Ways and modes of utilizing Brunswik's Theory of Probabilistic Functionalism: new perspectives for decision and sustainability research?

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Ways and modes of utilizing Brunswik's Theory of Probabilistic Functionalism: new perspectives for decision and sustainability research?

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Abstract
Several of the comments on the *Managing Complexity* paper deal with theoretical issues regarding Brunswik's Theory of Probabilistic Functionalism (TPF) (Mumpower; Hoffrage) or its application to sustainability planning groups (Mieg; Susskind). Other commenters extend the space of application of the TPF to better frame innovation or open data management (Steiner; Yarime) or focus frameworks of how to conceptualize modeling or transdisciplinary processes in sustainable transitioning (Wilson; Dedeurwaerdere). This response paper first clarifies several general issues, such as how to approach the evaluation of single TPF principles such as representativeness, in what way TPF may improve sustainability planning groups' performance, how sustainability may be conceived as a terminal focal variable, and in what way groups are organisms. Based on an acknowledgment of the eight comments and their groundbreaking ideas, we discuss two shortcomings in the current use of the TPF, i.e., the definition of cues (sign-significates) and the challenge of how motivational and emotional approaches can be related to Brunswik's framework of how the organism cognitively interacts with its environment. We conclude that the TPF will become a theoretical framework for structuring, representing, describing, understanding, modeling, and managing complex, inextricably coupled human–environment systems. This is of special interest not only for decision sciences but also for planning, environmental, and sustainability sciences.

Keywords Egon Brunswik · Theory of Probabilistic Functionalism · Representativeness · Cues · Decision sciences · Planning sciences · Environmental science · Sustainability science

1 General feedback on the comments

The *Managing Complexity*[1] paper presents Brunswik's Theory of Probabilistic Functionalism (TPF) as a general theory of perceptual and cognitive complexity management in inextricably coupled organism–environment interactions. The eight comments[2] acknowledge that the review on the current neurological and biophysical research on sensation substantiates Brunswik's cognitive (non-physiological) research on visual perception (Sect. 2[3]) (Brunswik 1952).

Author's responses to the open peer commentaries on "Managing complexity: From visual perception to sustainable transitions—contributions of Brunswik's Theory of Probabilistic Functionalism."

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1 In the following, we denote Scholz's discussion paper (2017a) as the *Managing Complexity* paper.

2 In a first round of comments, the following provided eight comments that appeared in this issue and are subjects of this author's reply: Dedeurwaerdere (2018), Hoffrage (2017), Mieg (2018), Mumpower (2018), Steiner (2018), Susskind (2018), Yarime (2018), and Wilson (Wilson 2018).

3 These unreferenced numbers with the preceding "Section" always refer to the *Managing Complexity* paper.

Most of the comments appreciate the "audacious transitioning" (Mumpower 2018) of the TPF to explain *sustainability planning groups' cognitive activity* when *constructing* and *evaluating sustainable planning variants* (Sect. 4). However, there are critical comments and controversial views regarding this "double step," e.g., on the question of in what way(s) *groups are organisms* or what way(s) sustainability is a meaningful terminal focal variable of planning and evaluation. There is also some controversial discussion about whether the TPF is *more than a descriptive metaphorical tool* and how it can function as a *prescriptive* tool or even as a *normative framework* of the organism.

The comments approach the paper from a wide range of perspectives. Mumpower starts with a discussion of several essential statements about Brunswik's TPF and points to the precursor function of the TPF to currently developing coupled human–environment research. He then refers to Hammond's (2001) suggestions for using the TPF for *disagreement among* (*planning*) *group members* and thus suggests applications of the TPF for *conflict resolution*. *Hoffrage* considers the planning group's work as "mental simulation" and decomposes the group's joint *representation of an "is state"* (i.e., the initial focal variable in a simplified conception of planning) into the phase of *forward-oriented planning* and a subsequent *implementation phase*. *Susskind* and *Mieg* stress that real-world planning processes are often politically contested and include dynamics (and learning processes) that are not included in the TPF principles. But both comments consider the TPF principles, pragmatically, as meaningful metaphors or tools.

There are four comments that utilize the TPF as a framework from a sustainable transitioning and sustainability science perspective. *Steiner* elaborates in what way an understanding of *innovation processes* can be improved when referring to the TPF principles. *Yarime* extends the application of the TPF to *organizations* and elaborates in what way *open data* is a necessary condition for sustainable development. *Wilson* discusses the potential and limits of the TPF given specific complexity, uncertainty, and ambiguity regarding sustainable transitioning. And *Dedeurwaerdere* (2018, Table 2) provides insights into the sustainability evaluation with the help of (heuristics as) cues and outlines how the different TPF principles are inherent in different theoretical approaches of sustainable transitioning.

Before responding to the comments (see Sect. 2), the following four subsections address critical issues that are relevant across the comments, i.e., Sect. (1.1) *How can research on the validity of the TPF in complex real-world situations be conducted?* Sect. (1.2) *In what way can the TPF principles improve sustainability planning groups' behaviors?* Sect. (1.3) *In what sense is "sustainability" a terminal focal variable of the TPF?* and Sect. (1.4) *In what way may groups be conceived as organisms*?

1.1 How can we approach an empirical/experimental validation of the TPF: The case of the representativeness principle

The *Complexity Management* paper focused on the application of the TPF to two *cognitive* group processes, i.e., the formation and the evaluation of *sustainable planning variants*. In it, we referred to 41 transdisciplinary planning studies. In many of them TPF was part of the training to the planning team members. And most of the planning team members were master students. However, in all planning groups, members of the city planning group, practitioners responsible for strategic planning, and scientists were included in the planning activities (these studies are documented in the Supplementary Information of Scholz and Steiner 2015a). The experience gained in these studies was seen as a reason to suggest future empirical or experimental research on the validity of the TPF principles, such as the *representativeness principle*. To do this, several comments (see Mieg or Susskind) demanded:

> ... we must take into account the full picture of the working conditions of planning groups for (sustainable) urban transitions, if we wish to understand the functioning of such planning groups (especially with regard to "evolutionary stabilization, ..."). (Mieg 2018)

Let us first briefly describe how Brunswik himself dealt with the challenge of finding a way to validate his theory. In his later work, he went beyond size constancy research to investigate cues of facial expression, among others. He stressed that, for this research, "real persons seemed unacceptable because of the large number of uncontrollable factors, a feature which, under the auspices of representative design, would be considered an asset rather than a liability" (Brunswik 1956b, p. 100). This is the rigid position of an experimental psychologist.

For sustainability research, however, we take a different or opposing position. We think that the complexity, particularly of the relationship of coupled human–environment systems, has to be maintained, especially when *socially robust orientations* (Scholz 2017a, b) are the goal of planning. But how can the validity of the TPF principles as characteristics of high-quality planning be validated? We will sketch this using an experimental study on sustainable urban development and the case of the *representativeness principle* (P6-r*epr*).[4]

[4] As keeping the meaning of the seven TPF principles in mind is arduous, we introduce the following notations to facilitate reading: P1-*func* (functionalism principle), P2-*dual* (dualist human–environment system), P3-*prob* (probabilistic information acquisition and processing), P4-*vicar* (vicarious mediation), P5-*repr* (representative design and representativeness), P6-*evostab* (evolutionary stabilization), P7-*interlink* (interlinkage of perceptors).

As the term *representative design* indicates, Brunswik introduced the representativeness principle primarily for ensuring that experimental tasks make sense to the subjects' perception (Brunswik 1944, 1955, 1956a). In his view, the challenge to an experimental psychologist is to present a sample of (experimental) tasks "in such a way that the … sample is representative of the actual demands of the whole environment made upon the organism with respect to the actual stimulus variable under consideration" (Brunswik 1944). Brunswik calls for "situational generality, environmental generality, circumstantial generality" (Brunswik 1944). This statement refers to the *relation* of organisms/subjects and the experimental tasks they have to cope with in experimental designs. We transferred the *representative design* principle to the *representativeness principle* when requiring that the texture and structure of what is perceived (or becomes the subject of a judgment) must meet the organism's (e.g., a planner's) experience or experiential knowledge. We want to note that also Tversky and Kahneman (1974) *representativeness heuristic* is based on P5-r*epr*. The fallacious judgment of their student subjects that Rome is south of New York is based on that the students are not professional geographers (and not literate with Gauss-Krueger coordinates of cities), and for them Rome represents a typical city of the south and New York a city of the north. An important prerequisite is that the subjects know Rome and New York and—in their incorrect judgments—are led by cues (Rome is warmer than New York and thus closer to the equator, hence, south of New York). If you were to use, as a comparison, Eibar and New York, the representativeness principle/heuristics cannot be applied, as this (Spanish) city may not be known to most subjects. Thus, some knowledge of the topic is a prerequisite so that properties regarding the issue are cognitively generated, brought before the mind, apprehended, or assigned according to the representativeness principle. Therefore, one can argue that planning groups must know the planning case sufficiently.

