ill-defined, (iv) real-world problems. They often show a high level of ambiguity. Perceptions and evaluations among and between scientists and practitioners are usually contested and, thus, are subjects of multiple trade-offs.*

Thereby, transdisciplinary problems postulate that analyzing and coping with them calls for a triangulation and integration of knowledge and perspectives provided both within and between stakeholders from science and practice and utilized in problem framing, representing, and transforming.

2.2. The complementarity of practice vs. science knowledge

The integration of theoretical, abstract scientific knowledge (which is empirically validated to the extent possible) with experientially proven, contextualized, high-profile practitioners' practical real-world knowledge is seen as a foundational pillar of the outcomes of a transdisciplinary process (Cockburn, 2022; Godemann, 2008; Hoffmann et al., 2017; Lang et al., 2012; Lawrence et al., 2022; Renn, 2021; Scholz, 2000; Scholz and Tietje, 2002; Vilsmaier et al., 2015). This complementarity of bodies of knowledge from science and practice (as two hypothesized complementary systems) refers not only to the knowledge but also to the roles and primary drivers and interests of scientists and practitioners. We follow the somewhat simplified traditional idea that the primary task of scientists is to contribute to scientific theories and methods as a public good which is valuable for all societal groups. Based on this definition, scientists, e.g., those from (public) universities funded by the public (taxes), must serve all stakeholder groups, principally in a similar manner. By contrast, practitioners generate and utilize knowledge and values that are experience-based, contextualized, and thus specific, and that work toward a satisfactory performance for particular practitioners and their interests (Balvanera et al., 2017). These are two major streams that are included in transdisciplinary processes.

Differences in the epistemology and genesis of science and practice knowledge are sketched on the right side/layer of Fig. 1. Scientific knowledge is theoretically framed, logically consistent, and—to the extent possible—empirically validated; its nature is fundamental, general, universally valid, codified (in terms of theoretical constructs) and, therefore, abstract (see, Scholz and Steiner, 2023). According to Piaget's genetic epistemology (Piaget, 1970), science knowledge—as higher-ordered knowledge—does not develop spontaneously in an individual but emerges from its phylogenetic institutional framing in schools and universities. These, in turn, organize the growing body of abstracted knowledge in an efficient manner that allows for technological and societal development. We can distinguish between pure basic research (as developed in quantum physics or theoretical physics) and the domain of applied research, which is solution-oriented, engineering-like problem-solving or theory-based, and use-inspired applied research (Stokes, 1997). According to the ontology of transdisciplinary problems, in general, transdisciplinary processes include use-inspired basic research.

Practice knowledge is based on experience, relies on rules of doing, and is founded on one's past or observed behaviors, actions, skills, or routines (Kolb, 1984). Often this knowledge is tacit and context dependent. Local knowledge is frequently a trigger for concern in socio-ecological systems (Martín-López et al., 2020; Norström et al., 2017; Vilsmaier et al., 2015). The acquisition of this type of knowledge is driven by a decision-maker's (conscious or unconscious) interests in improving performance, solving problems, or satisfying a need to achieve an inner equilibrium or to maintain the social order/justice that aligns with one's personal norms and goals. The drive to maintain viability may be seen as a general, overarching goal of practice-related knowledge.

The middle layer of Fig. 1 presents the template of a typical transdisciplinary process. We distinguish six phases (when differentiating the four phases by Scholz and Steiner, 2015d): (1) the triggering phase, which often links to a specific episode in which a 'basic idea' about a transdisciplinary process is born. Yet a study will not develop without (2) initiation, which includes successful networking, the finding of stewards and key partners from practice and science who share the basic idea. If a critical momentum of commitment of stewards has been attained, (3) the preparation can start. A transdisciplinary process is a time-consuming and rather expeditious process which needs resources or seed money for step (2) and proposal writing. The study team will be sequentially composed of the first four steps. The study teams will be finalized at the end of (4) the planning phase. The core phase (5), then, is a directed work of producing the outcome that will be (6) disseminated, evaluated, etc. in the post-processing phase. The detailed steps of the

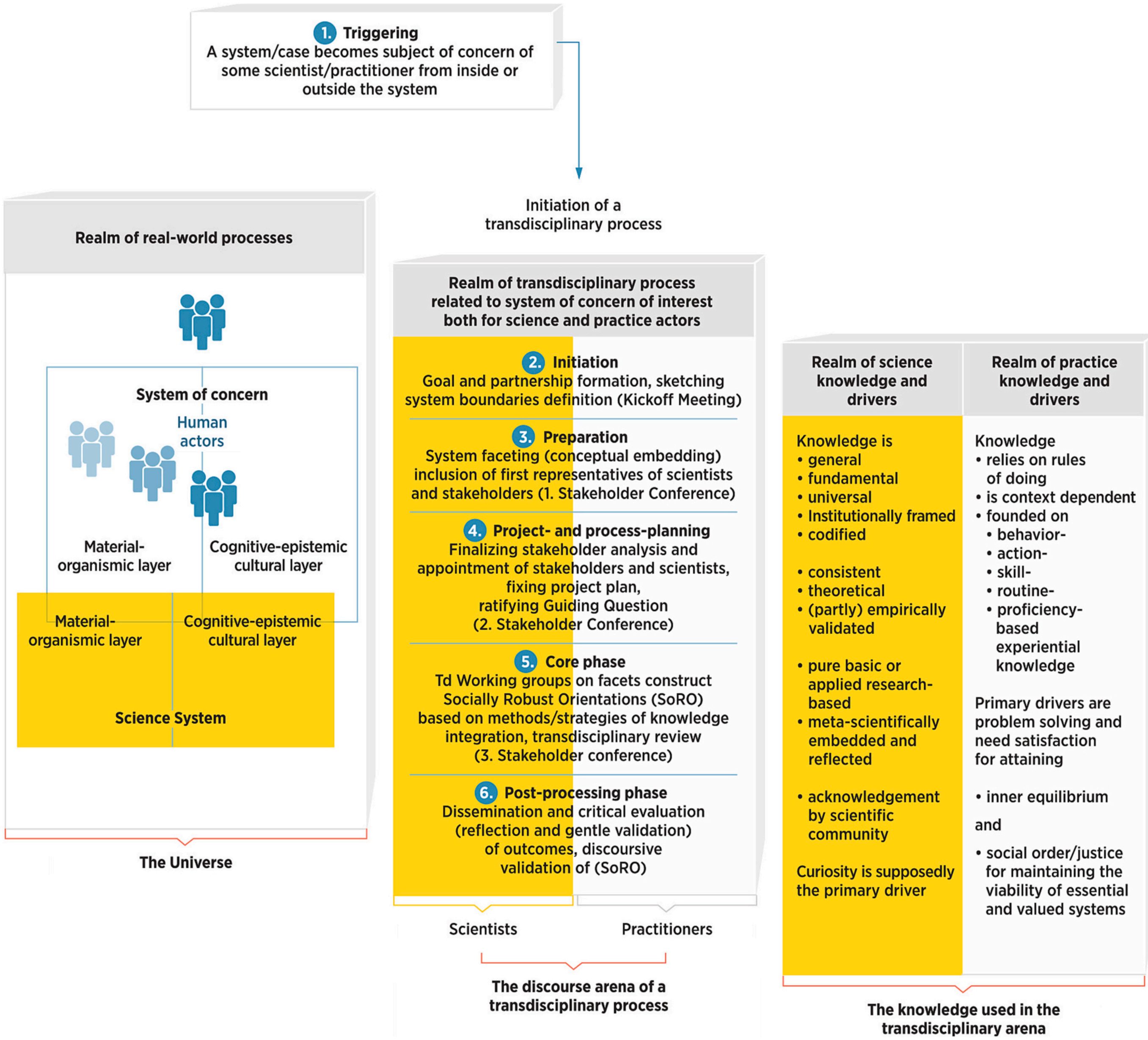

Fig. 1. A template for running a transdisciplinary process (middle layer) in relation to the human environment relationship (left layer) and the knowledge about a system of concern in science and society (right layer).

template and what tasks, challenges, and barriers have to be addressed are illustrated by the example of the DiDaT process in Part II (Scholz et al., 2024).

