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# Metacognition and Reflection by Interdisciplinary Experts: Insights from Cognitive Science and Philosophy

by

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***Abstract:*** Interdisciplinary understanding requires integration of insights from different perspectives, yet it appears questionable whether disciplinary experts are well prepared for this. Indeed, psychological and cognitive scientific studies suggest that expertise can be disadvantageous because experts are often more biased than non-experts, for example, or fixed on certain approaches, and less flexible in novel situations or situations outside their domain of expertise. An explanation is that experts' conscious and unconscious cognition and behavior depend upon their learning and acquisition of a set of mental representations or knowledge structures. Compared to beginners in a field, experts have assembled a much larger set of representations that are also more complex, facilitating fast and adequate perception in responding to relevant situations. This article argues how metacognition should be employed in order to mitigate such disadvantages of expertise: By metacognitively monitoring and regulating their own cognitive processes and representations, experts can prepare themselves for interdisciplinary understanding. Interdisciplinary collaboration is further facilitated by team metacognition about the team, tasks, process, goals, and representations developed in the team. Drawing attention to the need for metacognition, the article explains how philosophical reflection on the assumptions involved in different disciplinary perspectives must also be considered in a process complementary to metacognition and not completely overlapping with it. (Disciplinary assumptions are here understood as determining and constraining how the complex mental representations of experts are chunked and structured.) The article concludes with a brief reflection on how the process of Reflective Equilibrium should be added to the processes of metacognition and philosophical reflection in order for experts involved in interdisciplinary collaboration to reach a justifiable and coherent form of interdisciplinary integration. An Appendix of "Prompts or Questions for Metacognition" that can elicit metacognitive knowledge, monitoring, or regulation in individuals or teams is included at the end of the article.

***Keywords:*** interdisciplinarity, metacognition, team cognition, representations, expertise, assumptions, pluralism, philosophy

## § 0. The Challenger Disaster: Failure of Interdisciplinary Team (Meta)Cognition

When in 1986 the space shuttle Challenger exploded mid-air during its launch at the NASA facilities, killing seven people, this bewildered a global audience. That same audience was again astonished when the Presidential Commission on the Space Shuttle Challenger Accident (the Rogers Commission for short), which included Nobel prize-winning physicist Richard Feynman, explained the direct and indirect causes of this disaster. Among the problems found relevant was an optimistic "can-do" mentality at NASA and the risks coming along with that. This became obvious in a discussion with NASA employees about the infamous O-ring that was the cause of the leaking fuel that caught fire and caused the explosion. The decision to launch while the temperature was low enough to compromise material properties like those of the O-ring was a matter of concern to some participants in that decision-making process. According to witness Dr. Petrone, "The prime thing we were concerned about was the unknown baseline. We had not launched in conditions of that nature, and we just felt we had an *unknown*" (Rogers Commission, 1986, p. 114, italics added).

In the case of a complex interdisciplinary project it is not at all unusual nor directly worrisome that an element of the problem at stake is unknown. Indeed, there is no fundamental limit on what we might learn about a particular object or process, not just in the case of its interdisciplinary investigation but even from a single disciplinary perspective. How much should NASA's material scientists have known about the material of this O-ring and its behaviors under various conditions? What is the temperature range that would have been relevant for them to investigate? What chemical interactions with other substances should have been investigated by their colleague chemists other than those in the earth's atmosphere or released by the engine? Given that there were many factors determining the behavior of the O-ring, the team had to deal with a corresponding theoretical pluralism, with each theory–physical, chemical, meteorological–accounting only for a limited part of the ring's behavioral variability. Therefore, it was crucial for the individual scientists involved in the project and for the team as a whole to reflect upon the potential relevance and irrelevance of their insights and of their unknowns and to be ready to adjust their earlier relevance estimations.

In this case, the unknown that would turn out to be of fatal importance was shared during a management discussion on the launch decision, yet it wasn't taken seriously enough either by the team as a whole or apparently by the material scientists themselves. As a result and in terms to be clarified below, it did not figure sufficiently in the team's mental representations nor in the team metacognition that could have helped their project's coordination and organization. Instead, further consideration of the unknown was overruled in favor of other considerations in order to meet the orbiting deadline. Obviously, each unknown announced by a sub-team should not necessarily bring a team project to a halt, yet each should require a careful evaluation of the nature and relevance of the unknown in light of the overall goals and structure of the project. It appears that with regard to this case, the management discussion (and the interdisciplinary team cognition exercised therein) failed blatantly, as the group underestimated the relevance of the O-ring and hence of the lack of disciplinary knowledge about its properties under low temperature conditions. The Rogers Commission was concerned about this failure and devoted considerable time to discussing and analyzing it. One would have expected that in a high tech, big science project like this, conducted by a very large interdisciplinary team of top tier scientists and engineers, the value of metacognitive consideration or "knowledge and cognition about cognitive phenomena" (Flavell, 1979, p. 906) would have been recognized. Unfortunately, it was not. And indeed, that is too often the case.

As I will argue further below, even accomplished scientists are often not accomplished "metacognizers." Consciously monitoring one's cognition and cognitive processes and regulating them, for example by correcting or adjusting one's learning strategy, is difficult for everyone because our cognitive processes usually don't require such conscious control (Georghiades, 2004). In addition, all our learning and knowing involve the development of many mental representations, whether they concern the skill we're practicing or the phenomenon we're investigating or a scientific domain we're familiarizing ourselves with. For effective metacognition we must not only be aware of such multiple mental representations but also be able to navigate their peculiarities and limitations.

Clearly, with effective individual cognition requiring such metacognitive handling of the multiple mental representations involved, effective interdisciplinary team cognition among individuals will require even more. In addition to monitoring and regulating their own mental representations, the members of such a team need to communicate and coordinate their cognitive efforts with those of their collaborators. For this they will need to develop a mental representation of the team project and its relevant components, in which their own position and contributions must be somehow included. Moreover, as testified by the dramatic events caused by the insufficient consideration of the unknown affecting the Challenger launch, what probably does not need to be spelled out for a disciplinary colleague may need to be spelled out for colleagues from other disciplines, implying an even greater need for metacognition in such an interdisciplinary context.

Yet, though team metacognition is required for the process of interdisciplinary collaboration, it alone is not sufficient for the integration of disciplinary contributions into a more comprehensive understanding of the problem at stake. For such integration of disciplinary insights in an interdisciplinary or transdisciplinary context, there are multiple methods that can help resolve the barriers between different disciplines. One set of methods focuses on the fundamental assumptions that are specific to each discipline, as will be discussed below. Philosophical reflection and discussion within a team of the epistemological, metaphysical, and normative assumptions implicitly held by representatives of different disciplines are helpful in addressing and overcoming their differences. Individual and team metacognition and such philosophical reflection can be considered to be complementary and mutually useful. Making implicit assumptions explicit and adequately navigating these as a team presuppose a sound metacognitive process.

From this brief description it is obvious that collaborations among people with differing disciplinary expertise is difficult, partly due to the cognitive and metacognitive processes involved. When the Rogers Commission addressed that difficulty in its recommendations, it pointed out the need for "improved communications" because of a "tendency of management isolation" (Rogers Commission, 1986, p. 200). However, it is implausible that improved communications alone would make up for a team's apparent lack of metacognitive skills, a repair that would require different solutions including a better understanding of how metacognition should play an essential role in an interdisciplinary team project.[1] Indeed, we might expect the contrary, since team members to a large extent rely upon their tacit or implicit cognition and are subject to an associated "bounded awareness" (Kumar & Chakrabarti, 2012). They will either not notice their own lack of knowledge or not recognize the importance of insights that other members bring to the table.

Avoiding the deficits in individual and team cognition and collaboration asks for a better understanding of several underlying processes and their connections. To that end, I will bring various insights from cognitive science and philosophy to bear on expertise, interdisciplinary understanding, and collaboration. The Challenger launch will figure as an example of interdisciplinary collaboration as some of the potential goals of such collaboration are implied in it, these

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[1] Drawing lessons from the Challenger disaster, Weir refers to our "failure to learn" at four different levels: political, academic, administrative/managerial, and philosophical (Weir, 2002). The latter amounts to a lack of "comprehension of our own history," which still does not come close to the metacognition that is involved in adequate forms of learning.

goals ranging from the production of new and comprehensive–theoretical–insights to practical problem solving and the development of robust policies or technologies (Klein, 1990; Menken & Keestra, 2016).