How might we evaluate the idea that the representativeness principle is important for planning groups in order for them to produce "good," i.e., "evolutionarily stable" planning variants? Under what condition or conditions might such validation take place? We can argue that planners must have solid personal experience with the type of planning case. For spatial planning, one can argue that people educated in landscape planning do not have experience with urban brownfields (i.e., former large-scale industrial sites) that should become the subject of sustainability planning. This situation was highlighted in an urban study on sustainably transitioning a brownfield. A total of 105 second-year masters students who all had bachelor's degrees in environmental (natural) sciences as well as some knowledge of planning (yet only on natural and not on urban systems) worked in different subgroups on the sustainable planning of a large Zurich brownfield (Scholz et al. 1997).

We argue that experiential knowledge of brownfields site is important for developing mental structures that are needed in planning. Thus, we included experiential case encounters (i.e., all members of the case had to change sides and work in the field for one day, e.g., as road cleaners) as a means of developing or increasing familiarity of the planning trainees with the case. This may be seen as a prerequisite for planners to be able to provide more reliable judgments. Moreover, the planning trainees worked 40 to 50 days on the case partly in office spaces within the case area. Given this situation, one might hypothesize that, when a case becomes better understood, planners become better at assessing those *impact factors* (used in formative scenario analysis) *that allow for a description of the current situation of a case and its future development*.

Factually, we ran an experimental pre–post-study including the 105 planning trainees with a repeated measurement experiment. The impact variables were measured at the beginning of the case-based training course for sustainable planning with master students (N = 105) and again three months later. We were able to demonstrate that the impact factors listed by the trainee planners were significantly more similar to those of carefully selected planners (with knowledge of the case) who were experts in sustainability with considerable experience in this field (Hansmann et al. 2003). Thus, validation by benchmarking was achieved.

A methodological question is whether this experimental study can be taken as evidence for the *representativeness principle* from a predictive perspective. Direct experiential knowledge with the case brought it into the realm of experience, competence, and expertise—and this is what representativeness requires. Factually, the students were not working under the constraints of a real-world planning group. Although they participated in a *transdisciplinary process* that required coping with the full-fledged complexity of the case, they worked in a "protected discourse arena." As such, their work may have been less biased by "day-to-day policy" (as an imponderable confounding factor). This is a critical aspect of factual planning, as sometimes it does not allow for moving from positions to interests (Fischer et al. 1981; Islam and Susskind 2013).

We argue that a highly reduced setting or task (e.g., one provided by computer simulation) can be meaningful for studying specific cognitive processes. Moreover, we argue that the question of whether the investigation of how the TPF principles are involved in planning groups calls for (complex) *real-world settings*. We also stress that the planning setting, i.e., the case, should be well known to members of the planning groups, among others, to meaningfully refer to their experiential knowledge, which is the basic reference of representativeness. To design research that explores the cognitive group processes of sustainability planning groups, the researcher has to manage a *trade-off* between controlled (experimental) settings that allow him or her to follow (in a technical way, in order to measure) processes, structures and mechanisms of cognition, and decisions *as well as the situations* (i.e., a task in terms of Brunswik) *that are representative* of sustainability planning in a complex real-world setting.

1.2 The TPF provides general heuristics in an organism's successful coping with complexity, rather than a specific model of a planning group's operation

We want to clarify that we did *not* suggest that "the FSA Brunswik model" can "be considered a model for successful sustainability planning" (Mieg 2018). From our perspective, Brunswik's theory is not a silver bullet for the specifics of a planning operation. Yet we consider that following the TPF principles is beneficial for all planning groups' activities in order to cope with environmental complexity. We use the term "beneficial" to refer to the overall effectiveness (utility) of an activity, which Brunswik called evolutionary stabilization.

As elaborated in Sect. 6.3 of the *Managing Complexity* paper, we suggest that *properties and operations* of cognitive activities of sustainability planning groups can be *described* by the TPF principles. This was done when postulating that groups may be conceived as organisms (see below) and the TPF principles as generics of organisms' cognitive abilities. The statement that "TPF principles can be used as prescriptive tools" does not mean that the principles are operational planning tools. They rather mean that principles, such as P2-*dual* (which involves or even starts from a careful analysis of the environment) or P4-*vicar* (which help ensure that missing data do not harm the whole planning/judgment), are general principles or heuristics that cognitive operations should have in order to effectively and efficiently cope with environmental complexity. Let us illustrate what this means when looking at the interplay of the TPF principles in sustainability planning.

We postulate that the "TPF principles may serve as a reference [for] how successful planning groups can cope with environmental complexity in the frame of environmental stabilization" (see Sect. 6.3.2). We think that the idea of a functionalistic adaptation (P1-*func*) for attaining *evolutionary stabilization* (P6-*evostab*) in an ongoing (gradually or disruptively) changing human–environment (P2-*dual*) is related to or even inherent in sustainability as a process conceived as an ongoing inquiry for system limit management, i.e., the avoiding of hard landings (system collapses; this is the systemic definition of sustainability used). In considering sustainability planning, we have to acknowledge that this is done given multiple uncertainties (P3-*prob*) in information acquisition and processing and that vicarious mediation (P4-*vicar*; i.e., a certain redundancy of the cues that are acquired and processed) is meaningful given the limited ecological validity of the proximal cues.

To summarize, we suggest that (logically) "*following the TPF principles is neither a necessary nor a sufficient prerequisite for developing a sustainable planning variant.*" Groups may create meaningful sustainable variants when violating TPF principles in the course of scenario construction, and planning groups may follow all TPF principles and suggest a scenario that makes no sense (e.g., due to following wrong external goals). We think (and plan to validate empirically) that sustainability planning groups work more effectively when they know and follow these principles.

1.3 In what sense is "sustainability" a terminal focal variable of the TPF?

One of the concerns conveyed in the comments about this paper (as well as in the preceding ten extensive reviews of the *Managing Complexity* paper) is that *sustainability is not an end state* in the sense that it involves "a knowable environmental criterion," as there are "clearly substantial differences between ascertaining the true value of… the height of an object… in the context of visual perception, as opposed to ascertaining the optimal condition of a sustainable system" (Mumpower 2018). This author believes that such a view does not really align with "Brunswik's thought." Brunswik fully acknowledged the *uncertainties* (P3-*prob*) involved in the interaction of the organism and the environment, both on a molar and a molecular level of organismic behavior. We agree that sustainable development in the age of the Anthropocene (Crutzen 2002) is tremendously uncertain and that a lot of incomplete knowledge and ignorance is linked to future development. However, we doubt that Brunswik would have considered human decisions toward sustainable development an issue that is completely different from other decisions that organisms are facing. Let us look at an example that Brunswik presented at the Berkeley Conference on the Unity of Science (Brunswik 1955).

In a section on "behavior as a constant function" (Brunswik 1955, p. 198), Brunswik deals with the decisions of a *flock of (migratory) birds that flies southward*. He refers to a statement by the functional behaviorist Edwin Holt (1915), who stated that the organism's decision about movement is based on the situation (e.g., in the case of the flock's southward flight, the declining temperature may require a change of location). This is what he considered a molar, i.e., macro, analysis of the situation and the organism's behavioral response.

> But reaching the south or any other distal goal, be it behavioral or perceptual, can obviously become a more or less stabilized function only if the flight of the birds is allowed to take adequate advantage of the natural resources of orientation and locomotion. (Brunswik 1955, p. 198)

Yet what happens in the course of deciding to fly southward (which may be based on a generic disposition) is not conceived as a fully determined, mechanical process but rather something that is specified based on the particular situational constraints, the state of the organisms, unexpected events, etc.

> Constant psychological function thus is intrinsically limited, or probabilistic, rather than "universal." Flying southward, being right about object sizes, or any other gross or "molar" behavioral or perceptual function can never attain the status of an ironclad and universally applicable so-called "strict" law in the sense in which these laws were idolized in the classical phase of the natural sciences. (Brunswik 1955, p. 198)

Here, Brunswik conveys that decisions by organisms do not follow propositional logic in which a clear criterion exists for whether or not the decision made is the *correct* one. However, there are generic and specific components underlying perception, thinking, and other processes related to human behavior and decision-making, an idea that is also found in the comment by Dedeurwaerdere (2018), who suggests that sustainability groups may also use or learn a set of heuristics that are meaningful for sustainable transitioning.

1.4 In what ways are groups organisms?

When reasoning why Brunswik's TPF can be used for sustainability planning groups, we referred to the concept of the organism. Mumpower (2018) critically comments: "…, treating planning groups as if they were an "organism" will inevitably be incomplete and at least partially inaccurate, but such an assumption still might prove useful for purposes of motivating and organizing analyses."