2.3. Components of a transdisciplinary process

Fig. 2 supplements Fig. 1 and presents an idealized scheme of how scientists and practitioners interact in a transdisciplinary process. Simplified, a transdisciplinary process combines three components: (A) a facilitated, targeted interdisciplinary process; (B) a mitigated, multi-stakeholder discourse among representatives of key stakeholder groups; and (C) an enabled and supported process of relating and integrating the processes of (A) with those of (B). Moreover, it is mandatory for (A) to include representatives from science (see Fig. 2) who possess the relevant scientific knowledge from those disciplines that is beneficial or even necessary for the subject of the transdisciplinary process. The facilitation process (C) should further enable mutual learning among science and practice (Scholz, 2000). This mutual learning includes the search for a joint problem definition and goal formation, and for a joint problem representation that is understood by experts from both science and practice and contributes to the goal of attaining a desired transition of the system. Knowledge integration must be moderated by facilitators. A facilitator must understand the system under transformation, the drivers (goals) and motivations of researchers and practitioners, and be able to mediate between conflicting interests. Fig. 2 is similar to the view presented by Jahn et al. (2012), who differentiated between scientific and societal problems. These problems may become integrated over a limited time when both sides enter a joint discourse arena, which can become a kind of *agora* of public knowledge as part of a transdisciplinary process (Nowotny, 2003).

This idea was used in the 1970s and provides an image of researchers and practitioners in the same boat working to achieve the same goals (Rudvall, 1978; Scholz, 1978). This idea of contemporary, goal-oriented collaboration has also been called Scandinavian co-generative action research (Elden and Levin, 1991; Scholz, 2011a). Historically, there are related/similar approaches. For instance action research is more

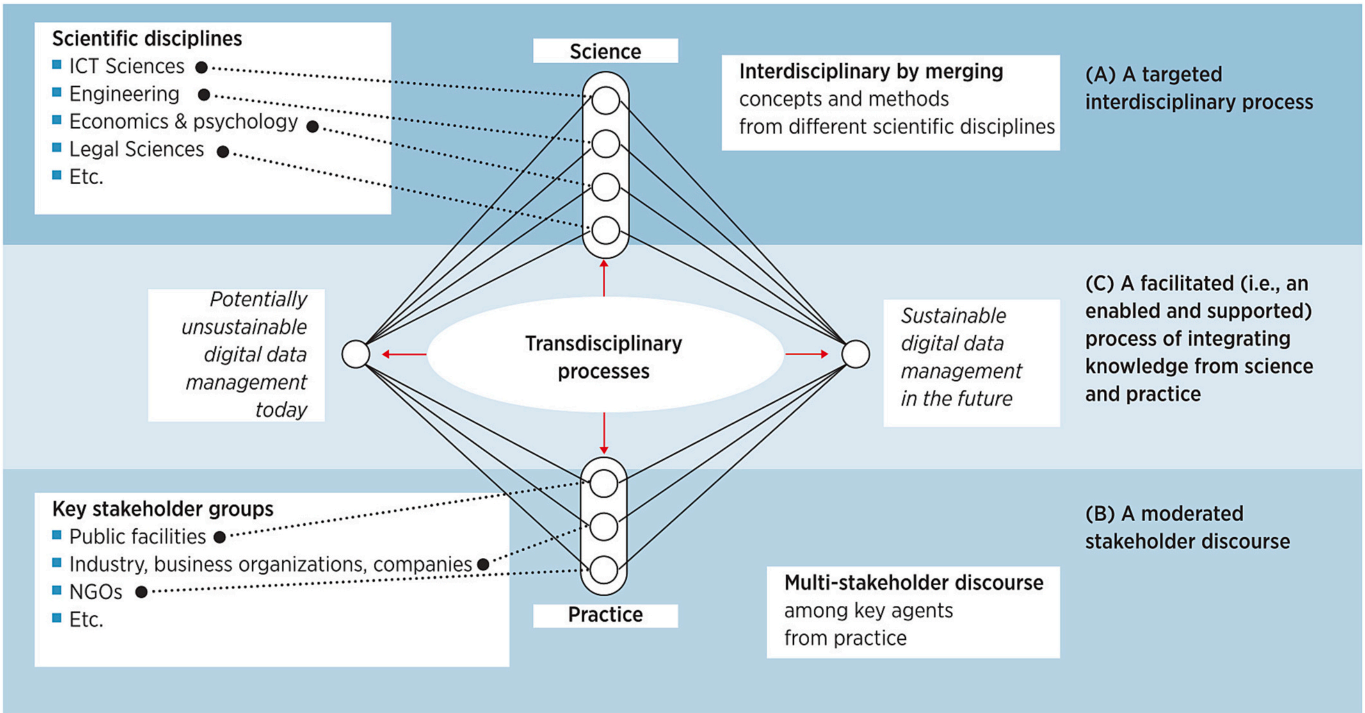

Fig. 2. The three components, (A), (B), and (C), of a transdisciplinary process as an interfacial process between a present state (left side) and a target state (right side) when including and relating scientists and practitioners (upper and lower circles) for the case of sustainable digital data management.

solution oriented (Lewin, 1946, 1947) than transdisciplinarity (Baskerville, 1997). Whereas living labs (Barker and Wright, 1955) delve into real world settings (Rogga et al., 2018) and, today, among others explore interactive innovation processes (e.g. open innovation; van Waes et al., 2021).

The three components of transdisciplinarity (see Fig. 2) described above pose various challenges for conducting a transdisciplinary process. There must be sufficient incentives for scientists and practitioners to be interested and participate to a productive extent. Thus, a transdisciplinary process must be considered beneficial for scientists and practitioners. This also includes that transdisciplinary processes should offer value that cannot otherwise be achieved or at least not achieved more economically in other ways. This paper conceptualizes the process of knowledge integration necessary within and between the two streams of epistemics in science and practice.

2.4. Mutual learning and an equal footing of science and practice

We refer to modes of transdisciplinarity rooted in science–practice collaboration on an equal footing for organizing mutual learning and knowledge integration in order to construct socially robust orientations (SoROs) (Nowotny, 2003; Scholz, 2000). This can be authentically established through science and practice co-leadership. In general, practice leaders ask for equal rights to ownership in the process of defining goals, co-designing the process, co-constructing knowledge and preferences among possible orientations and pathways, and co-responsibility for the process of collaboration. Finally, there needs to be co-accountability and co-responsibility for the impacts on both science and practice. Co-leadership is framed by a joint contract that includes responsibilities, access to data, utilization and dissemination of findings (Scholz et al., 1996). This is a particularly sensitive and important issue if financial or political stakes are at risk when running a transdisciplinary process. Co-leadership is not only an authentic form of partnership and equal control of the process but often a prerequisite for attaining co-responsibility, developing identity with the transdisciplinary process, and being open to mutual learning. Co-leadership should start with the joint problem definition and calls for mutual trust and an “explicit and transparent positioning of oneself” (Rosendahl et al., 2015, p. 26).

Mutual learning refers to actors having different types of knowledge (Scholz, 2000). This kind of learning requires trust and is a means of trust-building that includes, in particular, accepting the otherness of the other and his/her knowledge. It also requires a protected discourse arena allowing for the formation of exploratory, innovative ideas that might be developed or rejected in learning processes that include emotional-motivational components (Jordi, 2011; O'Brien and Sarkis, 2014).

2.5. Outcomes of a transdisciplinary process

Major outcomes of transdisciplinary processes are that numerous participants benefit by (i) capacity building and empowerment for sustainable decision-making; (ii) the search for a joint problem definition, representation, and understanding; and (iii) the anticipation of which unintended negative side effects refer to certain stakeholders. Thus, not a specific solution but orientations and strategies to cope with transdisciplinary problems are the objective. In this context, we relate to the concept of “socially robust orientations” (SoROs).

Often SoROs describe solution spaces. SoROs represent jointly negotiated and co-developed orientations for how to further manage a complex sustainability problem (see also Zscheischler et al., 2022). Referring to Gibbons and Nowotny (2001), Scholz (2011a) suggested that socially robust orientations (SoROs) are proper and powerful tools for problem structuring and complexity reduction that support (sustainable) actions. SoROs are characterized as (a) emerging from the different epistemics (in particular, from experiential real-world wisdom and scientific rigor) and (b) being compatible with the scientific state-of-the-art knowledge while simultaneously (c) acknowledging not only the uncertainties involved in scientific statements but also the incompleteness of knowledge involved. Further, (d) a SoRO should be understandable to everyone, and (e) the constraints of the process underlying its construction (i.e., funding, resources, time, etc.) should be openly conveyed. Ideally, a SoRO provides a shared window of opportunity, allowing for transition management related to the causes of concern for a joint description of the problem. For attaining understandability, a SoRO ideally includes a description of the causal relations (i.e., the causal structure) among the key system variables (or subsystems). Further, transdisciplinarily constructed SoROs include at least a rough description of action strategies that prepare for executive functions[s] of planning, organizing, coordinating, directing, controlling, and supervising processes of coping with a transdisciplinary problem when acknowledging the goal conflicts, trade-offs, and potential dilemmas involved. Part II (Scholz et al., 2024) presents an example of constructing SoROs and shows what forms of knowledge integration have been involved.