The article is divided in two main parts, section 1 being devoted to individual cognition and section 2 to interdisciplinary team cognition. In both contexts, I will consider how combined insights from cognitive science and philosophy can enhance the relevant processes involved. In § 1.1. I will present an account of expertise as being enabled by a process of Representational Redescription, yielding multiple mental representations that are increasingly structured and complex. This multiplicity of mental representations and their potential interferences can lead to undesirable results and § 1.2. describes how experts learn to monitor and regulate their cognition via metacognition and deliberate practice so as to avoid such results. Metacognition can also prepare an expert for interdisciplinarity, and § 1.3. considers how philosophical reflection upon disciplinary assumptions is complementary to metacognition. During team interdisciplinary collaboration, individual members are developing team mental representations,  a process that I will discuss in § 2.1. Successful team cognition is often supported by implicit team coordination, yet I argue in § 2.2. that team metacognition is also needed, for example if an unknown needs proper response. Finally, in § 2.3. I will again consider how metacognition and philosophy serve a joint purpose, it now being interdisciplinary team cognition. Having argued that metacognition and philosophical reflection prepare an interdisciplinary team for the development of a more comprehensive understanding, in the Concluding Remarks I will briefly consider the process of Reflective Equilibrium that can help teams to navigate the theoretical and methodological pluralism characteristic of collaborative interdisciplinary or transdisciplinary research.

Examples of "Prompts or Questions for Metacognition: can be found in the Appendix to this article.

## § 1. Individual Cognition and the Challenge of Navigating Pluralism

As mentioned in the introduction, even a simple object like a rubber O-ring can be investigated by different disciplines that might offer distinct insights or representations of it. For instance, a representation of its physical components and properties might look different from a representation of its chemical or mechanical components and properties. Each of these representations implies an explanation of a limited set of its characteristics and behavior under a specific range of circumstances, and the representations do not necessarily overlap. This might be easier to understand if we consider the case of a complex psychiatric disorder, the understanding of which depends upon a complicated bio-psycho-social model, with many additional historical and environmental factors playing additional roles. We can observe in almost every such academic domain a methodological and theoretical pluralism since the investigation of almost every object or phenomenon requires the application of different methods, yielding different theoretical accounts (Mitchell, 2002). It is important for all scholars–including in that term scientists and other academic experts–to realize that each theoretical account, focusing on one or more determining factors involved, has usually only a *limited relevance.* We can represent one and the same object or phenomenon and its determining factors in many different ways and each representation has some relevance while none has sole relevance in light of our present cognitive aims and goals (Wimsatt, 2007). Scholars should be aware of this, and also be aware that they need to learn to metacognitively monitor and regulate their own representations and navigate the corresponding pluralism both when working individually and when working as a member of a team in order to avoid some of the pitfalls associated. This first section will focus on issues involving individual cognition.

## § 1.1 Expertise and the Development of Multiple Mental Representations

It seems surprising that not all scholars are well aware of these pluralisms and the limitations accompanying each representation of an object. After all, we can observe something similar in our daily lives and those of our children and students. Indeed, in every instance of gaining expertise such as acquiring a skill or familiarizing oneself with a particular knowledge domain, we are as part of that process developing more than a single cognitive, or mental, representation. Indeed, a process of Representational Redescription is involved, elaborating upon a previously established representation as I will explain below.

As communicating beings, we are constantly using representations: gestures, words, and sentences that somehow contain information beyond the surface properties of the movements, sounds, and letters we share with each other. Since these representations "stand in" for the content or information they convey, they are in need of further cognitive processing or interpretation. Take for example, the representation of a simple arithmetic task: adding one and one. We can do that by using two fingers, by writing it in Roman or Arabic numerals or in digital bits, or by speaking. Irrespective of overlapping contents, each form of representation requires separate mastery, involves different frameworks of interpretation, has its own practical advantages and disadvantages, and brings along many distinct associations.[2] As a result, we might learn to select among representational formats, for example, to combine them–as in illustrating words with our fingers–or to adjust them, depending upon the circumstances and our aims. Such flexible use of representations is made possible by the "standing-in" position of representations that also entails that they are always associated with processes of interpretation and understanding (Von Eckardt, 1999). Learning to communicate implies therefore both becoming aware of these possibilities and taking advantage of them, while becoming equally aware of how others make such choices so as to be aware of the potential confusion and mistakes that may result as they do.

In the context of the study of cognitive states and processes, scholars have introduced the notion of "mental representations."[3] These are continuously and automatically formed by our brains and play a role in how cognitive states and processes handle various sorts of information–like about the task at hand, about relevant environmental cues, about motivations to continue or stop–during all our behavioral, communicative, and other actions.[4] Explaining these actions, scholars assume that these cognitive states and processes "are constituted by the occurrence, transformation and storage (in the mind/brain) of

[2] For this article I had to refrain from going into the corresponding philosophical discussion ongoing since Plato and Aristotle about the intimate interdependence (or dialectics) between epistemology and ontology, or between the representations of reality and how the world presents, appears, or discloses itself. This notion is particularly prominent in hermeneutic philosophy since Heidegger's *Being and Time*, and Gadamer's *Truth and Method*, forming a cornerstone of Dieleman's contribution on transdisciplinary hermeneutics in this Special Section of *Issues in Interdisciplinary Studies* (Dieleman, 2017).

[3] Other words have been introduced for referring to stored units of information, memorized and employed for multiple functions, each with specific characteristics, like "knowledge structures" (Grafman, Sirigu, Spector, & Hendler, 1993), "mental models" (Johnson-Laird, 2005), "schemas" (Norman & Shallice, 2000), and "scripts" (Cooper & Shallice, 2000).

[4] The concept of "mental representations" is not undisputed in cognitive neuroscience. Thagard notes that notwithstanding lack of agreement about their nature, mental representations figure at the center of cognitive neuroscience's interdisciplinary discourse (Thagard, 2005). Yet some authors even argue that such representations are unnecessary when describing brain and cognitive processes in dynamical systems theoretical terms (Keijzer, 2002; Van Gelder, 1995). However, such critiques fail to recognize that such terms can perhaps help in describing the behavior of cognitive systems,. We have to allow a complementary explanatory role to representations (Bechtel, 1998). Mental representations are particularly relevant for explaining forms of learning, knowledge transfer between domains, and correction of cognition and behavior (Clark & Karmiloff-Smith, 1993). They are also necessary for explaining "representation-hungry" cognitive tasks such as tasks that involve absent, non-existent, or highly abstract contents, or tasks that require selective attention (Clark & Toribio, 1994).

information-bearing structures (representations) of one kind or another" (Pitt, 2017). Interestingly, studies have shown how related yet different tasks can facilitate or rather interfere with each other because they activate some of the same mental representations. Different cognitive processes are not employing completely separate, dedicated representations, as it appears. Instead, whether it is for speech, for perception, for imagination, or for behavior, multiple cognitive processes are making use of partially "shared representations" (Grezes & Decety, 2001). Such–largely–overlapping mental representations help to explain why thinking about "kicking a ball" can facilitate our visual detection of a ball or why our body's moving in one direction does hamper the grasp of a sentence that describes the opposite direction. So although the production of a sentence about e.g. kicking a ball will involve representational elements that are specific for its linguistic or its behavioral features, there are also representational elements that are shared with our imagining of such an action that are employed in both cases (Barsalou, 2003).[5]

Studying particular forms of expertise more closely, psychologists and cognitive scientists can partly explain expert performance via the mental representations an individual has developed, their number, their structures, their interactions, and other properties. Investigating them can be difficult as such representations and their properties can often be only indirectly deduced from observations, since even experts are not always able to consciously articulate the relevant details of their cognitive states and processes–let alone animals and children who are acquiring skills.[6] Numerous studies have been able to demonstrate that experts have typically developed more, and more complex–often hierarchically structured, multi-level–mental representations than beginners. A consequence of this is, that even though an expert's specific action might be identical to a beginner's, his or her underlying mental representations might turn out to be quite different.[7] Such differences might then have notable consequences in some situations.

[5] Investigating the structure and contents of such representations and how they enable and constrain cognition and behavior can be done in relative independence from questions about how such representations are actually implemented in specific components of the brain or otherwise (Marr, 1982).

[6] As mentioned above, one way to investigate the mental representations that individuals use is to ask them to think aloud when solving particular problems. Other methods focus on experts' better, faster and more accurate recall of materials from their domains of expertise, or their superior perceptual skills or faster categorization ability (Chi, 2006a).

[7] The same holds for the brain processes that underlie expert cognition and behavior and that have developed in more efficient processes than beginners show, enabling further connectivity with additional cognitive tasks in experts: Experts and beginners appear also at the brain level to perform "different tasks" (Petersen, van Mier, Fiez, & Raichle, 1998).