This is certainly correct, as the concept of organism is a general one and refers to "something felt to resemble a living plant or animal such as … an entity having an existence independent of or more fundamental than its elements and having distinct members or parts whose relations and powers or properties are determined by their function in the whole" (Merriam Webster 2018). A critical question is whether and in what way the concept of "organism" today includes something that goes beyond a mere metaphorical use. Because of this, in the *Managing Complexity* paper, we referred to the revival of the concept of the superorganism in evolution (such as group; see Sect. 4.1.1). Let us briefly illustrate this idea. The paper refers to the discussion in theoretical biology of the behaviors of groups, herds, flocks, swarms, or colonies as a selective factor in evolution, an idea promoted continuously by Boorman and Levitt (1973), Wilson and Wilson (2007), although this view had long been abandoned. The dominant opinion was that the mutation of the (individual's) DNA was the only organismic evolutionary factor (Dawkins 2016). This view has been revised based on data and concepts from evolutionary biology, systems biology, developmental biology and psychology, and from philosophy of life sciences (Huneman and Wolfe 2010).

A critical argument in biology is that the genetic evolutionary timescale is on an order different from the ecological, learning-based timescale. However, this view has changed (Hairston et al. 2005). The history of fearless urban foxes may be taken as an example. Foxes migrated to Copenhagen around 1848; they've been in London since the 1930s and in many European cities for 40 years (Gloor et al. 2001; Pagh 2008). According to biologists, Zurich's urban foxes never move into the city habitat, whereas a single urban fox sometimes does, and the two populations already differ genetically. If we assume a behavioral, learning component of this pattern and not just a "fearless fox gene" as the cause, this may serve as an example that "group learning" or "behavioral colony patterns" are genetically relevant and thus an evolutionary factor (Wandeler et al. 2003). Today, many ecologists regard this hypothesis as widely accepted, if functional adaptation is considered (Pruitt and Goodnight 2014). Moreover, swarm intelligence has become a general concept that includes aspects of collective rationality:

> *Swarm intelligence*: two or more individuals independently collect information that is processed through social interaction and provides a solution to a cognitive problem that is not available to single individuals. (Krause et al. 2010, p. 28)

Stated in other terms, organisms are "evolutionarily structured by a division of reproductive labor among their parts" (Martens 2010, p. 372). We can also argue that small groups are, phylogenetically, a primary unit of human life and that—acknowledging fundamental differences in the mechanisms of human perception and decision-making—some mechanisms in non-human groups (such as rules for making group decisions) resemble or seem to be equal to those of human groups (Conradt and Roper 2003, 2005). This may hold true, in particular, if we take a functionalist perspective. Such a view has also been adopted in the proposed definition of a sustainability planning group

> … as a temporary or permanently designated group of members whose task is to assess critical aspects, develop strategies to overcome barriers, and design

future visions, states, and processes for sustaining a (coupled human–environment) system. (Scholz 2017a)

Let us briefly reflect on the evolutionary dimension related to planning groups. Here, we distinguish between the cognitive mechanisms applied by the planning group and the impacts of their planning. With respect to the latter, we can distinguish between short-term planning (e.g., an alternative route for road construction), mid-term planning (e.g., planning a subway system for a city), and long-term planning (e.g., energy planning for mitigating climate change). With respect to the last, it is evident that there will be impacts on human development if temperatures continue to increase and sea level rises more than 1.5 meters, as these will affect migration in many parts of the world and also shape socio-technological systems.

But what role do the inner, cognitive mechanisms play? Is it arguable or even meaningful to state that the rules applied in planning groups may become the subject of a "functional arc" of evolutionary stabilization (see Fig. 2 in the *Managing Complexity* paper) in the sense of Brunswik? If we look at planning sciences, we learn that planning schools (that may be conceived as groups) are culturally shaped. In developed countries as well, we can distinguish between different cultures of planning and design schools that developed in the early twentieth century. These differed with respect to uncertainties and innovations (Horovitz 1978), the inclusion of stakeholder groups (Healey 1997), the use of quantitative models (Mintzberg 1994a, b), the inclusion of sustainability (Stiftel 2009), etc. We can further explain the specific planning groups by some salient or extreme examples: After WW II, Britain's postwar town-planning efforts differed significantly from those of their counterparts in continental Europe (Faludi 2013). Such efforts were guided in large part by institutional contexts, normative ideas, and visions included in the New Towns Act (Parliament of the UK 1946). Building new towns on greenfield land, promoting neighborhoods, and planning groups (corporations) taking developmental control were part of this. That inner norms and rules of planning groups may have some (genetic) evolutionary impact is demonstrated by the totalitarian German spatial planning school's including the social exclusion (and even extinction) of others, driven by an obsession for orderly of space, materials, and national human genetics (Gutschow 2001).

But let us return to the concept of organism. This concept is differently defined by different disciplines, e.g., biology and philosophy. Brunswik used the term organism as a superconcept for describing human and other living beings' perceptions, according to the TPF. Studies of ecology and evolution provide some biological evidence for this. We illustrated that rules and norms of groups in the laboratory and also of planning groups may have long-term impacts and may be seen as parallel to non-human groups. Naturally, we assume that the rationales of decisions of humans and non-human groups differ, as there are specifics among different species. Thus, the term "reproductive work" may have fundamentally different meanings (ranging from genetic reproduction in some animal groups to group methods for maintaining the viability of a group). Yet we postulate that the principles of the TPF underlie and might improve (in a predictive sense) coping with the complexity of the organism–environment interaction. Whether this can have an ontological dimension depends largely on the philosophy of science position, as shown by Wolfe (Wolfe 2010). Some readers may feel uneasy that the concepts of organism and evolution have such a strong biological notion. But, the commitment to inter- and intragenerational justice as part of sustainability (planning) surely may be considered from a survival of the human species perspective and thus a means of evolutionary stabilization (also in a genetic sense).

2 Responses to comments

2.1 Mumpower: What is the environmental criterion in sustainable transitioning? From the one system to the N-system application of TPF

We have already addressed two of Mumpower's concerns with respect to the application of the TPF to sustainability planning groups (see above). *One* refers to the use and transfer of the concept of *organism* in the last section. Another, *second* concern expressed by Mumpower was that of the missing "knowable environmental criterion" in sustainability planning. Here, the example of migratory birds may be taken as example: "birds, a well-studied group of organisms, may respond to climate change, changing wintering areas, migratory routes, and breeding grounds…" (Muñoz et al. 2013).

For instance, storks (Ciconia ciconia) make decisions about whether or not to migrate based on external conditions and their inner state, e.g., the age and fitness of the flock or the attractiveness of a place according to the species' needs (Berthold et al. 2002; Berthold et al. 2001; Hiley et al. 2013; Kaatz et al. 2017). In Great Britain, following 600 years without storks, a pair of storks in 2014 nested in the county of Norfolk (Prynne 2014), and expert ornithologists expect the appearance of more storks. The environmental criterion (based on the prevalence of cues) for storks' nesting sites is related to cues indicating an adequate environment for securing and maintaining life and reproduction, and these decisions made by animals are sometimes group decisions (Conradt and Roper 2003) that involve consensus decision-making (Conradt and Roper 2005).

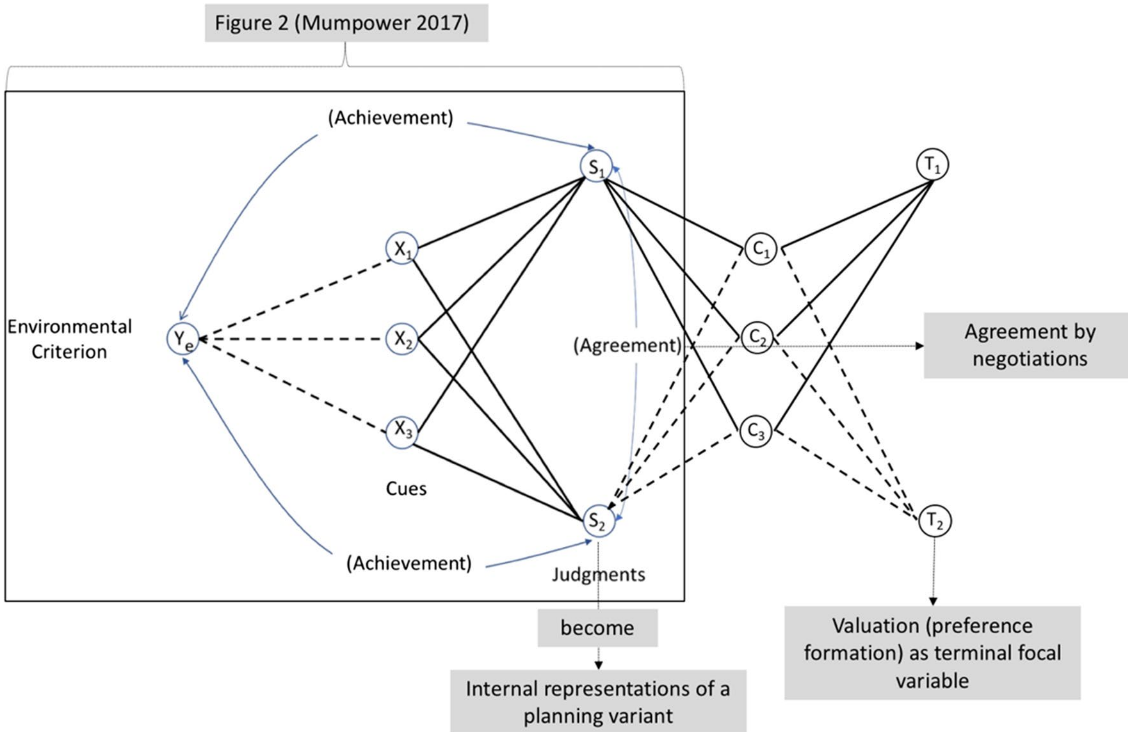

Fig. 1 Metaphorical representation of a two-stage, cue-based "cognitive representation"—"cognitive evaluation" process with subsequent negotiations