2.6. The contested role of scientists

What role scientists may or should take in transdisciplinary processes is contested in the scientific community (Scholz, 2017b; Wittmayer and Schäpke, 2014). There are two issues of interest. The first issue is the question of whether scientists (usually paid by taxpayers) should have to serve the public good. If so, this would mean that all stakeholders should have access to and the same right to benefit from scientific knowledge. By contrast, there is the position that scientists may function as activists (Loorbach, 2014; Rosendahl et al., 2015) who produce advocacy science and, primarily, should co-produce knowledge and solutions that meet a scientist's understanding of sustainability.

The second issue is whether scientists follow a normal and not a post-normal science conception. For the present work, we do not follow the idea that (i) due to the complexity and wickedness of a real-world problem, the aspiration to provide increasingly valid descriptions and explanations about mechanisms underlying the dynamics of this setting have to be relinquished. Also the stance (ii) that science is in a crisis because (peer review) validation is biased (Funtowicz and Ravetz, 1993; Saltelli et al., 2016) should not mean that unbiased validation should be aspired, as far as possible. We know and agree that, in some domains, the integrity of science is endangered. Yet, science may well aspire to a better, more realistic description of the world and function as a clearinghouse of knowledge. Otherwise, it is likely to become one voice among others and, thereby, be conceived as a (science) stakeholder group.

Hence, this paper follows a conception of normal sciences. Scientists follow roles and functions different from those of other stakeholders and may be considered a group that serves the commons and the public good. The co-construction of knowledge by utilizing the potential of improving the search for coping with transdisciplinary problems by a "merger of scientific and practical knowledge" (Renn, 2021, p. 5) is linked to a shift from science for to science with society (Scholz and Stauffacher, 2009) when postulating autonomous regimes of science and practice that are highly interdependent and reciprocal (Marcovich and Shinn, 2012). Scholz and Steiner (2023) showed that the degree of process ownership, i.e., the extent to which practitioners and scientists have control regarding the goals, procedures, and outcomes, can be taken to differentiate transdisciplinary processes from other forms of science–practice collaboration such as action research, citizen science, or the triple-helix approach.

3. Knowledge integration, complexity management, and levels of abstraction

Transdisciplinary problems are characterized by exceptional complexity, uncertainty, and value-related ambiguity. For a better understanding of what types of knowledge are integrated, we distinguish between seven partly overlapping perspectives of knowledge integration (see Table 1). The first, the integration of different systems [Syst] (and the knowledge related to them), is of a rather ontological nature. The issue here is what is considered part of the system included in a study's guiding question and what is not. The following four issues refer to the knowledge of philosophical-epistemological systems [Epi], cultural sciences [Cul], cognitive science [Cog], and sociopsychological conflict perspectives [Soc-Con]. For the integration of knowledge, also the evolutionary evolving levels of cognition [Evo-Lev], and the reduction/management of complexity [Com.] are key types.

3.1. Integration of systems [Syst]

In terms of theoretical or analytical philosophy, metaphysics (as the study of what might exist; Smith, 2012) and (general) ontology, we are dealing with a subdomain of reality of a certain nature (Hacking, 2002), the understanding of which may benefit from knowledge integration. Thus, a first view on integration relates to systemic integration (Table 1, [Syst]). The subjects here are real world subsystems viewed from different perspectives whose integration provides additional insights. An important task of the transdisciplinary team is to reflect on what system (case) will be examined (for coping with a transdisciplinary problem) and what knowledge must be available among the team of scientists in order to understand this system of concern (Fig. 1). The system that is considered depends on the physical system and on the concerns formulated by the transdisciplinary team in the guiding question. For instance, to discuss mobility (a subsystem) as a sociotechnological system and to anticipate the unintended (negative) side effects of

Table 1
Seven types of knowledge integration in transdisciplinary processes.

	What integration	Primary level of human system considered	Scientific domains
Systems			
[Syst]	Systemic integration	Depends on what human systems are involved	• Ontology • Depends on system and guiding question
Knowledge			
[Epi]	Scientific disciplines (interdisciplinarity), scientific vs. non-scientific knowledge	Human species	• Epistemology • Theory of science • Theory of knowledge
[Cul]	Culturally shaped inference system (interculturality)	Societies and groups	• Cultural theory (including religion) • Sociology of knowledge • Evolutionary psychology
[Cog]	Modes of thought/thinking	Individuals, groups, and organizations	• Cognitive psychology and science
[Soc-Con]	Conflicting, interest-driven perspectives	All human systems	• Game and decision theory • Negotiation and conflict resolution
[Evo-Lev]	Levels of cognitions (from intuitive perception via empathic understanding to causal understanding)	Human individuals/small groups	• Developmental psychology (genetic epistemology), theory of knowledge
[Com]	Integrating ecological valid cues	Complexity management done by all organisms, information processing	• Brunswik's probabilistic functionalism (TPF) and related approaches

digitalization and digital data use, perspectives from scientific disciplines and stakeholders are necessary that differ from those needed to discuss social media (see, e.g., Fig. 3). Both require knowledge from the computer and information sciences, but the social media subsystem needs specialized knowledge from political science, the humanities, or from representatives of civil society. We may find that what scientists contribute depends on the guiding question and the system related to the specific transdisciplinary goal. The same is true for answering the question of which representatives of which stakeholder groups are necessary for developing SoROs. We note that social system theory (Parsons and Shils, 2017) or coupled human environment systems approaches (Binder et al., 2013; Scholz, 2011b) which define roles of actors by values and drivers help to identify the different actors (stakeholders) in the underlying systems.

3.2. Epistemological integration [Epi]

A specific challenge for preparation and planning is to screen the science system to identify scientific disciplines that may be helpful for providing answers to unknown aspects of a guiding question. The study team has to reflect on what is known, what is not known, and what additional knowledge might emerge from a targeted interdisciplinary process specifically created to answer the guiding question (see Fig. 2 (*A*)). This leads us to epistemology. In simple terms, epistemology (Table 1, [Epi]) tells us why and how well we know what we know (Scholz, 2015; Steup, 2016). In the previous sentence, the term "we" needs specification. It makes a difference whether we speak about the scientific knowledge that has been acquired in the phylogenetic development of the human species (Piaget, 1970), about the knowledge of a specific community of scientists (Abbott, 2021), or about the knowledge of a specific person. The latter is rather a case of psychology (Bell and Linn, 2000). Column 2 of Table 1 lists the primary level of the human system (i.e., individual, group, organization, institution, society, or human species) that is considered in different (scientific) approaches to knowledge integration.

Kant's *The Critique of Pure Reason* (Kant, 1787/1965) had already provided epistemological reflections on the potential and limits of different types of reasoning. Kant distinguished between general (Aristotelian) logic and transcendental (scientific) logic. The former exists per se and does not abstract from empirical contents. Transcendental logic has been viewed "as a science that concerns the formal rules for thinking objects in general" (Grier, 2006, p. 192). General logic refers to everyday objects and experiences (i.e., common sense). Kant offered a strong plea for knowledge integration (by what he called dialectics). He declared that "neither the rules of general logic nor those of transcendental logic (the non-schematized categories) can alone (a priori) yield any knowledge of objects" (Grier, 2006, p. 192). The understanding of subjects is based on real-world experience-based general logics in the Aristotelian