In the case of chess masters, for example, De Groot and later colleagues described how the masters' better and faster recall, recognition, and understanding of a large number of chess boards depended upon a grouping process that was later called "chunking" (Chase & Simon, 1973; de Groot, 1946). Instead of cognitively representing all pieces and their positions independent from each other, chess masters assemble–implicitly–during years of practice and study tens of thousands of mental representations of groups of pieces in specific positions. These representations sometimes consist of small chunks, while others represent higher-level structures (Sala & Gobet, 2017). In addition to their role in enabling recognition of a particular chess board, these representations have after many years of active practice become associated with preferred chess responses. Indeed, it was discovered that some of the associations connected to certain representations are even emotional in nature, explaining the intuition or urge to respond with a specific chess move to a particular board (Chassy & Gobet, 2011).[8] Similar observations have been made in studies of musicians and sportspersons, for example, who've mastered complex motor routines in response to difficult musical scores or dynamic field positions. In the case of scientists, their representations tend to be very complex, containing not just superficial descriptive properties of the object under investigation, but also some deeper-level relevant organizational principles. Biologists were found, for example, to develop representations of a complex biological system that included complex causal structures with associated unobservable causes and multiple functional relations and interdependencies among those structures. Non-experts were found to lack such rich representations (Brulé & Labrell, 2014).

Yet an observation that is relevant in our context is that experts' development of such complex representations does not imply that the simpler representations they established at an earlier stage of learning are completely abandoned or replaced, as is made visible in Figure 1. Instead, it appears that development and learning are to some extent dependent upon a process called Representational Redescription (Karmiloff-Smith, 1992; Mareschal, et al., 2007). This implies that learning partly consists of the elaboration and adjustment–the redescription–of previously developed

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8 During reading and comprehension of a text, to give another example, the representation that a particular reader develops of its contents also co-activates other representations or representational elements that he or she has developed over time, including motivational and affective ones (van den Broek & Kendeou, 2008). Research into "embodied cognition" suggests that even mental representations of relatively abstract contents are grounded in action-oriented and situated interactions individuals have with their environments (Wilson, 2002).

mental representations, with both the older and the redescribed versions remaining available and being activated under particular conditions. In the words of the influential developmental cognitive scientist Karmiloff–Smith, in order to learn, a human can "exploit internally the information that it has already stored (both innate and acquired), by redescribing its representations or, more precisely, by iteratively re-representing in different representational formats what its internal representations represent" (Karmiloff-Smith, 1992, p. 15). Performing at an expert level does therefore also require that an individual become aware of this feature of the learning process, learning to monitor it and regulate it, for example regulating the activation and influence of less sufficient, older representations. This is not easy, as not all assembled representations are equally accessible to conscious monitoring and regulation.

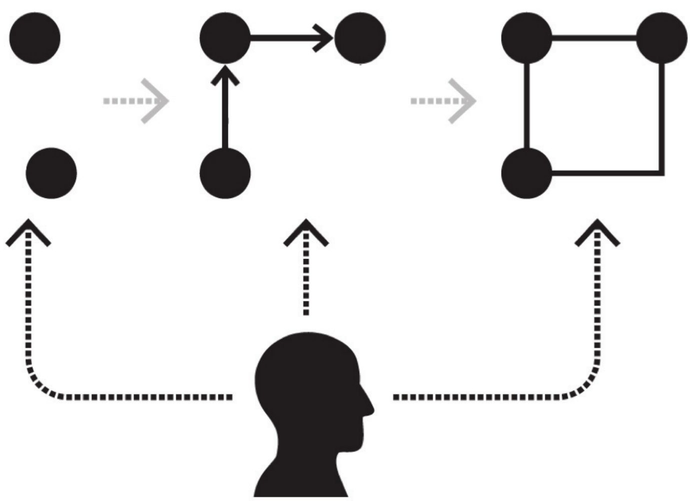

Figure 1. Learning and the acquisition of expertise in a particular field or discipline entail that an individual develops new mental representations pertaining to the domain at stake that do not replace previously developed, simpler ones. A beginner possesses just a few representations; they then increase in number and interrelation, with experts employing many more and more complex structured ones. Vertical lines show the parallel availability of representations stemming from these different learning stages.

Rapidly, and often without explicit instruction, children demonstrate in their cognition and behavior how they develop a large number of mental representations, like representations of linguistic structures, of named objects like houses or animals with many properties, of actions and skills, and so on. As children employ these representations for their perception, understanding, and behavior, they're continuously and usually implicitly adjusted in response to different forms of feedback, some from caregivers and educators, some from confrontations with their environment, some generated internally.[9]

Along the way, children slowly learn to articulate the mental representations they're employing when explaining their cognition or behavior, yet such articulations are often limited. In the case of language, for example, even adults can have difficulties in explicitly articulating why a certain sentence is incorrect even though they can claim explicit expertise in all relevant grammatical and syntactical rules. So even if development and learning do lead to our ability to partially explain the structure of mental representations underlying our expertise, we still don't reach a point where we can completely uncover all that we implicitly know about a certain domain and how we solve specific problems in it (Karmiloff-Smith, 1992).[10]

One might expect that since scientists master their trade through explicit education, practice, and assessment, they would always be able to make their scientifically relevant mental representations explicit and would not rely upon implicit ones. Yet psychological and other studies demonstrate that we should not expect such a strict distinction in this context. Even in higher and abstract cognitive processing humans do all employ mental representations that remain implicit: Indeed, it is appropriate to place implicit and explicit cognition and the associated implicit and explicit mental representations on a continuum rather than strictly separate them (Augusto, 2013; Cleeremans & Jiménez, 2002). Consider the fact that students do not enter university as a *tabula rasa* but usually have preexisting conceptions

[9] What is involved in learning and development according to neuroconstructivist accounts is a process of Representational Redescription, during which early developed representations are–implicitly, unconsciously–redescribed, rendering additional representations with novel properties available for other cognitive and behavioral tasks (Mareschal, et al., 2007). Apart from these properties, it is the implicit-explicit distinction that is relevant in most situations (Butler, 2007).

[10] Agreeing with Karmiloff-Smith's idea that learning involves a process of Representational Redescription during which novel representations are developed by the learner while he or she retains earlier developed–implicit–ones, Taber describes how in learning science such new representations often provide elaborated components of earlier representations, or offer wholesale alternatives (Taber, 2008).

of the phenomena in their disciplines. Academic education rather adds to their implicit representations than simply replacing them, so alternative representations often continue to influence their cognition by blending with newly developed mental representations, leading to inconsistent ideas, for example, about canyon formation in the case of geology students (Sexton, 2012). This continuum between implicit and explicit cognition explains why even experts' cognitive processes still unconsciously employ implicit mental representations of phenomena in their fields of expertise, albeit often in tandem with explicit representations they've derived from their education.

As noted earlier, mental representations may differ decidedly, too. For example, physics experts have been found to explicitly develop different kinds of mental representations in parallel, like a model that is an adequate structural analogue of the physical system in question and a mathematical representation of the relevant structures and their quantifications (Dunbar & Fugelsang, 2005). The challenge then is to coordinate and combine these multiple representations in a consistent and productive way, and perhaps add associated visual images as well. With growing expertise experts can gradually meet this challenge, even when not all representational details can be made explicit (Greca & Moreira, 2002). However, even physics experts are at times not able to monitor and control the influence of the more primitive and implicit representations that in children determine expectations about object mechanics. Physical forms are important in folk physics representations and even though experts know about their irrelevance compared to more abstract and invisible structures and properties, they still fall prey to mistakes that are due to their entertainment of such implicit representations (Rouse & Morris, 1986). Increased awareness of how our cognitive processes and representations figure in our performance, perhaps developed through education, can help people avoid such mistakes.

Explicit and verbal education exploits the process of Representational Redescription in ways that animals don't have at their disposal; language "emerges as just one more level of redescription, albeit one that provides rich manipulability and a powerful means of cultural transmission" (Clark & Karmiloff-Smith, 1993, p. 505). By establishing such explicit representations we can modify or correct the implicit representations we might have, perhaps quickly "debug" a flawed performance: A golfer might focus on changing the "wrist component of her swing . . . instead of learning the whole swing anew" (Clark & Karmiloff-Smith, 1993, p. 492). A novel explicit representation can also help the integration of previously separate representations, for example by representing abstract, functional properties of superficially different systems. Indeed science experts demonstrate intuition and creativity in their field by developing such novel and integrating representations when they discover analogies, draw comparisons, and so on, processes that often defy conscious control or articulation (Litman & Reber, 2005).[11]

Why all this attention to mental representations and the process of Representational Redescription in the context of investigating interdisciplinary research and collaboration? Because greater awareness of them may help those involved in such research to overcome some obstacles and to improve the quality of individual work and teamwork. Indeed, successful individual experts and successful teams are partly characterized by their attending more to these features. As studies in fields as distinct as music, sports, crafts, and science have shown, it is partly due to their assembly of large and varied sets of representations during many years of study and practice–adding up to at least some 10.000 hours–that experts can be characterized as individuals who reliably outperform most others in a specific domain according to relevant standards (Ericsson, 2006b; Sternberg, 1998). They, too, have to cope with different representations that are not always consistent with each other nor optimal in any given situation, potentially leading to suboptimal performance. Still, this is the reason why we should expect experts to be significantly better if not perfect at monitoring and regulating the processes and representations underlying their performance than beginners. The next section will delve into this subject, after which we will then look at the implications of these insights for those involved in interdisciplinary team collaboration, considering how the team performance can be supported by mental representations and the team members' cognitive processes employing such representations.