Naturally, the complexity of the decisions made by birds and those made by sustainability planning groups differs in several aspects. We can argue that they represent different magnitudes of imponderability, particularly as environmental changes in the age of the Anthropocene move at a different speed than those of environmental changes that influence animals' genetic mutation in the course of evolution (see 1.4). But are the cognitive processes of coping with uncertainties about the future really different in migratory birds and in sustainability planning groups? Here, the answers are "yes" and "no." The "yes" refers to the fact that cognition in the human species is cognitively superior to that of animal species with respect to a number of factors, for instance, understanding causalities. The "no" might refer to the TPF principles. In Sect. 2.1 of the *Managing Complexity* paper, we argued that *cues* (which might be conceived as fuzzy patterns of information or signals representing sign-significates) rather than *binary information* are at work in bees' decisions about hive location, such as planning groups' decisions about designing sustainable futures. And "evolutionary stabilization" (in contemporary terms, resilient structures) should be at the top of any list of preferences for flocks of storks and groups of human planners alike.

A *third*, theoretically interesting concern, relates to "the potential for disagreement among planning groups" (Mumpower 2018). Mumpower refers to Hammond's lens model of interpersonal learning and conflict (Hammond 1965). Two (or N) systems, organisms, or members of planning groups have access to the same cues but disagree in their judgment regarding the terminal variable (see Fig. 1, enframed section). The proposed model goes back to *cognitive conflict research* (Brehmer 1976; Dhami and Olsson 2008; Hammond 1965). The representation provided by Mumpower's Fig. 2 presents a common "cognitive conflict." Even given that two planning group members have access to the same cues, different *judgments* or *internal representations* (S_1 and S_2) might emerge, in terms of Brunswik's TPF, due to "stray causes" in cue acquisition and processing, and therefore, different judgments may result.

We may also consider that the cues X_1, X_2, X_3 are themselves cognitive representations for given planning variants (i.e., Y_e that were constructed by a sustainability planning group. This is, factually, a situation we find if variants are presented in one and the same way (e.g., by videos or booklets) to stakeholder (groups) S_1 and S_2. The valuation via a multi-criteria assessment with criteria C_1, C_2, C_3 is a follow-up step. We separate and link the *cognitive* and the *valence-interest-motivation* related sides of decision-making. This is a standard procedure applied in some studies of sustainable transitioning (Loukopoulos and Scholz 2004; Scholz and Stauffacher 2007). The diverging n-systems' judgments become subjects

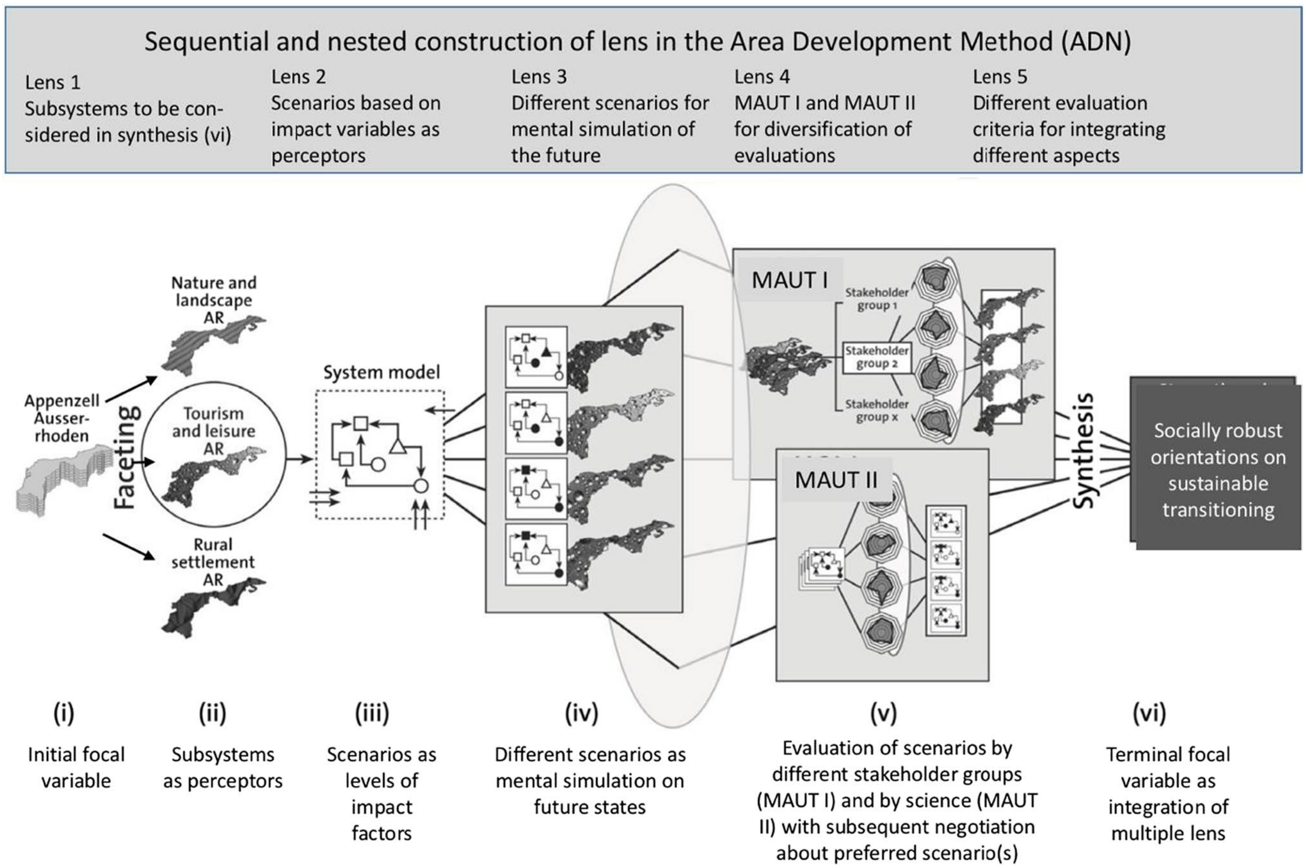

Fig. 2 Sequential and nested lenses as the basic structure of sustainability planning according to the Area Development Method (Scholz and Tietje 2002) for the exemplary case of developing robust orientations of a small Swiss Canton Appenzell AR. MAUT is an acronym for multi-attribute utility theory approach

of negotiation, as suggested by Susskind (2018). We consider this application as a typical *metaphorical description* of planning groups' operations. We used this way of thinking about the TPF for *describing activities of planning teams* including the *Area Development Method* or the *Biophysical Potential Analysis* method (see Scholz and Tietje 2002).

There is one more issue touched upon by Mumpower in his comment about Cognitive Continuum Theory that may be of interest for future research about the application of TPF in groups. Brunswik and Hammond developed the Cognitive Continuum Theory (Brunswik 1952; Hammond 1981), which suggests that thinking refers to a range of processes between intuition and analysis. Brunswik also used the term *ratiomorphic* to describe processes between intuition and analysis that appear rational, reasonable, and beneficial but (at least partly) "inaccessible to consciousness, especially the computational processes involved in perception" (Colman 2017). An interesting question would be how such a continuum might be identified in sustainability planning groups' work and, relatedly, what type of thinking is at work or most beneficial at which stage of the work.

2.2 Hoffrage: mental simulation and differentiating between stages of planning

Hoffrage's comment (2017) deepens the application of the TPF to sustainability planning groups. He presents (i) a more differentiated lens model of planning activity, and he (ii) suggests a statistical design for evaluating the hypothesized prescriptive value of following the principles of the TPF.