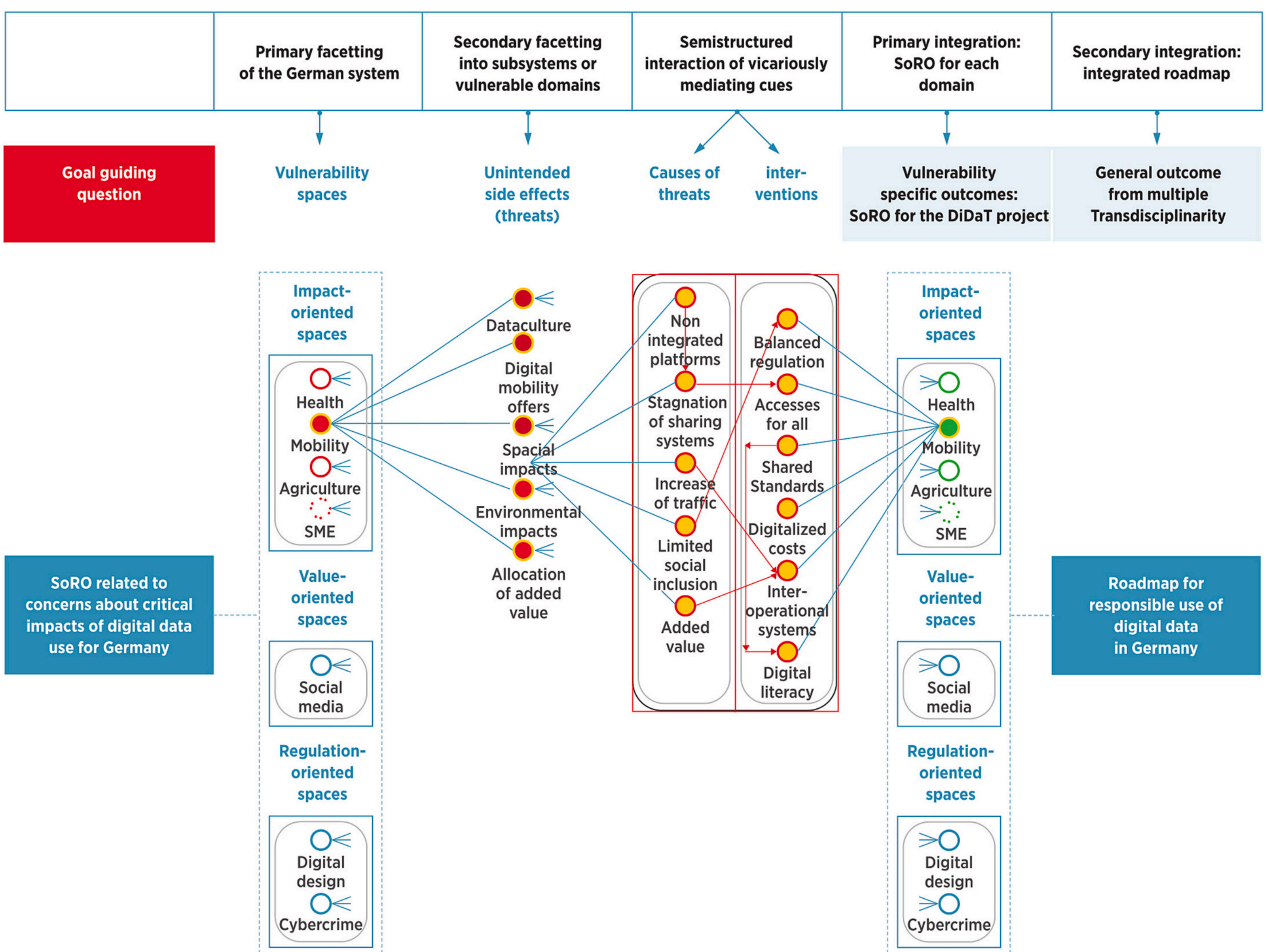

Fig. 3. Goal, structure (vulnerability spaces and vulnerability-space-specific threats/unseens), key cues (causes of threats), and potential means (and interventions) as foundations for deriving socially robust orientations (SoROs) for single vulnerability spaces and across all vulnerability spaces (this is the roadmap). The nested (two-step) differentiation integration is presented for only one vulnerability space (mobility).

sense.

Given complex real-world problems, there is no absolute, overarching knowledge (or reference system) in science. This also holds true for theoretical concepts. For instance, Moritz Schlick, the founder of the Vienna Circle (1924–1936), was first driven by the search for the “absolute,” i.e., the meaning of a theoretical concept “as a fact that is completely determined and has nothing uncertain about it” (Schlick, 1974, p. 20). But logical contradictions or inconsistencies (i.e. antinomies) or the exclusion of the middle (i.e., something between true and false) of the propositional logic indicates that other modes of logic than propositional logic are needed to overcome inconsistencies (Nicolescu, 2011; Stadler, 1982, 2003). The critique of Newton's conception of space and time by the Vienna Circle members Mach and Einstein may be taken as an example that scientific theories do not depict general validity but refer to a space of intended applications where they show validity. Additionally, we have to be aware that even (natural) science approaches may become contaminated by worldviews. Mach and Einstein, and later Heisenberg (Heisenberg, 1936) defended quantum physics against Aryan physics (promoted by two Nobel laureates in physics, Lenard, 1936; Stark, 1937) which is a common sense compatible knowledge (Scholz, 2017b).

Scientific theories are characterized by theoretical concepts, methods, and a space of intended application (Sneed, 1971). Reflecting on what sciences/theories may be helpful and which ones are not important for organizing targeted interdisciplinarity (see Fig. 2 (*A*)) as well as reflections on the different languages, codes, modes, or reasoning schemes in scientific disciplines (Klein, 2017) are part of initiating a targeted interdisciplinary process. The same reflections have to be made with resect to practice knowledge. In a recent contribution, Cockburn (2022) takes a critical philosophy perspective describing how epistemological and philosophical assumptions (e.g., worldview, reductionism, induction, or constructivism vs. positivism) affect the representation of a problem. For transdisciplinary processes, it is important to reflect what mode of epistemics is at work. This includes a reflection on what knowledge what scientific disciplines can provide and what knowledge is directly available by common knowledge.

3.3. Relating cultures [Cul]

A specific challenge of transdisciplinary processes emerges when stakeholders from different cultures are involved (see Table 1, [Cul]). Culture, in general, encompasses societal characteristics and knowledge including language, beliefs (religion), modes of reasoning, values, social practices, and music and the arts. This brings us to cultural theory (Thompson et al., 2018), the sociology of knowledge (Merton, 1973), evolutionary psychology (Tooby, 2018), and similar approaches. Cultures include a normative framing (often strongly shaped by religion; Eller, 2014), different forms of reasoning and decision-making, and particularly the rules of interaction for different societies. These rules are immaterial but real as they can be measured (Durkheim, 1895/1982). Integrating knowledge from cultures that are fundamentally different may be impossible (Harris, 1964, 1976). The same is true for different societally shaped sciences.

We should also note the relevance of intercultural transdisciplinarity and the difficulties of integrating essentially different knowledge systems when interacting with indigenous people (Steelman et al., 2015; Van Breda and Swilling, 2019). An example is a project in which (Western) oncologists' knowledge about cancer was related to Guatemalan Mayan healers' knowledge about this disease (Berger González, 2015; Scholz, 2012). Mayan healers do not have a concept of the cell and of genetics, which is fundamental for the oncological approach to cancer (Greaves, 2000; Weinberg, 2007). The Mayan conception of cancer as a malignant disease (bad tumors) is based on assumptions about violations of equilibrium in the emotional, social, spiritual (supernatural obsession), mental, and physical equilibria (Berger-González et al., 2016). This leads to fundamentally different views on cancer's origin, nature, function, diagnosis, and healing that often cannot be integrated (Grube, 2004; Harris, 1991). Thus, we prefer to speak about relating knowledge between cultures instead of integration.

3.4. Cognitive knowledge integration [Cog]

Next, knowledge integration is frequently viewed from a cognitive perspective (Table 1, [Cog]). The cognitive side of knowledge integration is “fuzzier” than an epistemological one: Cognitive “acts are vague and fleeting in character” (Schlick, 1974, p. 20). This brings us to psychology and modes of thought and thinking. The primary subject is the individual. Often a learner's perspective is taken (Linn, 2000). Yet, the performance of small groups and organizations is also a subject of psychology (Godemann, 2008; Kerr and Tindale, 2004; Mulder, 2020). The latter is of special interest because transdisciplinary project teams are somewhere between groups and organizations. Organizations have a formal membership. Transdisciplinary processes can form an organization. Complexity management presents a special cognitive challenge when coping with transdisciplinary problems. The participants of a transdisciplinary team are in a continuous process of “… adding, distinguishing, organizing and evaluating accounts of phenomena, situations, and abstractions” (Linn et al., 2004, p. 30). This has to be done by each member of the team along all of the steps in Fig. 3. The interactions among members, among scientists, and between all scientists and practitioners strongly depend on (1) who is participating and (2) on how the process is organized (Fig. 2 (C)). The process can be planned, for instance, in a way that, depending on the task to be accomplished, both groups work together (this usually takes place when formulating goals, designing the project, and synthesizing the results). Or the groups may conduct their work independently (e.g., when scientific inquiries or operative modeling work is done or practitioners are networking or preparing data); or one group or the other may take the lead. We call this functional-dynamic mutual participation (Krütli et al., 2010; Stauffacher et al., 2012).