## § 1.2. Monitoring and Regulating Cognition: Metacognition and Deliberate Practice

Concurring with our common expectations, the superior performance of experts depends upon their superior ability to cognitively process complex situations or tasks in their field of expertise, while responding also more flexibly and adequately than beginners in the same field. Nevertheless, there are limitations to expertise and even some challenges that are precisely the result of having gained expertise. Indeed, one can even refer to the "brittleness" of expertise, for experts can sometimes perform worse than

[11] Scientific creativity can hence be explained in similar terms to those used to explain other forms of creativity, by referring to cognitive processes and the representations involved in them, with experts being somewhat able to better–albeit not completely–control these than beginners (Boden, 2004; Thagard, 2012).

beginners in exceptional situations when relying upon expertise can be counterproductive. Overly confident in recognizing a particular situation and allowing the response that is associated with the situation's mental representation to be executed, an expert may overlook a relevant but novel detail (Lewandowsky & Thomas, 2009). Indeed, studies of experts in several domains have found such a weakness in their performance, together with other weaknesses, like their demonstrating a bias or fixedness towards sometimes inadequate responses. For example, medical experts have been found to be inclined to offer a diagnosis of a patient that falls within their own domain of expertise even though a more creative solution may be required (Chi, 2006b).[12] In such cases, the beginner's lack of expertise and lack of a large set of implicitly employed mental representations can be a blessing, requiring him or her to carefully scrutinize the situation and consider potential response options without such a bias or lack of creativity.[13] One may wonder, therefore, whether interdisciplinary work would be better served with beginners, who are less vulnerable to some weaknesses than experts are? Fortunately, though, it is not impossible for experts to meet these challenges and mitigate the weaknesses they may be prone to.

Given these challenges it is not surprising, therefore, that learning and acquisition of expertise usually include raising awareness of these challenges and instilling some capabilities that will assist one in coping with them, by guiding one's own cognitive processes. This requires that time and effort should be devoted to what has been called "metacognition" for some 40 years now: "knowledge and cognition about cognitive phenomena" (Flavell, 1979, p. 906). In the decades since metacognition was first defined it has usually been further subdivided in two components: metacognitive knowledge and

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[12] In other cases, experts such as experienced teachers can succumb similarly to stereotypical or even prejudiced social responses. Specific strategies can alleviate that risk as I've explained elsewhere (Keestra, 2017).

[13] Notwithstanding these questions and in accordance with the arguments presented here, both for individuals and teams, (cultural) metacognition and creativity have been found positively linked to each other (Crotty & Brett, 2012).

metacognitive skills. Based upon a review of the research on metacognition in science education, these two components have been further specified.[14]

I'll quote the authors' explication of the three components of metacognitive knowledge in full:

> *Knowledge of persons* refers to self-knowledge of the variables that influence the individual's cognitive activity, knowledge of the cognition of others and knowledge of the universals of people's cognition. *Knowledge of tasks* refers to understanding how the nature of task conditions, demands and goals affects cognitive activity. *Knowledge of strategies* refers to knowledge about thinking, learning and problem-solving strategies that students might use in order to achieve goals. (Zohar & Barzilai, 2013, p. 123)

Metacognitive skills include the skills of planning, of monitoring, of evaluating, and of self-regulating cognition.[15] Such skills help to answer questions like what are current priorities, how must consecutive steps be planned and evaluated, where can further assistance be found? These skills determine how we select tasks and strategies in a given context, assess and evaluate our own progress towards a cognitive goal, change our strategies accordingly, and so on (Zohar & Barzilai, 2013).[16] An additional target for these skills can also be the environment in which an expert has to perform; removing obstacles or developing facilitating structures can help to improve outcomes or ease the task itself, for example (Zimmerman, 2006). Coping

[14] Zohar and Barzilai add in their review a third component of metacognition that receives relatively little attention and is also left further aside here, to wit: metacognitive experiences. Flavell offers a description of these: "Many metacognitive experiences have to do with where you are in an enterprise and what sort of progress you are making or are likely to make" (Flavell, 1979, p. 908), like when you're feeling surprised, close to a solution, confident about your memorization, and so on. Obviously, such motivational and affective features of our cognitive processing play an important role in learning and development as well. Science education could be improved by taking metacognition more seriously as an ingredient, because such meta-reflections and skills help students to better navigate the difficulties of scientific inquiry (White, Frederiksen, & Collins, 2009 ).

[15] A slightly different account proposes a three-step metacognitive cycle: an initial step of planning goals and strategies, a monitoring step, and then an improvement step that consists of reflecting on past and future goals and strategies (White & Frederiksen, 2005).

[16] Hofer has drawn attention to specific epistemic beliefs that are involved in both metacognitive knowledge and metacognitive skills. An important dimension of the former concerns whether a learner believes that knowledge is simple or complex, and whether it can be certain or rather tentative and evolving. Metacognitive skills are also determined by beliefs about knowing as a process, which concern both the evaluation of the source of one's knowledge and also its justification (Hofer, 2004).

with environmental challenges will become more important in the case of interdisciplinary collaboration.

Since some of the expert's cognitive processes and the representations involved are implicit and hence escape consciousness, as I've argued above, the application of metacognition might not be an easy task. Indeed, as we'll see below, experts develop within their scientific field or discipline so many routine procedures in response to a great number of well-observed, unsurprising events that their metacognitive alertness might not be optimal. Instead of recognizing that a current event deviates in meaningful ways from similar recurring events, experts might find it so familiar that they overlook the event's deviation, responding automatically in a habituated fashion.[17] Optimally prepared experts would therefore have to have the metacognitive knowledge about the risk they might automatically employ a suboptimal strategy before they would apply their metacognitive knowledge and skill in selecting adequate strategies to avoid this lapse. Adequately metacognizing experts would consequently devote more time and attention to the situation and–based upon their expertise and acquired set of representations–focus on notoriously difficult or overlooked features of the situation, for example. That is, in addition to the allocation of extra cognitive resources, they would also strategically select particular representations to articulate and further scrutinize, develop, modify, or combine with other representations in order to adequately respond to the situation (Sternberg, 1998). In such situations of self-monitored and self-regulated representational or conceptual change, "intelligibility, plausibility and fruitfulness are *metacognitive* considerations," playing an important role (Rowlands, 2009, p. 18, italics added).

These observations underscore once more why expertise cannot rely solely upon implicit cognition. Admitting that explicit cognitive processes and conscious development of mental representations may play a role early in the learning process, as during instruction, phenomenological philosopher Hubert Dreyfus has nonetheless denied that those who develop expertise learn to consciously guide all their cognition (Dreyfus & Dreyfus, 1986). However, this view of multiple stages of expertise acquisition has not received convincing empirical support. Observations of expert behavior disprove the notion that experts are just engaged in "holistic intuition" without invoking more analytical processes when solving a problem (Gobet & Chassy, 2009).[18]

[17] Such predictions of likely future situations, like the probability of next moves in chess, are also dependent upon the complex representations that experts develop. These have a template structure with "empty slots" that allow the representations' application even if some details are different from time to time (Didierjean & Gobet, 2008).

[18] This is not to deny that hampering the automatic performance of experts or asking them to explicate their performance can disturb and impede their superior performance.

On the contrary, observations confirm that what distinguishes experts from other accomplished learners is that experts "counteract automaticity by developing increasingly complex mental representations" whereas those in the latter group do not commit much more time and attention to the practice required for that further development – often out of a lack of motivation (Ericsson, 2006a, p. 685).

In other words, expertise consists of an intricate interaction among different cognitive processes: conscious, explicit cognitive processing that includes metacognition on the one hand, and automatic, implicit cognition on the other.[19] This interaction can be particularly well observed in the process of deliberate practice, which plays an important role in acquiring and improving expertise. Not just amateurs during the early learning phase but also accomplished experts improve their performance by engaging in deliberate practice, aiming to improve the memorization, employment, and refinement of the mental representations involved in cognition and behavior, as well as their integration with other representations. Indeed, we are all familiar with the reading, musical, mathematical, or sports exercises that we have carried out in order to increase our reading speed, to learn a particularly difficult piano passage by heart, or to master new mathematical computations. These efforts benefit from deliberate practice, the focused and repeated practice of predefined exercises accompanied with conscious monitoring and evaluation of our performance with the immediate identification of errors and their correction via new strategies or procedures.[20] It is the amount of such deliberate practice in any and all areas, more than biological or social factors, that explains the development of expertise (Ericsson, Krampe, & Tesch-Römer, 1993). Moreover, experts distinguish themselves from merely decent performers in that they continue to engage in deliberate practice even after they have reached the level of decent and virtually automatic performance, which for most individuals is satisfactory enough that they lose the motivation to invest more time and attention in such practice.