The differentiation of the planning process is based on a "decoupling of representation and action" (Hoffrage; Fig. 1). He adapts this model when distinguishing between phases of representation ("Model construction lens"), a

"Planning lens" in which an "ought state" is chosen, and an action phase (Implementation lens). This suggestion aligns closely with the middle section of the five steps of planning (see "Box 1: Five steps of sustainable transitioning" of the *Managing Complexity* paper). But Fig. 2 in this response also aligns with this suggestion; steps (ii)–(iv) of this "Model construction lens" and (v) and (vi) are nothing more than a differentiated construction of the "ought state." The (physical-, action-, muscle-based) implementation is not part of a transdisciplinary process. These processes follow the philosophy that the planners' or stakeholders' participtaion in the planning process as documented in Fig. 2 is, itself, part of the implementation, as all key stakeholders, together, build a joint vision of the "ought state."

From a planning perspective, two issues might be of interest in relation to the TPF. One has been touched upon by Hoffrage and refers to the role of *visions*. The other is somewhat related to this and is the "backward planning principle" (Scholz et al. 2006). In the course of many transdisciplinary planning processes, we could see that the visions of the stakeholders (as well as those of the planners) have a strong impact on what system is chosen ((i) in Fig. 2); what information is sampled (ii), e.g., what subsystems are chosen as perceptors); what impact factors are defined for scenario construction (iv); and what scenarios (iv), evaluation criteria (v), and even stakeholder groups (v) are chosen. We may consider the *terminal focal variable* (vi) as a key *governing factor*. This may be well included in P1-*func,* a functionalist perspective. But if we apply computer-based or "mental simulation," for instance, along the steps presented in Fig. 2, the choice of the evaluation criteria in MAUT depends (iv) on the type of orientation we want to generate (v). And if we want to find the "ought state" by evaluation, i.e., the most preferred future state (v), we must know what information/cues the scenarios must include (iv). This is the challenge of "backward planning" (given that there is a forward operating of the planning group's factual construction of a scenario). From a TPF perspective, this might mean that we have nested processes in what Hoffrage referred to as the *Planning phase*. Visions may be considered as drivers and the construction of planning variants as the planners' "cognitive craftsmen" work. This has been developed in one of the transdisciplinary studies where the eliciting of (ratiomorphic) visions preceded the construction of scenarios and followed by multi-criteria assessment, and an iterated perspective was taken (Trutnevyte et al. 2012a, b).

Finally, we agree completely with Hoffrage's suggestion that "it may not be too hard to start" for "several groups of master students, who function as planning teams…" an experimental study to validate the effects of following the TPF principles from a prescriptive perspective. Let us assume that we include an experimental group of planning teams participating in a planning course; half the group undergoes training on the TPF principles. The other half works on the same sustainability planning task. Then, we let sustainability experts judge the planning documents and variants and TPF experts evaluate the presence of the TPF principles in the planning variants. This certainly allows for a straightforward validation of the *prescriptive* notion and function of the TPF for sustainability planning.

2.3 Real-world planning and the challenge of assessing the added value of the TPF principles (Susskind)

Larry Susskind rephrases the key question of the *Managing Complexity* paper in the following way:

> Are the participants in these [planning] groups able to reach a stable conception or a shared understanding of what sustainable transitioning in their context might require by applying something like the seven key steps in the TPF steps?

This adequately refers to the *prescriptive* notion, i.e., the question of whether sustainability planning groups are more effective when they apply the TPF (see above). This is embedded in the five steps of planning (see Box 1 of the *Managing Complexity* paper, ranging from "problem definition and goal formation" to "socially robust orientations").

Susskind critically comments:

(a) "the planning groups in the practice of transdisciplinary processes [that] emerged at ETH were made up mostly of students and scientists who were trained to use the framework."

He stresses that:

(b) in "real life… decisions… are politically fraught," that groups "spend a great deal of time… to ensure that all relevant stakeholder groups have a chance to participate,"

and that:

(c) "the participants… always see themselves as political representatives fighting for their interests."

Let us take a closer look at these three statements related to utilizing the TPF in practice.

(a) The TPF-based training referred mostly (but not exclusively) to the students and science staff of transdisciplinary processes on the sustainable transitioning of urban and regional systems, industrial branches, and policy processes (e.g., on the question of what policy process is accepted by the Swiss public for nuclear waste management); all these studies are listed in the Supplementary Information of Scholz and Steiner (2015b). But this was not an academic sandbox exercise (see below). The students were involved in the multi-stakeholder discourse, but this took place—according to the rules of transdisciplinarity—in a protected discourse area. The results were publicly communicated after the planning variants had been designed. This was always done in close collaboration with the planners of the communities, public enterprises, industrial associations, etc.

(b) All studies were run using societally relevant, contested, complex, ill-defined, real-world problems. Many of the 21 transdisciplinary projects were co-led by a scientist and a key stakeholder (e.g., a lord mayor or leader of the industrial branch). In addition, all *steering boards* responsible for the strategic planning and co-construction of "socially robust orientations" included practitioners; in some cases, the practitioners were the majority. Figure 2 presents a typical design for sustainable transitioning planning in terms of the Brunswikian lens model (see also Scholz and Tietje 2002, p. 198, p. 266, p. 268). This study design has been used in more than 10 studies. The planning of these steps was always a result of the co-production between scientists and practitioners (e.g., in Fig. 2, agreement on what the goal of the study is (vi), which system and subsystem are selected (iv), etc.).

(c) Susskind is correct in noting that most of the operative construction of scenarios was done by student teams. However, we mentioned that the definition of the terminal focal variables (i.e., of the goals) was developed jointly by practitioners and scientists. Factually, whether the activities are planning group-driven (i.e., primarily based on methods and data) or stakeholder-driven (i.e., based on values and interests) has been conceived as a dynamic process along the course of planning (Stauffacher et al. 2008). The inclusion of all relevant stakeholder groups is most important, both for the representation of a planning case and for the construction of future scenarios, their evaluation, and subsequent processes. Fighting for particular interests is a common habit of stakeholders. However, a basic prerequisite of transdisciplinary processes is that such conflicts take place in a ("Habermas-like") protected discourse arena. Susskind himself is part of the Harvard Negotiation Program and highly experienced in the theory and practice of negotiation; he has contributed (Susskind and Ali 2014; Susskind and Cruikshank 1987) to an essential aspect of the basic negotiation rule "from position to interest" (Fisher and Ury 1981; Ury 1993) which is supported by a protected discourse arena, in general. The difference between mediation—to which Susskind refers—and transdisciplinary processes is that the former is designed for ongoing open conflict. The latter, i.e., transdisciplinary processes, create processes of mutual learning in which stakeholder roles are acknowledged, yet any deviation from the position is in danger of being penalized.

Another concern of Susskind's is whether the "TPF principle[s] [are] a useful prescriptive framework. Unfortunately, it's not possible to know." Here, this author completely disagrees. We have shown in the response to Mumpower (see 2.1) and in the *Managing Complexity* paper that we have the means to use the TPF principles as a framework of describing and promoting the way cognitive processes are performed in planning processes. As sustainable development itself is a long-term issue, there is no doubt that science must develop methods that go beyond the present program evaluation standards (Newcomer et al. 2015). Moreover, whether the TPF principles are useful can be, in principle, tested by a classical experiment. Let's think about an in-service training program for professional planners. Let us assume that half the group would receive TPF training and the other half would not, and then, let's give them a group-planning task. Let's ask a (carefully selected) group of sustainability planning experts to analyze the records and the products. If the (synthesized) rating showed that those who were trained in the TPF did significantly better, wouldn't this be a gentle verification of its prescriptive usefulness? Unfortunately, we do not yet know, but it would be possible to find out.

2.4 Mieg: TPF—no more than a metaphor?

Mieg concludes, "The FSA–Brunswik model cannot be considered a model for successful sustainability planning, neither in general nor for (transdisciplinary) planning groups." This is undoubtedly correct, but this was not the message of the paper. We did not aim to make the TPF a planning tool. The steps and process of planning were, rather, presented in Box 1 of the *Managing Complexity* paper as "Five steps of sustainable transitioning" and are widely independent of the TPF principles. We were instead dealing with the challenge of *describing the cognitive processes of planning groups* when working through these five steps of the course of planning under the goal of sustainable transitioning. When considering groups that have a mind (see P2-*dual*), we argue that the TPF "principles can be used as a descriptive tool" for the "operation of sustainability planning groups." When referring to the vicarious mediation principle, P4-*vicar*, this would mean that functioning, as experienced by (normal) planning groups, follows a redundancy-based cue sampling rather than a mathematical, efficient orthogonal (disjunctive) sampling of information.