A key challenge in such collaborative processes between science and practice is to find a joint representation of the defined problem, e.g., an impact graph or flow chart, that is understood, accepted, and actively utilized in the communication about the issues. If scientific graphs or written/spoken language are not helpful, rich pictures (Bell and Morse, 2013), i.e., iconic representations of the common concern of the transdisciplinary team and what are considered major characteristics of the status quo, threats, or visions, might help. Rich picture mapping may also be considered as a complexity reduction tool when “a bigger picture and the maze of processes and structures operative in the context [are] gathered together in one format” (Open University, 2004, quoted after Bell and Morse, 2013, p. 33; see Table 1, [Cog]). Rich pictures rely on iconic, visual cognition. We should note that, typically, different modes of thought or thinking styles are at work within each member and between the members of a transdisciplinary process. We may distinguish between concrete figurative vs. abstract conceptual-numerical, sequential vs. parallel processing-based, divergent vs. convergent, intuitive vs. analytic, and many other complementary thinking styles (Hammond, 1981; Kahneman, 2011; Scholz, 1987; Sternberg, 1999) that may be appropriate at certain phases of the transdisciplinary process. The epistemological study of reasoning primarily relates to codified hypothesized reasoning whereas the psychological theories describes what is actually ongoing in the minds (Lewin, 1931; Tateo, 2013). Both modes overlap. Both levels are important from the perspective of facilitating the discourse. There are some rules of thumb such as starting from the intuitive and the switching to the analytic. In general, it is a major task of the facilitator (see Fig. 2, (C)), i.e., a pivotal person who is structuring and organizing a transdisciplinary process, to launch an adequate thinking style which meets the characteristics of the challenges related to the problem and to the available knowledge in a project team.

3.5. *Conflicts: integrating different perspectives (interests) [Soc-Con]*

Not only stakeholders, but also scientists, have diverging interests regarding what is considered the best solution and how consensus should be attained (Table 1 [Con]). This leads to the fifth type of knowledge integration. The participants have different roles and functions that are liked or disliked by others. Usually, they have a different discursive power. Rhetorically and socially weak participants, such as smallholder farmers participating in a transdisciplinary process may need a spokesperson (Njoroge et al., 2015). To develop trust, it is helpful for all participants to agree on a code of conduct that includes major "principles of (ideal) transdisciplinary participation." The principles (see, e.g. Renn and Scholz, 2018) describe how a discourse takes place, the participants' roles, and the rights and duties each member has.

The conflicts of interest related to a transdisciplinary problem may be benign or malignant (Scholz and Tietje, 2002). For benign types, win-win situations may be constructed. This is not the case for malignant situations. Values, goals, and drivers causing conflicting evaluations are subjective and may be based on different, and sometimes incompatible, worldviews. This is a significant challenge for the facilitation of a transdisciplinary process (see Fig. 2 (*B*)) as this may cause spiraling aggression that renders mutual learning impossible. If the fundamental principle of accepting the otherness of the other is not completely abandoned, a reframing of the problem at hand may help to overcome a lock in (Forester et al., 2019; Laws and Rein, 2003). Here, the reference to common, unambiguously accepted scientific concepts and theories may help. In particular, the facilitator of a transdisciplinary process must be aware that the discourse on the way to producing SoROs may be viewed as a permanent process of negotiation and that the participants will continue to collaborate only if they expect that their results and participation will provide an overall positive outcome for themselves and for those they represent.

3.6. *Levels of abstraction [Evo-Lev], the architecture of knowledge*

The evolutionary epistemological view [Evo-Lev] goes beyond the first four modes. This view distinguishes levels of experiencing, understanding, conceptualizing, and explaining. The approach emerges from German philosophers such as Kant and Leibniz. We argue that the interplay between the (direct, enactive) experiencing and of empathy and holistic understanding (see Fig. 4, upper level) is the source of developing a primary concern about a transdisciplinary problem, i.e., about a complex, societally relevant, ill-defined, real-world problem that is ambiguous and contested, and thus, the subject of multiple trade-offs (see Fig. 1, left side). For describing and structuring the problem, a conceptual grid is needed (that properly acknowledges the holistic nature). This is what Robert Yin (2018) called embedding a case in a conceptual grid. Furthermore, the relevant hypothesized causal schemes that are considered essential for a system's dynamics may call for a

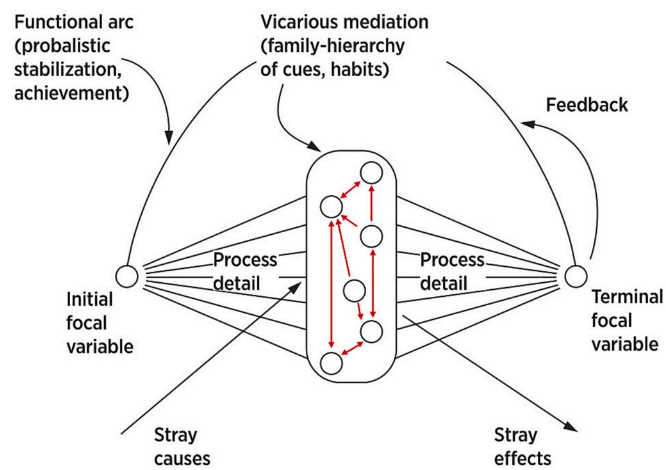

Fig. 5. The key principles of Brunswik's Theory of Probabilistic Functionalism (Brunswik, 1952) presented as an extended Lens model (Scholz, 2018) that stresses the inner organismic interactions among the cues (i.e., cognized information, right side; for further explanations, see Box 3).

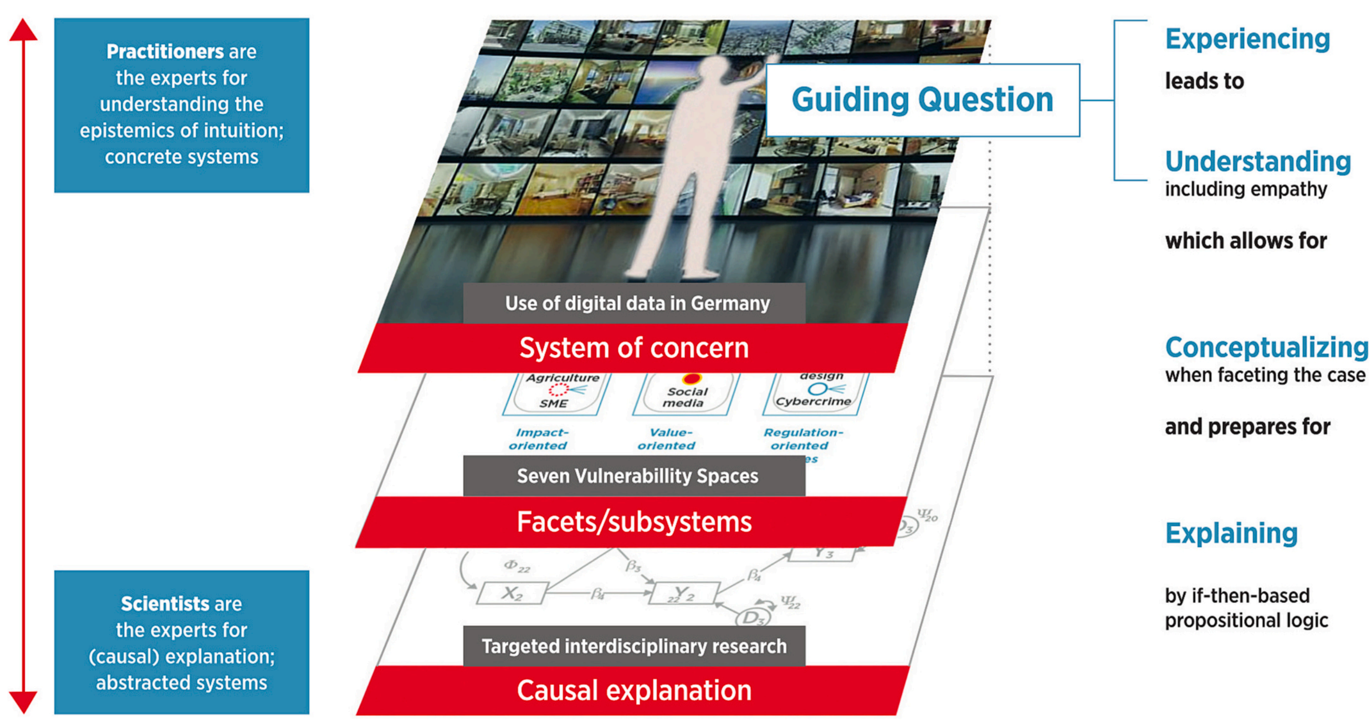

Fig. 4. The architecture of knowledge; three levels of abstraction related to four different types of knowledge in the course of coping with a complex transdisciplinary.

causal explanation which is based on symbols, algorithms, scientific methods, etc. This is a genuine part of science and targeted interdisciplinary research (see Figs. 1 and 2).