Concurring with the earlier observation that expertise and its properties are

[19] This interaction has led to so-called dual system (or process) theories of expertise, according to which the implicit and automatic system and the explicit, controlled system contribute differently to expert performance (Kahneman & Klein, 2009). Concurring with the analysis presented here, metacognition implies Representational Redescription that occurs during the interaction between these two systems (Timmermans, Schilbach, Pasquali, & Cleeremans, 2012).

[20] As I've argued extensively elsewhere, even consciously developed, explicit rules and intentions can after sustained practice sink in and become implicit and affect in unexpected ways ongoing cognition and behavior (Keestra, 2014).

also relevant in the domain of academia and science is the fact that deliberate practice influences the acquisition of scholarly expertise, as well. Such deliberate practice impacts the development of a large and differentiated set of representations and their cognitive processing in scholarly experts, supporting their performance in their disciplinary fields. This holds not just for the perceptual and behavioral tasks that have to be performed in many academic disciplines, like the observations and diagnoses that medical doctors make as well as their subsequent surgical procedures. Deliberate practice also has an impact on the complexity of the patterns scholars discern and the reasoning underlying their description and explanation of their observations (Ericsson, 2004). In addition, creativity and problem solving benefit from deliberate practice when it involves recognizing analogies between different representations of the same or similar systems, connecting structural system models with their mathematical descriptions, recognizing pattern similarities between different studies of the same phenomena, and so on (Bruun & Toppinen, 2004). Such deliberate practice can take the form of collective deliberate practice performed in an interdisciplinary team, which we will investigate further below. Before we go there, I will briefly discuss how philosophical reflection can add to metacognition and deliberate practice in improving expertise and particularly the capacities and skills necessary for interdisciplinary problem solving.

### § 1.3. Preparing for Interdisciplinarity: Metacognition and Philosophy

It may appear that I've presented an unrestricted praise of expertise above, yet earlier I mentioned the risks of brittleness, bias, and fixedness on certain task representations or performances from which experts often suffer. Related to these weaknesses and especially relevant to our investigation of interdisciplinary team collaboration is the fact that expertise is found to be relatively domain specific. This is not surprising as expertise depends upon the time and attention invested in the development of a large but special set of implicit and explicit representations that are exercised, memorized, further elaborated, combined, adjusted, re-organized, and so on. Indeed, one becomes an expert precisely by developing this specific and large set of rather complex representations that are underpinning cognition and behavior.

Particularly with regard to behavioral routines and procedures, such domain specificity is apparent. A violin virtuoso relies on very specific hand patterns and sequences that are different from those of a piano player. Similarly, a football player's "perception-motor cycles" are different from those of a basketball player. Yet with regard to the processing of possible scores or of field positions–i.e. the perceptual and cognitive processes preceding the motor actions–the generalizability or transfer of expertise is much greater. Important here is the concreteness or abstractness of the representations in question. For muscle movements, the representations determine particular and minute body movements and are hence very concrete and specific. In contrast, representations involving the decision where to move the ball are less dependent upon such specific body movements and hence more generalizable across different positions–like keeper and attacker–and even across different sports (Abernethy, Baker, & Cote, 2005; Bruce, Farrow, & Raynor, 2012).

Comparison of sportspersons and persons like sports writers and coaches–who are equally involved in sports as observers without employing any perception-motor cycles–has demonstrated that the observers are better than non-experts but worse than sportspersons in making correct perceptual judgments about ball shots (Aglioti, Cesari, Romani, & Urgesi, 2008). Apparently, only players can rely upon embodied cognition when perceiving and judging visual cues from another player's posture and shot that feed into their cognitive processing and contribute to their superior anticipation skill. Being engaged in actual sport performance implies they have established many connections at different levels of detail among the representations underlying different features of their domain specific expertise (Williams, Ward, Knowles, & Smeeton, 2002).[21] When it comes to interaction and communication among experts more generally, embodied cognition does play an important role in "transdisciplinary hermeneutics" according to the arguments provided by Dieleman in his contribution to this Special Section (Dieleman, 2017).

If we now consider scholarly expertise and its domain specificity, we have to remember the pluralism implied in the study of complex phenomena I've discussed earlier. Complex phenomena can be investigated from multiple disciplinary perspectives, each associated with its own theoretical accounts and methodological approaches, and each having only limited relevance. As we now know, the Challenger's leaking O-ring can be explained partly by its chemical and associated mechanical properties and partly by the meterological conditions during launch that had a critical impact on those properties. During the launch decision discussion among those at the table neither had neither sufficiently developed a comprehensive cognitive representation to integrate all

[21] This implication of the embodied nature of our cognition and cognitive representations confirms once more that–and this holds generally–representations are always relative to a certain purpose or practice. It is in that sense radically different from what has been called a Cartesian idea of representation as "mirroring" nature (Rorty, 1979).

the relevant elements and their interconnections, nor sufficiently evaluated their respective weights. This is not surprising as scholarly expertise privileges "self-referential communication," exchanging insights and experiences regarding a particular domain or discipline within a specific communication network and ignoring those from other domains or disciplines (Weingart, 2010).

Academic disciplines differ in what Kuhn has called their "disciplinary matrix," consisting of heterogeneous elements like the discipline's prominent theories, laws, and symbolic generalizations, particular metaphysical assumptions, pragmatic values for conducting proper studies, and prominent exemplars that students have to make their own in order to become a member of the discipline's community. Consonant with what we've said above about how acquiring expertise depends upon the collection of a set of implicit and explicit representations, Kuhn has pointed out that aspiring scholars usually do not learn this matrix explicitly by itself, but learn it indirectly through their immersion in concrete applications and problem solving. The lack of conscious direction in the learning process means their metacognitive ability to monitor and regulate their cognitive representations and processes is not necessarily well developed, often making scientists "little better than laymen at characterizing the established bases of their field, its legitimate problems and methods" (Kuhn, 1970, p. 47).[22]

The self-referential nature of disciplinary communication and its limitations do not rule out the fact that, like other experts, scholars have learned within their discipline or field to develop and employ multiple representations that support their perceiving, thinking, and acting. Indeed, both cognitive and computational studies suggest that abstract and conceptual knowledge is preceded by perceptual skills, building upon the complex implicit representations of patterns and chunks that support these skills (Gobet, 2005).[23] However, notwithstanding such remaining influence of implicit representations, particularly characteristic for most disciplines is the central role of explicit and idealized abstract or formal representations–

[22] Kuhn refers with approval to Polanyi's concept of "tacit knowledge," writing "much of the scientist's success depends upon 'tacit knowledge,' i.e., upon knowledge that is acquired through practice and that cannot be articulated explicitly" (Kuhn, 1970, p. 44, footnote 1).

[23] Such inconsistency in responses can be due to the engagement of the two distinct cognitive systems or processes that underlie human cognition and behavior: one automatic and implicit, the other conscious and explicit. Avoiding such inconsistency would require an explicit estimation of whether implicit intuition might be reliable in current conditions, or not (Kahneman & Klein, 2009), or a conscious attempt to "debias" the often biased implicit reasoning that scientific experts at times rely upon (Croskerry, Singhal, & Mamede, 2013).

be they concepts, models, functions, or otherwise.

These abstract representations may initially be more difficult to cognitively process than concrete and detailed representations of an object or system, but learning to do so is important because they serve important scholarly goals. An important benefit is that, due to their "concreteness-fading" and abstractness, such representations are easier to transfer to other disciplinary domains that may appear different but that share abstract similarities (Goldstone & Son, 2005). However, for such transfer of abstract representations across domains, it is crucial to distinguish properly which concrete details or connections must be captured in the abstract representations, and which can be left out, a process requiring extensive metacognition. An abstract representation of a mechanical system can usually exclude temperature conditions, for example, yet such exclusion might not be wise where more extreme temperatures are concerned, as the Challenger's launch team discovered. In other words, relevance again can be seen to play an important role in the use and development of representations in a discipline. And of course it is needless to say that this relevance is often context-dependent and changes during a discipline's sometimes erratic history.