A second argument by Mieg refers to the above-discussed restriction to cognitive operations of planning groups. This was expressed in the above, "We must take into account the full picture …" statement which we addressed in Sect. 1.1 above,

Mieg's message is that Brunswik provided a "metaphor for taking into account coupled human–environment systems" (Mieg 2018). He argues that metaphors must "not be true: they should be fruitful and inspire thinking." I assume that this statement has been made primarily in relation to the lens model, which has been used by this author for more than 25 years (actually) in a metaphorical way to present and to illustrate various methods and processes. However, this was done *not only* for representing the "coupled human–environment system," which refers to just one of the seven TPF principles (P2-*dual*). In the literature, the concept of *metaphor* is mostly related to analogy as "a kind of mapping or isomorphism and relationship between two systems" (Way 1991, p. 9). The key purpose of metaphors, from a cognitive perspective, is *structure mapping* (Gentner 1983; Matlen et al. 2014). Scientific analogies are metaphors (Gentner and Jeziorski 1993). Factually, when this author used the lens model in a metaphorical way, the idea was to illustrate the structure that perception judgment and other cognitive processes is a process starting with a decomposition of a system representation by cues (or aspects of evaluation) followed by an integration of cues for presentation or judgment. This has been done in (the multistage) Fig. 2 (in various stages). The two MAUT boxes present the process of stakeholders and scientists in this three-step logic. The starting point at this stage is a planner's internal cognitive representation (and not the environment, as suggested by Mieg). The endpoint (terminal focal variable) is a valuation.

Mieg presents the distinction of "scientific constructions: representations, models, and metaphors" in a somewhat uncommon way. It is clear that the models "are abstract." But the use of representation as "more or less detailed descriptions" is rather unusual. There is literature that addresses "theoretical models as representation" (Stefanov 2012) and metaphors as abstract and serving as representations (Efron et al. 2001). We agree that the lens model is a metaphor and a didactic tool. However, we claim that the TPF principles are more than that. They may serve as foundations for *descriptive* models and as *prescriptive* means of describing and improving (this is the kernel of the prescriptive notion) the cognitive processes of planning groups, also in the context of sustainability planning. We also suggest that the TPF is or may be of an *ontological nature*, in the sense that the TPF principles describe the properties of the nature and functioning of the organism's cognitive mechanisms when interacting with a (complex) environment. This has been seen in analogy to Darwin's principle of heritage, mutation, and selection, which describe the order of evolution. Factually, philosophers speak about *functionalist ontology* (P1-*func*; see Shapiro 1997). Both types of dualism present fundamental assumptions regarding organismic systems and their environments. Postulating that some processes in nature are genuinely probabilistic and that there is a fundamental uncertainty in the acquisition of any cues is a fundamental assumption about human–environment interaction. And evolutionary stabilization in relation to functionalism (P1-*func*) is related to the conception or ontological realism and is, given this perspective, an important aspect of sustainability. Thus, we do not agree[5] that the principles do "not allow the unambiguous definition of core entities" (Mieg 2018). We think that it is the other way around, which—following Mieg's argument—may qualify the TPF as ontological.

2.5 Yarime: open data as a prerequisite for evolutionarily stable societal development

Before reflecting on the relationship of biology and evolution to economics and business science, Yarime provides an amazingly accurate and dense description of those issues of the *Managing Complexity* paper that are relevant for his *sustainability science perspective*. His paper focuses on economic and societal change. He reflects on how physics and biology, as lead sciences, affected economic and planning theories and points out that evolutionary theory significantly affected economic modeling (Nelson and Winter 1982) and TPF. But we want to note that the relationship between biology and economics is a two-way interaction. For instance, the core idea of *panarchy*, one of the most frequently cited biological theories (Gunderson and Holling 2002), has been inspired by, if not based on, Schumpeter's conception of destructive construction (Schumpeter 1950), and many economic theories have been strongly affected by the ideas of evolutionary theory.

Yarime considers the TPF "as a prescriptive tool for how a planning group for sustainability transitions can successfully cope with the significant level of uncertainty and

[5] This author also disagrees with other statements, such as "The oil crisis of the 1970 s put an end to the decision theory-based general planning approach." The "foundations of decision analysis" were laid in the late 1960s and included models of the "intuitive decision maker" (Howard 1968, p. 211) when facing the uncertainty of a myriad of variables (Howard 1968; Raiffa 1968; Savage 1972). This is closely aligned with the TPF and is still a major subject of decision science. Here, we think that Mieg is mixing *decision research* and (linear model-based) *operations research*. Factually, as he described, the fall of formal, computation-based prediction (Mintzberg 1994a, b) to a non-Euclidean, partly post-positivist conception of planning was related to the breach of (linear programming-based) operational research that claimed to provide quantitative long-term predictions.

complexity involved in the environment." He stresses that economic actors such as sustainability planning groups are facing much faster changes in the social environment than species are facing in their natural environments (if natural disasters are excluded). Against this backdrop, Yarime stresses two issues; one is the *learning of the planning groups*, and the other is *open data* for all domains of society to maintain resilience. If we refer these claims to the TPF, we may state that the latter, i.e., access to unfiltered and unbiased data, is what is factually included in "ecological validity." The principles of "vicarious mediation" (P4-*vicar*) of uncertain (probabilistic) data acquisition (P3-*prob*), in a system of highly interacting drives and interdependent cues (P7-*interlink*), are linked to today's sampling of data. Here—in line with Brunswik's focus on ecological validity—he stresses that open data are a prerequisite for an adequate representation of the environment (for societal relevant stakeholder and sustainability planning groups) and thus a prerequisite for sustainable development.

2.6 Steiner: TPF, innovation, and sustainability planning

Steiner (2018) defines innovation in line with the TPF principle P1-*func* as "an aim-oriented endeavor with specific outcomes in relation to particular purposes or interests." Sustainable transitioning is seen as a special form of innovation, and innovation is conceived as a mental simulation (pre-view) of future events. Thus, he concludes that innovations are of interest from a dualist, functionalist conception of human–environment systems, P2-*dual*. Therefore, innovations are of interest for many activities ranging from successful business planning to sustainability planning. Based on this view, somewhat uncommonly, innovation is seen as an *object*. With respect to Brunswik's TPF, it may reverse the time order. Something in the future is seen as an "initial terminal variable" (Brunswik 1952) that is approached by the organism (such as innovators and planning groups) by mental simulation. The genesis of innovation is based on mental deliberation, coincidence, or by the environment itself.

The focus of Steiner's paper is the "mental simulation of an innovation." Here, obviously a pre-view and a post-view (see Fig. 1 in the paper of Steiner) are taken. The *organism* is both the forward-thinking driver of the innovation and the recipient that cognizes innovation processes, innovations, or innovation systems. Basically, this is an interpretation of the inextricable coupling of organisms and environmental systems and has been described as proactive and reactive adaptation toward innovation. The innovation is seen as something that changes the environmental system and is, simultaneously, a cause of subsequent change. Let us illustrate this by an example. For doing this, we refer to a distinction which we apply for concepts such as technology (or similar constructs such as innovation). A technology can be conceived as a (physical) *outcome* (e.g., a specific vehicle), the whole *process of producing* a certain technology, or the *knowledge* for constructing or establishing a technological process. Thus, digital technologies that have developed in the course of history can be seen as the machines (i.e., the computers) that are storing, retrieving, (smartly) processing, and transferring digital information in real time (i.e., the outcome or effect of innovation) and can be conceived as entities of the environment. But, simultaneously, they induce social innovation and mental processes (i.e., the idea of future innovation) on how to modify the given machines.

Innovations include a component of intentional (creative) destruction. This is not (intentionally) involved in any invention or planning and this may make the difference between an *innovation group* and a *sustainability planning group*. In Steiner's view, the resilience of future (social) systems is a property of the thoughts of *sustainability planning groups.* This can be attained by collaborative processes, collaborative planning (Healey 1998), or strategic sustainability management and planning in transdisciplinary processes. The comment by Dedeurwaerdere elaborates this; he suggests by what cognitive means (i.e., heuristics), sustainability planning groups can become "able to reflect on inherent vulnerabilities and opportunities that might be related to organisms, the environment, or their interrelatedness" (2018). Innovation may also be seen in relation to visions, scenarios of formative planning, and the implementation of scenarios. When we investigated planning groups in transdisciplinary processes, we gained several insights into how innovations emerge (Trutnevyte et al. 2012a, b; Trutnevyte et al. 2012b). We were able to show that local community members and planners begin with visions of how a community energy supply might look. When planning processes operationalize these visions by means of formative scenario analysis and a multi-criteria evaluation reveals that the visions cannot easily be made real, they revise and adapt their visions. Please note that this study refers only to what has been described in Sects. 4.2.2 and 4.2.3 of the *Managing Complexity* paper.

2.7 Wilson: potential and limits of the TPF with respect to sustainable transitioning

Wilson (2018) reflects on the contribution of the TPF to key questions of sustainable transitioning. She acknowledges, "TPF may be a foundational framework that can help to bring together… multiple perspectives and theories." This author agrees completely; however, we also have to reflect critically on what issues are not adequately included or integrated in the TPF that could be important for sustainable development. Wilson presents three interesting examples. These include

(a) the organism's (evolutionarily) limited sensitivity to respond adequately to gradual changes, given a developed alertness to respond to abrupt pulse events;
(b) the focus of humans on intended action and their ignorance with respect to unintended side effects (the so-called unseens; Sugiyama et al. 2017); and
(c) the individual's coping with biased (seemingly probabilistically appearing but often) politically distorted information. Here, she offers a useful example of how one and the same information may have different messages, depending on the opinion of the receiver.