Fig. 4 has been called the "architecture of knowledge" (Scholz and Tietje, 2002). In principle, the three levels – the system of concern, the conceptually defined subsystems, and the causal explanation – are related to different levels of abstraction of cognitive representation that are supposed to develop in the genesis of knowledge in human development (Piaget, 1997; Scholz, 2011a). A direct, immediate experiencing leads to (perception-based conscious and subconscious) understanding about the specifics of a case. This is essential for defining "the right" guiding question. The faceting of the system of concern with the aid of concepts helps to structure the complexity and may lead to gaining access to explanations for wanted and unwanted dynamics of the system. The approach refers both to the distinction of the enactive, iconic, and symbolic representation (Bruner, 1964; MacBlain, 2018) and to Piaget's genetic epistemology which links representation to causal reasoning. In general, practitioners have experiential, insider knowledge about a transdisciplinary problem that is unavailable to scientists. By contrast, scientists are the experts for general theories on causal relationships. For

Box 2
Using the architecture of knowledge for transdisciplinary processes.

The term "experiencing" (German: *erfahren*) as defined by Kant (Cohen, 1885) denotes what "consists in the synthetical connexion of phenomena (perceptions) in consciousness, so far as this connexion is necessary" (Kant, 1783/1912/2016, §22). The direct sensual, perceptual, observational encounter with a subject, i.e., the immediacy with the real-world setting, is the essential characteristic. This includes the specificity of the contextual constraints. Anthropologically, we are dealing with the insider's view (Young, 2005), i.e., local, situated, holistic experiential knowledge. Experienced medical doctors insist on having seen a patient before they provide a reliable and valid diagnosis or therapy. Similarly, an ecologist cannot provide a comprehensive and reliable assessment of a biotope/habitat without having had a walk through it. The method "experiential case encounter" (Scholz and Tietje, 2002, [Evo-Lev]) suggests that scientists make an undercover-like side change for some time (i.e., living as a case agent/practitioner for some time).

"Understanding" (German: *verstehen;* see Fig. 4) focuses on the comprehension of or grasping of what is essential or what the problem is in a transdisciplinary process. Understanding is close to the cognition of meaning (Table 1 [Cog]) and linked to evaluation (i.e., a feeling about what is good and what is bad). For instance, the understanding of social situations calls for empathy, i.e., being aware and sensitive to another's feelings, needs, desires, and thoughts (Hauswald, 2019). We call this primary, embodied understanding and distinguish it from secondary understanding. The latter may be defined as cognition that follows explanation, which provides "fully comprehensive and maximally well-connected knowledge" about an issue (Boyd, 2021; Kelp, 2015, p. 3799). The meaning of primary intuition has been described by the following sentence: If a dog has done something wrong, the dog can understand it, but the dog will never be able to explain it (Wellek, 1953). The distinction between the understanding of an individual (without or with only few explanation; David-Rus, 2021; Strevens, 2013) and the understanding of a group is important for transdisciplinarity (Boyd, 2021; Hauswald, 2019). Groups have their own minds, values, norms, decision rules, wills, etc. that determine how the opinions and beliefs of their members are incorporated (Scholz, 2011a).

"Conceptualizing" (German: *begreifen*) is the translation of properties and dynamics of a system, i.e., transferring what is experienced in practice into the abstract world of concepts. The philosophical roots of conceptualizing were defined by Kant as complementary to the German concept of *Anschauung* (which may be translated as intuited or perceived objects; McLear, 2020). Pragmatically, we simply emphasize that—as conveyed by the sequence "cognition, notion, representation" (Gloy, 1984, p. 5)—the essence of how cognition becomes a representation of meaning is something in the mind. When facing the complexity of a transdisciplinary problem, the challenge is to find a conceptual grid that allows us to structure the complexity with respect to the guiding question, which represents the relevant/meaningful aspects of the system representing the transdisciplinary problem. We call this faceting by a conceptual grid. The taxonomy of bodily organs such as the heart, lungs, kidneys, etc. in medicine can serve as an example of conceptual faceting. In DiDaT (see Box 1, Fig. 3, 2nd column), both the vulnerability spaces and the unintended side effects of the use of digital data (Fig. 3, 3rd column) are conceptual grids that help implement a differentiated analysis of a subsystem.

"Explaining" (German: *erklären*) provides explicit descriptions of the reasons for the appearance of a phenomenon; the causal relationships between elements of a system or among systems; the impact of an action; the grounds, rationales, and justifications of beliefs, etc. In general terms, an explanation describes the causes for something that has happened, is happening, or will happen. Explanations generally follow the scheme of propositional logic, which allows for sequential and refined justification. This is also called "statement logic." Propositional logic, in particular, provides "if–then" relationships (and differs from higher-ordered logic [see the Section 3.2 on epistemology], which is not a common basis for communication. Explaining (explicit) propositional, concept-based reasoning is an abstract and reductionistic activity. We should note that whether "if–then" relationships are believed to be true can differ between actors. A challenging task for transdisciplinary projects is to develop "cause–impact" knowledge for developing joint (group/team) knowledge. This has been displayed previously in the lower layer of Fig. 3 and the middle columns of Figs. 3 and 5.

From this, we may learn that sharing explanations (i.e., "if–then" relationships) is a prerequisite for mutual learning in transdisciplinarity. If the explanations provided by some group members do not meet the "acceptance systems" or the "evaluation systems" of others, then developing shared group knowledge will be difficult (Steup, 2016). Thus, the facilitator in a transdisciplinary process has to ensure that the justifications and propositions used for the construction of SoROs "cohere with the relevant part" of the "cognitive system" of all participants. This may become especially challenging when different worldviews, experiences, and belief systems coincide.
We argue that the codified science system (see Fig. 1) is a major source for providing coherent, logical, consistent, and well-reasoned causations. Thus, scientists are viewed as experts for explaining generics, whereas those who live directly in the real-world system are experts for understanding the problem in detail (see vertical arrow in Fig. 4). For building the bridge between science and practice, the scientists (the outsiders; Headland et al., 1990) may also need direct, immediate knowledge about the transdisciplinary system.

coping with the complexity of real-world settings, these evolutionary levels, which are prevalent in high profile experts. Thus, e.g., a meaningful definition of a transdisciplinary problem calls for some consistent interactions among the three levels. The architecture of knowledge describes the interactions of different epistemics within one participant. It is an aspect of the utmost importance as, in the end, not what is written but what is recognized is essential for the genesis of knowledge. As this point is that interesting, Box 2 provides a more-detailed description.

3.7. Complexity management with Brunswik's theory of probabilistic functionalism [Com]

A primary challenge of any transdisciplinary process for sustainable transitions is complexity management. Yet any multi-cell organism has to cope with a myriad of diverse internal and external, partly interconnected signals that are intra- and intercellularly processed. What signals are received and processed is neither deterministic nor unique nor unambiguous. Nevertheless, the human individual—as well as human systems such as organizations—must have strategies for filtering, selecting, reducing, and prioritizing environmental information needed to successfully adapt to complex environmental settings. This has to be accomplished especially in complex environments:

> *The goal is to find a "satisficing" set of ecological valid and cognized cues (see middle layer of Fig. 5) that allow for a sufficient representation to derive a satisfying judgment, action, etc. (i.e., "terminal focal variable") that provides resilient feedback and a functional, probabilistic stabilization for maintaining the viability of the relationship between an organism and an environment (a detailed explanation of this statement is provided in Box 3).*

The last sentence is the message of Egon Brunswik's Theory of Probabilistic Functionalism (TPF). Brunswik provided a unique approach toward living systems' cognitive principles for coping with challenges of evolutionary, ecological, and environmental complexity (Brunswik, 1952; Hammond and Stewart, 2001; Scholz, 1987, 2017a).