In addition to metacognition, scholars benefit from philosophical reflection on (implicit as well as explicit) assumptions underlying the cognitive representations and processes common in their field.[24] Philosophical reflection appears indeed to be a natural ally to metacognition, given that both entail a second-order activity or reflection, requiring individuals to not take their own thinking and thoughts for granted but to critically scrutinize them (Rowlands, 2009). Philosophical reflection in this context is understood as particularly focusing on the epistemological and ontological but also normative assumptions that have shaped the focus of those in a field on some causes and factors and not others, preferences for certain models in their discipline, interest in some details with others considered irrelevant, application of some methods deemed best for investigating theoretically constructed objects, and so on (Menken & Keestra, 2016; Repko & Szostak, 2017). According to the current approach, assumptions form part of the background against which representations are grouped, structured, and interpreted within a discipline. They imply a certain hierarchy among its percepts or concepts, for example, or they determine why certain dimensions of a phenomenon are considered useful for empirical research and others are not. In scholarly disciplines as in music or sports, beginners gradually

[24] In his 1978 essay on the question "Why Interdisciplinarity?" Kockelmans already argued that disciplines "in the final analysis rest on implicit philosophical assumptions" (Kockelmans, 1998, p. 85).

develop more complex and structured representations by implicitly applying the assumptions common in these fields. Assumptions are implicitly contributing to experts' representations and performance as, for example, when scholars quickly distinguish primates from monkeys in biology or recognize non-linearity in a certain graphs, even as musicians resolve the famous Tristan chord, or players pass the ball while avoiding offside. In turn, when scholars start reflecting philosophically upon these assumptions, they come to recognize some of the principles underlying their complex representations. Such philosophical reflection can help to prepare them to recognize potential connections to neighboring fields by sensitizing them to alternatives and clarifying differences and similarities among assumptions in different fields (Looney et al., 2014). Figure 2 illustrates how an expert further develops expertise with the processes of metacognition and philosophical reflection playing an important role, preparing him or her for drawing connections with insights from other experts.

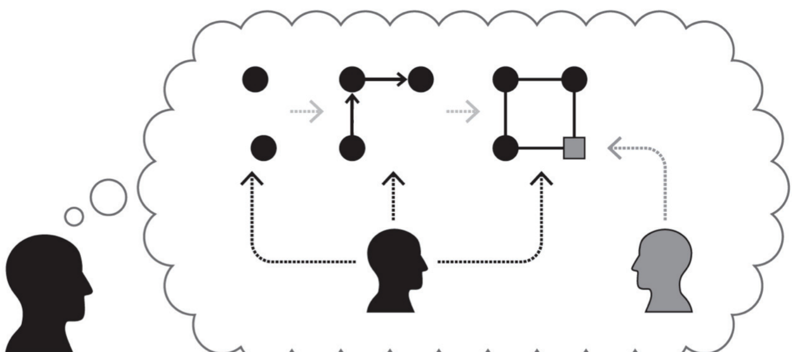

Figure 2. An expert engages in metacognition and philosophical reflection about his or her thinking. The expert reflects specifically about a learning process (in the cloud) and the set of representations it has yielded. Such second-order reflections also prepare the expert for the integration of an additional insight from another expert incorporated into the complex mental representations, such as the grey square added here.

However, one obstacle to scholars' preparedness for connecting to other disciplinary fields is the widely held yet mistaken assumption that insights from their discipline will remain intact once these are put into connection with others. More often than not insights concerning the properties of a phenomenon observed in isolation must be modified once it is integrated as a component into a more complex phenomenon, or connected otherwise. Emergence of a complex phenomenon like consciousness from the large collection of neurons and their connections that constitute the brain is only one of many examples. Representations–explicit and implicit–underlying scholarly work on a phenomenon should be adjusted in tandem with novel insights (Bechtel & Richardson, 1993), requiring necessary metacognitive knowledge and skills.

Summarizing the preceding sections, we've arrived at the following insights: (1) Irrespective of the particular domain–music, sports, or scholarship–the acquisition of expert cognition and behavior consists in part of the development and employment of a large set of representations that are organized and differentiated in complex ways with some being implicit and others being available for conscious and explicit articulation; (2) Although acquiring expertise partly depends upon deliberate practice which entails the monitoring and regulation of their cognitive processes and representations, experts are still relatively weak meta-cognizers; (3) Theoretical and methodological pluralism imply a limited relevance of specific representations, which makes it crucial that scholarly experts keep on monitoring and regulating their disciplinary representations; (4) In addition to metacognition, scholars would benefit from philosophical reflection on the epistemological and ontological assumptions that constrain this pluralism and its corresponding representations, preparing them for forging connections to those in other disciplines and their representations.

In the next sections of this article, we will extend these insights to interdisciplinary team collaboration, clarifying how they have an impact both on the mental representations team members need to develop and the extra metacognitive and reflection implied as necessary in that task.

## § 2. Interdisciplinary Team Cognition: Facing the Next Level

The Challenger team offers an obvious example of failure to acknowledge and respond to a reported unknown adequately. A more positive example of interdisciplinary team collaboration, also from aeronautics, is given in an influential article on distributed cognition titled evocatively "How a cockpit remembers its speeds." Its author draws attention to the fact that in the context of a team effort such as flying an airplane we should focus not just on individual cognitive processes and the mental representations involved in them, but also on the whole "socio-technical system." In the cockpit's case this system operates adequately with clearly divided tasks, appropriate lines of communications, and well defined decision procedures based upon familiar kinds of information, employing all the individual experts' cognitive processes (Hutchins, 1995). In contrast to the team involved in the pioneering Challenger launch, a regular airplane's cockpit team follows well practiced and standardized routines and protocols while sharing a common language. How, though, can we be sure that if a novel unknown presented itself to such a team, it would elicit an adequate response from the team?

It is useful to reflect in more general terms on what it takes to collaborate. As philosopher Michael Bratman points out, even a relatively simple task like painting a house together usually involves collaborators dividing up the task and coordinating the distributed component tasks involved in the project. They agree upon the color, whereupon one buys the paint, another sands the house before a set date, after which another grounds it, and so on. Many of the cognitive and behavioral tasks are being carried out by an individual, with the others trusting and relying upon him or her.[25] Importantly, they must keep each other posted about relevant changes in their individual contributions or new ideas they'd like to implement. However, and this is important, according to this philosophical theory of planning agency the collaborators don't need to know all details of each other's contributions as long as they are supportive of each other and responsive to each others' intentions and actions. Finally, all the collaborators need to remain committed to the joint activity and its goals so they can work trustfully towards them (Bratman, 2013).[26]

Collaboration thus entails a mixture of the relative independence of individual contributors and a purposeful communication and coordination of these contributions on the basis of mutual trust and support. In the case of interdisciplinary scholarly collaboration, though, collaborators usually cannot rely upon standardized routines and protocols and a shared language. On the contrary, as was noted above, their disciplinary training has prepared them for "self-referential communication" with disciplinary "networks of meaningful communication" being more fractured and specialized than ever. Even though there is increasing demand for cross-disciplinary collaborations, "disciplines and their derivatives, specialties, and research fields, remain the

[25] The cognitive processes of mutual understanding and empathy required for collaboration are supported by the development of "shared mental representations," enabled by so-called mirror neuron systems. This cognitive neuroscientific explanation concurs in several respects with a hermeneutic approach to understanding and "mimesis" (Keestra, 2008).

[26] In order to support trust and commitment in interdisciplinary teams, organizational measures can be implemented like the strategic agreements presented in this Special Section of *Issues in Interdisciplinary Studies* by Lash-Marshall, Nomura, Eck, and Hirsch, 2017. Naturally, irrespective of such formal agreements, implicit trust and commitment still play an important role.

principal organizational unit for the production and diffusion of knowledge," prohibiting rather than advancing interdisciplinary collaboration (Weingart, 2010, p.13).[27] In addition, disciplines are still the source of the criteria commonly used for assessing such collaborative interdisciplinary research (Holbrook, 2010). And yet, scholars are expected to be able to collaborate, integrating the insights from their primary discipline with those of colleagues from other disciplines–when engaging in interdisciplinary research–and with those of extra-academic participants–when engaging in transdisciplinary research (Klein, 2010; Menken & Keestra, 2016; National Academy of Sciences, 2004).[28] It will not surprise the reader that I will argue that for such collaboration to be successful it should be supported by metacognitive knowledge and skills complemented with philosophical reflection.

As we have seen in the previous sections of this article, disciplinary expertise is to some extent based upon the metacognitive ability to monitor and regulate the implicit and explicit cognitive processes and representations involved when collaborative work is attempted. Yet, the complexity of interdisciplinary collaboration means that additional requirements must be taken into account by the team and its individuals. We will discuss these now in terms of the additional *team* mental representations and *team* metacognition required.