Let us briefly reflect on these three examples. As (a) it has also been mentioned by Mieg (2018; when referring to the presented example of scenario construction) that the TPF does not incorporate *time* well, beyond the "functional arc" in Fig. 2 of the *Managing Complexity* paper, this may be considered discontinuous learning. The comment of Steiner (2018) may have shed some light on how the time concept might be coped with. Naturally, if changes are below the perceptual or cognitive detection threshold, causal relations to effects (such as soil sealing as a cause of flooding) are not noticed. Evolutionary stabilization (P6-*evostab*) thus calls for new, artificial means such as computerized simulation as a kind of perceptual aid. This also holds true for (b): identifying unintended side effects; the link between ratiomorphic perception and conscious, overt thinking has to be viewed from a proper model, presumably when linking cognitive and motivational processes (see below).

We also think that, with respect to (c), the TPF may not really help, as the *social nature* of environmental information and cues has not been broadly considered. Brunswik was considering *social judgments* also as judgments *on* personality. He acknowledged a social environment in particular with respect to the representativeness postulated in his paper *Organismic achievement and environmental probability*. However, he states, "social perceptual problems have been rooted in the applied disciplines" (Brunswik 1943, p. 264) and not in psychology, which works or should work as "'exact' experimental laboratory psychology" (Brunswik 1943, p. 264). We may note here that Brunswik's TPF also widely excludes differentiated views on "motivation, a topic even more complex and subtle than that of… intellectual abilities" (Brunswik 1946) or personality traits. Most interestingly, Brunswik must have had insight into this statement, as his wife, Else Frenkel-Brunswik (1908–1958) had provided fundamental contributions to *Motivation and behavior* (Frenkel-Brunswik 1942), a monograph, and in her article *Intolerance of ambiguity as an emotional and perceptual personality variable* she relates perception with motivational issues (Frenkel-Brunswik 1949).

2.8 Dedeurwaerdere: the TPF for formative transdisciplinary processes

Dedeurwaerdere opens a couple of new doors for utilizing the TPF. As a theorist and practitioner of transdisciplinary processes (Popa et al. 2015), he provides a strong argument that the TPF is more than an "ecological approach to perception and social judgment." He considers the TPF as a framework "for taking the agenda of transdisciplinary sustainability research forward." Here he emphasizes two issues: *first*, a proper acknowledgment of the uncertainties in the range of natural science laws and natural and social probabilities and ambiguities, and *second*, he elaborates in a most fundamental, innovative way the potential of the TPF to better conceptualize processes of adaptation in a forward-looking, constructivist, reflective way. To achieve the latter, he refers to the groundbreaking idea to *utilize heuristics on how sustainable systems function as perceptors*. Thus, mental constructs on how biodiversity may develop, whether a specific composition of human and environment systems may be judged as resilient, or whether intergenerational justice is established in a socially sustainable manner are considered. But this is only one of three challenging issues this author finds in the comment. Conceptualizing "heuristics of what makes sustainability" as cues (which humankind may have to construct, learn, and embody) is, factually, something new for sustainability planning that might be developed.

A second challenging issue refers to how the TPF might contribute to transdisciplinarity and to other forms of theory–practice collaboration. The uncertainty and incompleteness of environmental data (P3-*prob*) call for vicarious mediation (P4-*vicar*) between experiential wisdom (the ultimate perfection of practitioners' knowledge) and academic, methodologically based scientific rigor (in this author's view, this idea is related to, but not identical to, the Brunswik-Hammond cognitive continuum hypothesis of analytic and intuitive thought). Dedeurwaerdere emphasizes formative learning. *Formative learning* means—in the context of transdisciplinary sustainability planning processes—that (scientists as sustainability) planners and practitioners (among them representatives of key stakeholder groups) construct planning variants that inform practitioners (here, the key decision makers) in order to help them make more sustainable decisions (see Scholz 2011, p. 358). Naturally, this is genuinely transdisciplinary and refers to what has been called co-representation, co-design, or co-construction of knowledge "between scientists and societal actors" (Dedeurwaerdere 2018). This author fundamentally agrees on the visionary view on utilizing the TPF for structuring the (decision theoretic layer of) sustainable transitioning.

Dedeurwaerdere also deals with niche regime interaction and constraints when systems (or system lock-in) call for "radical transformative innovation." This issue plays a significant role in sustainable transition management (Frantzeskaki and Loorbach 2010; Loorbach 2014; Popa et al. 2015; Rotmans and Loorbach 2009; Scholz 2017b). Here he talks about (advocacy-driven) "innovation niches" in which certain social "change agents often have firsthand knowledge … about transformation possibilities." He also mentions that such processes often forget about the formative learning process, particularly if the institutional diagnostics (of the regime) and the "institutional transformation dimension" are in the foreground. Thus, transdisciplinary processes appear to be superior when: the full range of agents (which function as perceptors in this place) is superior; socially robust solutions (built on societal learning and adaptation) are targeted, and lock-ins overcome. In this way, co-constructed research processes are organized.

3 Summary and discussion

The discussion briefly summarizes what has been acknowledged (3.1) and what are seen as shortcomings of the TPF and of the *Managing Complexity* paper (3.2). The conclusions (4) provide an appraisal of TPF in the light of decision, environmental, and sustainability science.

3.1 Strengths of the TPF: a powerful tool for describing perception, judgment, decisions, sustainability planning, and adaptive processes in coupled human–environment systems

3.1.1 The epistemological status and the challenge of validation of TPF

There has been some consitencies and some inconsistency with respect to the epistemological status of the TPF. All reviewers considered the TPF to be a powerful tool for describing perception, judgment, decisions, sustainability planning, and adaptive processes in coupled human/organism processes. The majority of them could see the potential of the TPF as a prescriptive tool for improving basic structures for managing complexity in the organism's interaction with the environment.

The reviewers did not really address two issues that have been discussed in the *Managing Complexity* paper. One is whether the TPF is a general theory for organisms (see 1.4) or whether it is (just) a framework for human perception, decisions, and planning. The second (which is partly touched by Mieg 2018), is related to the question whether the TPF is a normative-nomothethic theory of coupled organism–environment systems. With respect to the *first* issue, we referred to the example of the decisions of migratory birds, with the example of the stork, presumably the most liked and investigated bird breeding in Northern Europe. We argue that, with respect to complexity, uncertainty, and significance, the migration decisions of storks closely resemble individual human decisions on sustainable action. Dependent on environmental and internal factors, adult storks decide whether and when they will migrate, whether their route will be eastward or westward, whether they will return to the north or stay in the south, where and when they will roost and finally nest, etc. Given the new insights gained by GPS monitoring, their behaviors are much less genetically primed than laypersons may think. It is clear for ornithologists that storks make group decisions, but according to GPS data monitoring, whether or not to join a group is a somewhat variable decision (Berthold et al. 2002; Kaatz et al. 2017), and the decisions made are essential for their survival, ontogenetically and phylogenetically.

With respect to the *second* issue, it is evident that the normative-nomothethic value may not be proven. However, we think that, beyond the idea of the *gentle validation* of a single TPF principle, we may think about a process in which pieces of evidence are related that substantiate or refute, e.g., a certain pivotal statement of a theory (such as the representativeness principle). We might also ask how big theories can become validated. As examples, we could consider Charles Darwin's theory of evolution and origin of species (Darwin 1859), Jean Piaget's theory of cognitive and intellectual development (Inhelder and Piaget 1958; Piaget 1977), Herbert Simon's conception of bounded rationality (Simon 1972, 1982), or John R. Anderson's theory of adaptive control of thought (ACT) (Anderson 1983, 1993). We argue that these theories are validated in a kind of narrative, inquiry-guided discourse among scientists from different disciplines who refer to (empirical) evidence and different modes of validation from their disciplines (Mishler 1990). Thus, the acceptance of a scientific statement is socially constructed (Ruse 1975, 1999; Scholz 1998). The present *Managing Complexity* paper on Brunswik's TPF, ten extensive reviews and subsequent eight comments, and this response may be seen as an important part of this science narrative, which leads us from data to stories that provide more *general gentle validation*.

If we look at key arguments in this general form of gentle, narrative-based validation, arguments of the following type are essential: There is evidence that many or even all of the principles of the TPF are helpful for describing properties of basic processes of organismic cognitive/mental interaction with the environment. This includes cognitive activities of groups and presumably other supersystems.