Brunswik initially focused on visual perception. The TPF came to be applied in many fields such as social perception and learning (Mumpower, 2001), cognition (Goldstein and Wright, 2001), social judgment theory (Brehmer, 1976), and behavioral decision theory (Slovic et al., 1977). Brunswik's TPF has been applied for structuring sustainable transitioning since 1995 and then utilized as a foundational framework for describing methods of integrating quantitative and qualitative knowledge (Scholz and Tietje, 1996, 2002). A recent discussion on how the TPF can be used in transdisciplinary processes was framed by two papers (Scholz, 2017a, 2018) and eight contributions on:

- structuring complexity for transdisciplinarity (Dedeurwaerdere, 2018; Mumpower, 2017; Susskind, 2018);
- representing, planning, and sustainable action among multiple members of an organization (Hoffrage, 2018);
- conceptualizing human–environment interactions (Mieg, 2018), finding means for resilience (Steiner, 2018), and understanding environmental responsiveness (Wilson, 2018); and
- understanding the role of open data in the digital transition (Yarime, 2018).

Based on these, the TPF can be applied to all the types of knowledge integration presented in Table 1. For instance, it may be used to frame and reflect the modeling of formative (participatory) scenario analysis, system dynamics, or material-flow analysis [Syst]. Likewise, the conflicts among stakeholders [whose judgments may be viewed as cues; Con] can be well-modeled by a TPF-based multi-criteria modeling (see Scholz, 2018).

Brunswik's TPF is also an excellent means to cope with a key challenge of transdisciplinarity processes, i.e., who should participate in a transdisciplinary process.

Box 3
Different types of complexity in transdisciplinary problems.

Complexity is not unambiguously defined. We distinguish between definitions of physical and information-theoretic complexity and biological complexity. Physical and information-theoretic complexity offer several quantifiable approaches such as Kolmogorov (Li and Vitányi, 2008), computational (Du and Ko, 2011), and entropic (Tsallis, 2016) complexity. Biological complexity includes multiple processes in and between cells, organs, and organisms such as humans as well as groups, organizations, and other systems up to the human species (Capra, 2005; Scholz, 2011a). This includes structural (Heylighen, 1999) and functional complexity (McShea, 2000). Knowledge integration—in an increasingly complex world and universe—calls for a deep theoretical understanding of evolutionary principles of development and adaptation.

Ecological validity is a key concept of Brunswik's TPF. Ontologically, the main challenge of an organismic being is to sample the proper informational cues out of the myriad of seemingly infinite amount of information coming from the environment. When studying how the human perceptual system manages this, Brunswik referred to the interaction of differentiation and integration as a basic evolutionary strategy of organismic information-processing. A simplified (didactical) representation is Brunswik's Lens Model (Brunswik, 1952; Gigerenzer and Kurz, 2001, see Fig. 4, left side;; Scholz, 2011a; Stewart, 2001). The basic idea of Brunswik's complexity management is that an organism perceives a small but sufficient set of probabilistically acquired cues, information, signals, or perceptors whose (probabilistic, i.e., non-deterministic) processing enables an internal representation of the environment and actions (called terminal focal variables) that provide evolutionarily stable feedback (Fig. 4, upper part). The feedback is probabilistic. Proper and improper representations, actions, etc. are rewarded with certain likelihoods. In current terms, "evolutionarily stability" means resilience and a system's ability to maintain the viability of human actors/systems.

Evolutionary stability, thus, requires that the relationship between input and output is beneficial for an organism, given the uncertain (probabilistic) positive and negative environmental feedback (reward vs. punishment). The acquisition of the perceptual cues should be substitutable. This means that a process of "vicarious mediation" may take place among the organismically represented cues (Scholz and Tietje, 2002, see the middle ovals of Fig. 3a and b,). For instance, if a certain cue is not perceived (e.g., by the eye because of a blind spot or other reason for non-accessibility), the necessary knowledge can be attained from other cues. The cue processing for substitution is presented in the oval of Fig. 3 on the right side. The concept of ecological validity and vicarious mediation (substitutability) are the most essential properties of TPF.

1. The roles participants should play as representatives of disciplines or stakeholder groups should be assigned to the participants (by the facilitator or the project leaders). In a transdisciplinary process, practitioners should represent the interests and perspectives of a specific stakeholder group. Here, the system analysis (see Table 1 [Svst]) is the basis for a stakeholder analysis, and the epistemological analysis is a starting point for the selection of the scientists). If participants represent different roles, they should participate when taking one role/perspective [Con]. Changing roles (temporarily) should be explicitly communicated to all participants.
2. The selection of representatives of stakeholder groups should be done in such a way that the participating stakeholders possess knowledge about the key subsystems with high ecological validity. We should note that functional validity may be best attained if those stakeholders are selected who have (a) the most profound knowledge and (b) who are able to best collaborate to attain the "terminal target variable" (e.g., a SoRO) from an integrated perspective.
3. Naturally, securing a pluralistic-democratic perspective is an explicit or implicit goal of the presented type of transdisciplinarity in democratic societies. A balanced political perspective should (ideally) be available on all levels of the transdisciplinary team so that scientists and practitioners have the same amount of control (Mielke et al., 2017; Mielke et al., 2016). In particular, the practice co-leadership should be able to integrate all stakeholder groups' interests. If this is not the case, two practice leaders (e.g., one representing civil society and the other business/industry) may be an option..

4. Discussion

4.1. What has been provided thus far

Section 2.1 presented an ontological definition of a problem as subject of a transdisciplinary process. This included the systemic, epistemological-cognitive, and social-conflict-related normative aspects. We argue that such a problem cannot be approached by a process less elaborate and less expeditious than a transdisciplinary process. The construction of SoROs as a means of strategic sustainability management is based on the extensive collaboration of practitioners and scientists along six major steps and types of activities (Fig. 1). The main contribution of this paper (Part I) is a structured description and analysis of what types of knowledge integration occur in transdisciplinarity. This is done when taking a history and theory of knowledge and science perspective and against the experience gained in about 40 former transdisciplinary processes (see Scholz and Steiner, 2015d) which developed, applied, and discussed the presented seven forms of knowledge integration. This goes beyond the current literature which presents many examples of how specific knowledge is used (de Melo and Caves, 2020) or describes how knowledge integration takes place in groups (Godemann, 2008), in a transdisciplinary consortium (Schönenberg et al., 2017) or how different stakeholders are involved (Huning et al., 2021). Hitziger et al.'s (2019) paper (Scholz, 2018) may be considered the closest to the intention of the present paper as it relates thinking, planning, learning, and collaboration to look at a broad range of transdisciplinary projects.

Another issue is the description of the different phases of a transdisciplinary process (Fig. 1) as it is suggested in Part II of this Paper (Scholz et al., 2024). The first four phases, i.e., (1) the concern-based triggering phase, (2) the initiation, (3) the preparation, and (4) the planning phase end with the formulation of a guiding question. The guiding question embeds the transdisciplinary problem in a (sustainable-)transition-oriented, i.e., normative, framing which reflects the (negotiated) stakeholder interests [Con]. The reader should note that the first four phases are far more time-consuming (typically over 70 % of the time for the entire process; Scholz and Steiner, 2015) than the core phase. When formulating the guiding question and designing the (5) core process, the multitude of forms of knowledge integration should be anticipated, reflected, and pragmatically improved. For planning a transdisciplinary process, it is important to understand and to reflect that different scientific disciplines may follow different, sometimes incompatible, modes of causation and validation ([Epi], Hirsch Hadorn, 2022; Nicolescu, 2011). Stakeholders from different social, professional, or cultural backgrounds possess and demonstrate different thinking styles and negotiating strategies. Part II of this paper presents the practical experiences gained by five concurrently conducted transdisciplinary processes for the DiDaT project (see Box 1) and delineates what type of knowledge integration is of special interest at what phase.

4.2. Theoretical foundations of knowledge integration

The seven presented approaches of knowledge integration may be considered as a triangulation of different forms of knowing (epistemics) and addressing a transdisciplinary problem (Scholz, 2020). They deal with different scientific subjects and disciplines. A systemic integration [Syst] requires relating knowledge about different (material-biophysical and cognitive-epistemic-cultural) real-world systems for understanding the system of concern (see Fig. 1). The (scientific) subject is (the ontology of) specific levels of a real word system. The disciplinary background is systems and complexity theory when applied to real world systems (Scholz, 2011a, Fig. 14.6).