### § 2.1. Interdisciplinary Collaboration and Team Mental Representations

The tasks of an expert meteorologist who was a member of a cockpit team – or of the Challenger launch management team – look rather different than if the expert were working alone. Obviously, being part of a team implies that good communication is now an additional task. Yet team collaboration is not identical with a number of experts doing their own jobs in isolation with the addition of some communication about their task performance and its results. To begin with, the team tasks and goals now influence the goals

[27] This remains the case even when there is a clear trend towards various forms of scholarly collaboration that can be observed in recent decades, given an increasing number of multi-authored articles in many fields and an increasing number of academics operating in collaborative teams, a portion of which are interdisciplinary (Porter & Rafols, 2009). Yet at the same time, it has often been noted that the institutional and educational structures that surround and constrain scholarly work are still far more supportive of disciplinary than of inter- or transdisciplinary collaboration (Pfirman & Martin, 2010).

[28] The "dilemma of expertise" that affects scholars is that they can generally no longer just display their expertise but will always be interacting with situations and audiences external to it (Nowotny, 2003).

of each individual expert's performance and the constraints under which he or she has to operate. In the case of a meteorologist, what meteorological insights are required given the aircraft's trajectory and when, and how, must these insights be made available to the rest of the team? Keeping the Challenger launch's fatal unknown in mind, a meteorologist might well ask what information he or she needs from other team members and whether they are aware of such expectations. For example, it may dawn on him or her that a change of the aircraft's flying altitude would be relevant because meteorological conditions might change accordingly, yet the navigator might not be aware of this and might not communicate such a change, so the possible relevance of such information should be made explicit. However, only larger altitude changes would be truly relevant, so the navigator should know when to inform him or her and when not to bother about altitude changes. Clearly this meteorologist must metacognitively reflect upon his or her own–partially implicit–knowledge and then consider what others might know, how they might appreciate meteorological insights, when might be the right time to present these, and so on. Obviously, such reflection is also necessary for other team members, adding many extra challenges to their usual tasks. Yet even apart from such metacognition, teamwork as such requires that members develop pertinent mental representations over and above the ones associated with their individual performance.

As team members, experts need to develop mental representations of how their performance is now part of a team performance involving others' mental representations, too. Studies of the interactions of such team mental representations have yielded different results, with some convergence among them. Since teams differ in their composition, team tasks, and goals, as well as the conditions under which teams operate–under fast-changing conditions, for example, or divided over different locations–team mental representations do differ. However, notwithstanding these differences, team members usually develop mental representations concerning their collaboration that include the following four types of information: task-related, team-related, process-related, and goal-related. With these types of information, the "who, what, why, when, and how of the team" are represented cognitively (Wildman et al., 2012).[29] I will review what is

[29] An earlier proposal about the contents of team mental representations suggested that information is included about equipment, task, team, team interaction, and the problem situation (Cannon-Bowers, Salas, & Converse, 1993), whereas a more recent one suggested an additional role for the representation of interface tools and

implied by this inventory and then add insights presented earlier about how expertise depends upon the development of multiple representations and metacognitive knowledge and skills.

In *task-related* representations the team members represent what they know about the task at hand and the situation in which they are performing the task: The meteorologist was determining relevant weather conditions during the upcoming Challenger launch, for example. Yet for actually carrying out this task, members invoke *team-related* representations that capture information about the location of necessary expertise in the team. Who is an expert in what domain or skill, for example, and what levels of expertise can be expected from each of them? Building together upon their collective, yet distributed, expertise requires the coordination mentioned earlier, including the necessary commitment and trust as preconditions for the coordination to succeed. Such contents belong in the third category of *process-related* representations that contain information about the teamwork and the interaction processes it involves. Finally, the fourth category of *goal-related* representations "is not referencing the requirements of the task, the characteristics of the team, or the team interaction processes but rather is focused on knowledge or understanding of an overarching goal or mission relevant to the team" (Wildman, et al., 2012, p. 93).

Representing information concerning the task, the team, the team process and the goals of the interdisciplinary project does not exhaust the relevant information required for the team mental representation. As we learned in the previous sections of this article, experts are also characterized by their ability to monitor and regulate their cognitive processing and representations, even though not all of them can be made explicit and available to conscious control. Development and learning, we argued, depend in part on a common cognitive process of Representational Redescription that allows humans to build upon previously acquired knowledge and skills and to develop new and creative insights by employing previously established representations (Clark & Karmiloff-Smith, 1993). Indeed, experts have been found to engage in deliberate practice during which they explicitly focus on modifying a flawed representation or developing a novel one, often after verbal instruction or after physical demonstration by someone else (Ericsson, 2006a). Once an expert starts collaborating with other experts, this challenge of monitoring and regulating relevant representations so as to

communication skills (von Davier & Halpin, 2013). The latter reflects probably the increased importance of virtual networking and managerial skills in academia and underscores how mental representations are a function of learning and development, even if they gradually become implicit.

allow for learning is expanded, complicating the collaboration significantly. How can a team of experts working together develop comprehensive and coherent representations if it is already such a challenge for individual experts to monitor and control their own sets of activated representations when solving a problem while avoiding inconsistency among them?

Clearly, then, attending specifically to this dimension of cognitive processing and representations is important for collaboration to succeed. If a team is neglecting the complexity of aligning cognitive processes and representations for a team composed of interdisciplinary experts, it might easily slip into forms of groupthink, for example. Since experts' previously assembled sets of representations steer their subsequent perception, recognition, understanding, and responses to novel tasks and situations, there is a tendency for team mental representations to converge gradually to the overlapping representational contents that are shared by all team members. As non-overlapping knowledge and skills are more difficult to perceive, understand, and work with, they may receive less attention, and as a result the team may miss out on such knowledge and skills (Cacioppo, 2007). Avoiding this risk, each interdisciplinary team should learn to recognize and make productive use of non-overlapping representations, acknowledging that neglecting to do so can seriously impede its efforts and successes. Consequently, in addition to paying attention to the information involved in team representations, an interdisciplinary team should also specifically attend to representation-related or meta-representational information. Importantly, such meta-representational information should also concern the team's doubts or convictions about its own cognition or knowledge that stems from elsewhere (Sperber, 1985). The Challenger's team failed in adequately meta-representing at several levels–both among the material scientists and within the management team–the fatally important unknown.[30] Below we will argue that such meta-representational monitoring and regulation should be included in the task of team metacognition. (The questions included in the Appendix to this article are meant to be relevant for this team metacognitive task.)

[30] A positive development is that explicit meta-representation is becoming increasingly common in the context of interdisciplinary and transdisciplinary research into complex problems, as can be seen from reports of the Intergovernmental Panel on Climate Change. Included in what is called "2nd order science," in addition to their (1st order) findings, scientists report about theoretical presuppositions of their models and uncertainties inherent in these models (Aufenvenne, Egner, & von Elverfeldt, 2014).

## § 2.2. Monitoring and Regulating Interdisciplinary Team Cognition

Obviously, if an interdisciplinary team can employ standardized routines and protocols like those of a navigating cockpit, the need for team metacognition will be limited. Yet even if such routines and protocols are in place, some coordination will be necessary. There will be need for mutual exchange of relevant information required for the performance of subsequent tasks, attentive timing of individual task performance such that it facilitates integration with the tasks of other team members, and so on. Much of this might occur in the form of implicit team coordination, but even then team members still have to employ representations of how their colleagues represent their individual and the team's tasks and take these meta-representations into account in shaping their own cognition and behavior. According to a review of effective implicit team coordination, it consists of two elements:

> (1) anticipation, which is revealed in the expectations and predictions team members formulate regarding the demands of the task and the actions and needs of others, without being directly notified of these actions or needs; (2) dynamic adjustment, which appears in those actions taken by team members on an ongoing basis in order to mutually adapt their behavior. (Rico, Sánchez-Manzanares, Gil, & Gibson, 2008, p. 165)

Since implicit coordination does not require the time or (cognitive) resources necessary for explicit coordination, keeping coordination implicit appears to be most effective and particularly attractive under stressful circumstances (Burke, Stagl, Salas, Pierce, & Kendall, 2006). However, anticipation and dynamic adjustment in many cases are not sufficient to optimally coordinate an interdisciplinary team. Perhaps coordinating implicitly will suffice for a narrowly interdisciplinary team, composed of experts in closely related disciplines like the natural or the life sciences that largely share overlapping representations concerning concepts, theories, and methods. However, in the case of a broadly interdisciplinary team, implicit coordination may no longer be sufficient since the team members' cognitive processing and representations typically diverge much more in such cases (cf. Newell, 2007; Van Dusseldorp & Wigboldus, 1994).[31] In all cases, teams that do not metacognize will easily fall prey to the risks noted earlier, like missing out on underestimated unknowns, group thinking, or experiencing brittleness

[31] "Disciplinary adequacy" in other disciplines is always required of persons engaged in interdisciplinary collaboration, as without it neither implicit nor explicit coordination will be possible (cf. Repko & Szostak, 2017). Collins and Evans' distinction between "interactional expertise" and "contributory expertise" is useful here, as the former is generally sufficient for members of an interdisciplinary team to have regarding the disciplines of other team members (Collins & Evans, 2002).

outside the team's domain of expertise.