3.1.2 From binary information to cues

The TPF, in particular the principle of vicarious mediation, indicates that organismic behavior is not bound to binary bits but rather to cues that comprise complex environmental patterns, i.e., sign-significates or signals whose processing is important from an ontological and (if we reflect on the role of sustainability planning) from a phylogenetic perspective. We doubt that bit-based information theory and propositional logic are sufficient to model this for organismic-biological systems. We might think about redundancy-, robustness-, and resilience-oriented processes and strategies (Scholz et al. 2012). The idea of adaptive heuristic as it has been discussed in evolutionary psychology (Holcomb 2001) or other concepts such as biologics (biological reasoning instead of chemical reactions) in which the complex physiological response to (non-natural) chemicals is modeled is meaningful. We also think that analog information (i.e., gradual changes that may be approximated by digital information but may be linked to different algorithms in perception) and reasoning (Gentner and Holyoak 1997) is essential for cue processing.

3.1.3 Breaking the ground for sustainable human–environment systems

The comments encourage further applications of the TPF to sustainability planning and—though a serious and spirited discussion is ongoing—even sustainability is seen as a meaningful terminal focal variable, for instance, for planning groups. The TPF is acknowledged as an overly valuable framework to represent, describe, and manage coupled human–environment systems, and one can read this between the lines of comments by Yarime, Steiner, Wilson, and Dedeurwaerdere. For instance, not only Brunswik's assumptions about ambiguous environmental data (P3-*prob*), the necessity of vicarious mediation (P4-*vicar*), the interaction of system variables (P7-*interlink*), and functionalist adaptation (P1-*func*) for evolutionary stabilization (P6-*evostab*) but also the limits and strengths provided by the representativeness principle (P5-*repr*, which may cause limits to [social] innovation) provide much insight into the foundations of socially robust solutions.

We can end this part of the discussion by pointing to what the present author considered to be the most groundbreaking idea in the comments, although, in this author's opinion, there are two groundbreaking ideas. Dedeurwaerdere suggests considering heuristics as perceptors, i.e., as cues (criteria) for the evaluation of sustainable planning variants. This aligns closely with the idea of the "sustainability potential assessment." Here, the idea was that system properties such as robustness and resilience, size and speed of change rates, and dependence of survival from other (unreliable) systems (Lang et al. 2007; Scholz and Tietje 2002, p. 310) are taken as perceptors. The second is Steiner's idea to consider innovations as objects formed by the human mind and, simultaneously, as drivers that affect human thinking, adaptation, and the search for innovation. This nicely illustrates that both components of the P2-*dual* principle, i.e., the body–mind and the human–environment systems, are inextricably interwoven.

3.2 Flaws, deficiencies, and perspectives of the TPF

From a theory of coupled organism–environment system perspective, we discuss two major deficiencies. One is the definition and understanding of cues; the other is the separation, if not exclusion of, motivational and emotional factors of organisms. Some other deficiencies have been identified in the comments, see, in particular the comment by Wilson (2.7).

3.2.1 What is a cue?

We have repeatedly pointed to the differences between a *cue* and (binary or digital) *information*. The interchangeably used terms *sign*, *sign-significates*, *signals* for cue indicate that *meaning* makes the difference between cues and information. However, a clear, comprehensive definition of cue is lacking. This is unfortunate, as this concept is central to the vicarious mediation principle, P4-*vicar.* The substitutability of one cue by others is mostly explained and operationalized by the concept of correlation, which refers to the relationship between, at least, ordinally scaled variables and is independent of meaning. This is done, for instance, in the lens equation model when it provides numerical values and weights for different criteria (cues). Thus, the "cues" in the lens equation model are of the same quality, but their input strengths can be continuously changed.

We can learn a little about what makes a cue from *How big is a chunk?,* Herbert Simon's (1974) paper. A key message of this paper has been that the "scale of meaningfulness [of chunks]… reduced learning time" (1974, p. 482). A chunk (e.g., set of words), which is a basic memory unit, may become bigger if it is familiar (e.g., represents a known phrasing). Based on this, we conceive a cue as a patterned cluster of information that provides meaningful evidence about something.

We have mentioned above that meaning of a cue has roots both in nature and nurture. Here, *familiarity* is an important feature. This is closely linked to representativeness, as—for instance, in the definition of the representativeness heuristic (Tversky and Kahneman 1974)—the similarity of an issue to something familiar (which presumably also correlates with cognitive salience) shapes the likelihood of its appearance.

Dedeurwaerdere (see above) has provided suggestions about cues as *systemic sustainability heuristics* in the evaluation of sustainable planning variants. We suggested an operationalization when referring to bio-ecological system analysis. We also think that the factors of perceived risk by

Slovic, Fischhoff, and Lichtenstein (Slovic et al. 1986) may be well conceived as cues. People focus on certain situational properties when exposed to threats, i.e., voluntariness, dread, control, knowledge, equity, and catastrophic potential. These cues constitute what has been conceived as risk. This author has worked in credit risk management for a number of years. An interesting issue in the practice of some German banks is that a company inspection by a credit officer is an essential part of risk assessment. Based on observing and talking to many credit officers, we may hypothesize that—similar to the psychometric approach on perceiving personal risk—a small set of cues are taken as indicators, such as tidiness, agility, signs of a worker's commitment, outmodedness. We suggest that future empirical research is needed to better understand what makes a cue for organisms in certain situations/tasks in the specific and in the generic.

3.2.2 In what way are motivation and emotion related to the TPF?

Brunswik's TPF did not include motivational factors such as need or drives and remained a purely perceptual cognitive framework. As Dhami and Olson (2008) noted, the exclusive focus on cognitive factors of Brunswik's approach was also maintained by those proponents of the TPF who long utilized and developed it, even in the domain of social psychology, such as conflict theory (Brehmer 1979; Hammond 1965). Brunswik was dedicated to environment-oriented objective probabilistic functionalism and to a "science of objective relations" (Brunswik 1937, 1943). Moreover, he was looking, rather, for a psychology of the "generalized mind" (even though, in some instances, the generalized human mind has become a generalized animal mind) (Brunswik 1943, p. 64) or, to express it in other terms, for "constant psychological function[s]" (Brunswik 1955, p. 194).

In just a few papers, Brunswik discussed how impacts of motivation and personality, i.e., internal factors, affect the "contribution of the organism." As a trained experimental psychologist, he appreciated Bruner and Goodman's (quasi-experimental) study to introduce rich vs. poor as independent variables and to show that poor children overestimate the physical size of coins more often than rich children do (Bruner and Goodman 1947, p. 33). Needs and values may affect perception (Dunning and Balcetis 2013), and Brunswik considered them as "emphasizers … in establishing figure ground organization." The differential roles of emotions (Herwig et al. 2007) and motivations in perception are now also traceable by physiological parameters (Radel and Clément-Guillotin 2012).

Some reviewers, particularly Mieg as well as Susskind, focused on the motivational factors of planning groups. The motivation side of groups includes emotional dynamics, group leadership, team memory (Liang et al. 1995; Tindale and Sheffey 2002), emotional resentment, empathy, (inter) gender effects due to interpersonal antipathy, (situational or general) animosity, disfavor, and lack of trust among group members, etc. In the search for generic principles, in the *Managing Complexity* paper we restricted the "mind of the group" in a somewhat idealized manner to "*group norms, values, preferences, decision rules…, group intentions, group knowledge*" (Scholz 2017a) and considered the before mentioned, often-idiosyncratic inner-planning group factors—in terms of Brunswik—as stray causes. But the motivation of the group members and of the group, and the impacts on group interaction and group performance, has not yet been well investigated and related to TPF yet.

4 General conclusions

The comments provided a broad scope of theoretical (Mumpower and Hoffrage) and methodological contributions (Mieg and Susskind), presented new ideas and perspectives for applying the TPF to business and innovation (Yarime and Steiner), or outlined how it can be used as a framework to organize, structure, and understand activities in sustainable transitioning (Wilson and Dedeurwaerdere). The contributions also bridge the psychology of perception, judgment, decision, planning, sustainable action, transitioning, and knowledge integration (e.g., with stakeholder groups as perceptors) in transdisciplinary processes. Together with the amazing consistency of the outline of the biological, neuropsychological, biophysical knowledge about processes of sensation and its overly consistent relation to Brunswik's cognitive, system theoretic approach to perception (see 3 in the *Managing Complexity* paper), the eight comments provide a remarkable apprisal of Bunswik's TPF.

We discussed and suggested how the challenge of validation of sustainability planning variants in the *Managing Complexity* paper can be mastered, and we illuminated two key shortcomings. These are the conceptualization of meaning in a generalized way in cognitive models (i.e., the definition of cues) and a better relating of motivational and emotional processes to cognition. But these may become the subjects, such as other challenges, to follow-up comments and research.

In general, we conclude that Brunswik's framework of the TPF is one of the significant psychological approaches to cognition, behavior, and the new field of coupled human/organism–environment interactions. The TPF is going to become a theoretical framework to structure, represent, describe, understand, model, and manage complex, inextricably coupled human–environment systems, an issue which is most relevant for many sciences, in particular sustainability science.

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