The subject of epistemology and philosophy [Epi] are hypothesized ideal forms of knowledge. These disciplines reflect on nature, sources, genesis, functions, limits, etc. of epistēmē ("knowledge") and logos ("reason"). Kant's distinction (see 1, above) between common, general reasoning and a formal, scientific (transcendental) logic provides a main dividing line. But, also within the science system, we may find fundamentally different modes of epistemes and reasoning. For instance, approaches using variants on Karl Popper's critical rationalism (which focusses data and evidence) are much different from approaches using qualitative hermeneutics which focusses the meanings, intentions, and social contexts of reasoning (Ekström, 1992). A key challenge when running a transdisciplinary process is to reflect what aspects of a transdisciplinary problem are included in certain bodies of knowledge utilized and what not.

We introduce a sociocultural perspective [Cul]. The main subjects are human societies and their religions, customs, habits, behavioral rules norms and values, beliefs, etc. as they are analyzed in cultural anthropology (Herzfeld, 2001), cultural studies (Hall, 2006), or cultural sociology (Alexander, 2006). Thus, the cultural perspective is different from the cognitive [Cog] whose main discipline is psychology. The science of psychology deals with thought (i.e., the specific processes thinking, mind, or brain functions, forming motivations) and behavior (which builds experience) in living individuals, small groups, etc.. Further, the rules of interactions and conflicts emerging from different interests among stakeholders [Soc-Con] are subject of social psychology as part of sociology and psychology. When analyzing stakeholders, an understanding of their functions, roles, interests, worldviews and responsibilities is essential. Based on this, the biased preferences and perception can be identified (Lange et al., 2022; Zscheischler et al., 2022) and models of game and decision theory may be applied.

Evolutionary psychology [Evo-Lev] goes beyond psychology (Buss, 2019; Downes, 2018). It includes evolutionary biology's knowledge on the ontogenetic- and phylogenetic developmental patterns or levels of cognitive representation. The scientific subject may be viewed as an understanding how the genesis (ontogeny) of mind, from the zygote's interaction with the environment via early childhood and other states of the environment to the present state (including different modes and processes of cognition) may or have to come together when coping with problems of exceptional complexity such as transdisciplinary problems. We presented the architecture of knowledge by Scholz and Tietje (2002, p. 30), which differentiates four levels of abstraction and representations of knowledge These are (i) (directly) experiencing the real-world setting, an (ii) (empathic) understanding of imbalances and problems, (iii) the construction a conceptual grid can for structuring a transdisciplinary problem as a prerequisite of providing (iv) access to (symbolic) causal (if–then) explanations as shown in Fig. 4. This triangulation helps to differentiate between subconscious, concrete and abstract knowledge.

Finally, we presented Brunswik's TPF, a means of complexity management that provides "evolutionarily stable" perceptions (see Fig. 4a), judgments, decisions, system analyses, evaluations, stakeholder analyses, etc. The basic idea is that a small set of ecologically valid, mutually substitutable cues allow for an integration that can provide satisficing, robust representations, decisions, or actions. Cues may be system variables, evaluation criteria, stakeholders, etc. (Scholz, 2017a, 2018). As typical for later Vienna Circle contributions, Brunswik's theory is between epistemology and psychology.

4.3. Epistemic triangulations on processes for sustainable transitioning

Renn (2021, p. 5) denoted the presented approach of transdisciplinarity as a "merger of science and practice" knowledge [Epi]. Transdisciplinarity, as a deliberative activity, is conceived as a problem-oriented approach that takes place between science and practice. Thus, we consider it a tool for strategic sustainability management. The presented form of transdisciplinarity is different from "action-oriented research" (Caniglia et al., 2021). Transdisciplinary action research may follow the presented, strategic management oriented one. The presented type of transdisciplinarity aspires the construction of widely acceptable goals and SoROs that also acknowledge goal conflicts among stakeholders [Con]. Given the exceptional complexity of transdisciplinary problems, attaining this goal often asks for reframing and transforming problems (as a product of knowledge integration) rather than (directly) solving them.

The presented notion of transdisciplinarity includes knowledge integration as a unifying approach of different types of knowledge for real-world-based challenges. It is a genuine pluralistic approach (Norström et al., 2020). The multi-triangulation of different bodies of knowledge may be seen as key means to improve the systemic, epistemic, and interest-(stakeholder-)based robustness of SoROs.

We argue that knowledge integration between practice and science requires direct interactive collaboration. The collaboration includes co-production of knowledge and co-creation of the design for a transdisciplinary process. This asks for co-responsibility, co-accountability, and sometimes even for co-liability for process and outcomes. The acceptance of the otherness and trust formation are prerequisites. Critical questions, for instance, are who is/are the owner/s of the data (produced in transdisciplinary processes) and who decides what statements are included in a SoRO. Actually, we have learnt from many transdisciplinary studies (Scholz and Steiner, 2015) that some form of (informal or formal) a science-practice-co-leadership (on all levels of the project) is necessary to convince stakeholders to participate and to show commitment to a transdisciplinary problem and process.

However, the particular interest and focus of this article was on transdisciplinary knowledge integration. We have not discussed the socio-political and cultural conditions under which transdisciplinary processes can take place. In general terms, the social rule system must enable the different types of knowledge integration discussed. The answer to this question is addressed in a recent paper on codes of conduct for transdisciplinary processes by Scholz and Renn (Scholz and Renn, 2023). The general message here is that acceptance of the otherness of the other is the fundamental sociocultural prerequisite without which knowledge integration and transdisciplinarity cannot take place.

5. Conclusions

We define transdisciplinary problems as a specific type of complex, societally relevant, ill-defined, real-world problems which show a high level of ambiguity, included contested perceptions and evaluations and multiple trade-offs. The presented type of problem is characteristic for sustainable transitions. Transdisciplinary processes serve for joint problem framing and for the construction of SoROs. Transdisciplinary processes include, ideally, a targeted interdisciplinary process, a mitigated multistakeholder discourse and a facilitated collaboration (i.e., mutual learning) of scientists and practitioners (Fig. 2). The processes of mutual learning among science and practice and the construction of SoROs are conceived as key parts of strategic sustainability management.

We suggested a template for organizing transdisciplinary processes presented in Fig. 1. The template includes a triggering, initiation, and preparation phase. These phases take a tremendous amount of time and widely ignored in literature. They are characterized by a comprehensive networking and extensive complexity structuring including the formulation of a truly consented guiding question and system model. This can be seen as prerequisites for a committed inclusion of practitioners and scientists and for a successful planning. Naturally, the types of triangulation of knowledge, including a differentiation and integration, is key for the core phase [Com].

Also, the selection of stakeholders is part of knowledge integration. Following Brunswik's TPF, we have to include participants who have (ecological valid) knowledge and who may substitute to some extent—as a group—the knowledge of those who could not be included. This also holds true for the selection of scientists. Yet, in an analog way, TPF can be applied to the selection of subprojects/facets, system variables and other issues which ask for complexity reduction. We argue that reflexion on knowledge integration reveals what types of knowledge have been included and what knowledge is not included. This is a most important tool to critical reflect a transdisciplinary process as a prerequisite of appraisal of a study and to improve follow up studies.

We showed that the seven types of knowledge integration deal with different subjects that are approached in different scientific disciplines. For instance, it is essentially different whether we consider hypothesized forms of knowledge [Epi] or real thinking processes [Cog]. Thus, the different types of knowledge integration overlap less than a first view may convey.

The present paper provides a theoretical reflexion on what types of knowledge interaction take place in transdisciplinary processes. Part II (Scholz et al., 2024) shows how this reflection may be applied in practice. This is done for the case of the DiDaT project (see Box 1). Part II will elaborate tasks, challenges, and obstacles for each type of knowledge integration for each of the six phases of a transdisciplinary process and include an empirical study of how the balance of scientists and practitioners can be measured and what added value can be attained by utilizing the modes of knowledge integration for better reflection, assessment, and management of transdisciplinarity.

CRediT authorship contribution statement

Roland W. Scholz: Conceptualization, Funding acquisition, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Jana Zscheischler:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Heike Köckler:** Conceptualization, Investigation, Writing – review & editing. **Reiner Czichos:** Conceptualization, Investigation, Writing – review & editing. **Klaus-Markus Hofmann:** Conceptualization, Investigation. **Cornelia Sindermann:** Conceptualization, Investigation, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

The source of all data, figures etc. is genuinely produced by the authors.

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Ethics approval and consent to participate

The rules of the Committee on Publication Ethics (COPE) are appreciated and have been applied.

Consent for publication

All authors agree on the content and have the permission to name the institutions to which they have been affiliated when writing this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2024.123281.

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