Remember that team mental representations that accompany collaborations have been found to generally include task-related, team-related, process-related, and goal-related information (Wildman, et al., 2012). So how might team metacognition have an impact on these and influence the process of interdisciplinary collaboration? The coordination of such team collaboration, I am arguing here, requires any team to engage with both elements of metacognition that were distinguished in § 1.2: metacognitive knowledge and metacognitive skills. As noted in that earlier section, metacognitive knowledge can be divided into three elements that influence cognitive processing and representations: knowledge about how persons function as knowers, knowledge about how tasks can influence cognition, and knowledge of cognitive strategies. Metacognitive skills are involved in guiding, monitoring, controlling, and regulating cognition and learning (Zohar & Barzilai, 2013).

Particularly during the start-up phase, team members individually and as a team determine tasks and divide them up according to their respective expertise and also determine a process to reach their collective goal. If they are not involved in a routine task, this start-up will require explicit team coordination demanding that each individual member explicitly articulate and discuss his or her expertise. In § 1.1 we argued that this is in itself a challenging task, and it is even more challenging now it is part of a process during which initial team mental representations are formed and then subsequently adjusted as a result of the team's metacognitive discussions. If team members are developing different representations and don't address these differences, failure to do so will impact negatively on the team's tasks, process, and goals. This situation is shown in an analysis of a case of flawed team collaboration.

The authors of this analysis describe how "misalignment" of team representations started early on as the team's data-analyst implicitly assumed a support role and defined his expertise and tasks much more narrowly than his colleagues did. The other team members implicitly expected him to be able to perform more tasks, based upon practical considerations and their expectations concerning his expertise. (Such expectations are often influenced by the available tools, impacting implicitly upon the representations of potential tasks and goals of the team and its individual members.) Resolving these inconsistencies and the consequently misaligned team representations would have required much more explicit communication in order to adjust and align them. Unfortunately, the team did not recognize how valuable such team metacognition would have been, since the "Failure to communicate, or even to be aware of the need for communication, was particularly striking" (DuRussel & Derry, 2005, p. 217). However, what the analysis still fails to emphasize is that such communication would only have been possible and useful if the analyst and other team members were able to individually and collectively subject their own mental representations–including their team mental representation–to metacognitive reflection.

Given the difficulty of individual metacognition, does this interdependence between individual and team metacognition make it unlikely for most teams to sufficiently metacognize together about their tasks, team, process, and goals? Fortunately, research shows that metacognition in social settings can help to mitigate some of the challenges of individual metacognition. It can foster individual metacognition as each team member is confronted with the metacognitive self-reflections of others, receives feedback, and considers the self-regulation strategies of others, for example. The positive effects of such social metacognition can include enhanced individual motivation (Chiu & Kuo, 2009). This may be even more the case when collaborators from other disciplines–or who otherwise bring other dimensions of diversity to the team, for that matter–invite the individual experts involved to reflect upon their expertise and contributions in uncommon ways and hence foster their metacognition.[32] Indeed, in this way, metacognition at the individual and at the team level can mutually reinforce each other, allowing the team to develop into an effectively learning team (Salas, Stagl, & Burke, 2004).

Investigations from the field of the "science of team science" offer valuable insights into how team metacognition might be facilitated, starting from the observation that metacognition can indeed contribute to the effectiveness of science teams (Fiore & Vogel-Walcutt, 2010). One lesson from these investigations is that during the different phases of the knowledge acquisition process by science teams, different sets of "metacognitive prompts or metacognition inducing strategies" can be used for team metacognition conversations. Wiltshire et al. present a list of such prompts that fits a three-phase training cycle of preparation, execution, and reflection upon a project; the prompts are applicable to adaptive interdisciplinary teams in general.[33] The listed metacognitive prompts mainly target the knowledge, tasks, and goals that individuals have and need, information on which is useful for the

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[32] Chiu and Kuo also note that care is needed regarding some potential difficulties associated with individual and social metacognition. Although social metacognition can limit some of the difficulties of individual metacognition, it can in turn lead to unnecessary confusion, impede collaboration, and suffer from implicit effects of status and cultural differences (Chiu & Kuo, 2009).

[33] "Adaptive responding" is taken to be characteristic of effective teams, whether they're engaged in training or in problem solving tasks (Burke, et al., 2006).

others to know, too. Some prompts address specifically the collective level of the work and focus on team cognition and behavior (although less on social and affective topics). Examples of prompts for each phase are: What roles will each of you play? Why is certain knowledge important for your teammate to know? Are there alternatives to your chosen planned and executed behaviors, and if so, what are they? (Wiltshire, Rosch, Fiorella, & Fiore, 2014, p.1157). Further examples of "Prompts or Questions for Metacognition" may be found in the Appendix at the end of this article. Importantly, such questions will affect both individual and team mental representations, which will be modified or redescribed: Interaction between intra-personal and inter-personal representational change is the result. Such representational change is particularly important for team cognition to succeed, but it is also challenging (Hall, Stevens, & Torralba, 2005).

Understandably, given the at times problematic mutual interactions between individual and team metacognition and the complex ways in which these affect the team mental representation, it has been noted that leadership can fulfill an important role in this context. As the metacognition that occurs at the individual and team levels affects also the mental representation that individuals hold concerning the team itself–including information about the tasks, team, process, and goals of the team's project–it can also create divergence and confusion within the team. Leaders can help to develop and maintain the coherence of a team, creating shared affect, cognition, and behavior, in part by fostering the team's metacognition (Salas, et al., 2004). The contribution by Lash-Marshall and colleagues to this Special Section of *Issues in Interdisciplinary Studies* discusses facilitative leadership and its role in guiding discussions on perceived obstacles to collaboration, on group decision-making, and on goals and processes necessary to reach those goals (Lash-Marshall, et al., 2017). These contents imply that a facilitative leader should be able to guide conversations that allow the team to develop a coherent team mental representation, thus engaging in metacognition even if metacognition is not mentioned as such.

The concern for the divergence or convergence of the members of a team is usually framed in terms of shared or distinct assumptions. Although it was mentioned in § 1.3 above that metacognition and philosophical reflection are kindred, since both are second-order activities, it is the latter that is much more prominent in strategies that aim to improve team cognition and collaboration (and convergence). It was also mentioned there that, in addition to metacognition, philosophical reflection on the epistemological, metaphysical, and normative assumptions of their disciplines could aid individual experts in understanding the principles that guide and structure their mental representations pertaining to the field. Moreover, this activity would also prepare experts to connect their representations to those of colleagues from other disciplines, facilitating future interdisciplinary integration. The next section will consider how team philosophical reflections can be connected to team metacognition and further contribute to interdisciplinary collaboration.

### § 2.3. Interdisciplinary Team Cognition Enhanced by Metacognition and Philosophy

Team metacognition, we noted above, helps team members monitor and regulate their individual and collective representations concerning the distribution of tasks within a team and the process that offers the necessary coordination to fulfill the team's goals. Such coordination is facilitated yet not entirely ensured with the presence of shared protocols, concepts, methods, etc. Even in the case of a navigating cockpit, the team needs the metacognitive knowledge and skills to consider whether these protocols and other elements are coherently contained in the representations assembled by team members, including potential alternative strategies they could employ. More importantly, metacognition is required in order to raise awareness about the inapplicability of these representations in a particular situation. Such team metacognition was blatantly lacking during the Challenger's launch when the unknown about the O-ring should have alarmed the engineers more and subsequently played a different role in the team process.[34] It seems, though, that the engineers themselves were hesitant about the value of their insight and that the dismissive response from the management cut their metacognitive process short, instead of encouraging them to engage in further team metacognition.[35] The heterogeneity of the team making the launch decision should have been reason enough for such team metacognition, particularly given the broadly interdisciplinary composition of the team.

In light of this example and many other examples, it is remarkable that metacognition does not appear as an omnipresent ingredient in interdisciplinary education and research, and in the discussions about these. Indeed, in the circa 1500 pages of the array of literature that has appeared

[34] The risks implied by the unfamiliar temperature conditions were exacerbated by the team's apparent assumption that even during launch the motor segments would not deform, as did eventually happen (Rogers Commission, 1986).

[35] The installment of an Office for Safety, Reliability and Quality Assurance independent of other NASA responsibilities was one of the recommendations of the Rogers Commission.

in recent years about interdisciplinarity, about transdisciplinary research, and about the integration and implementation sciences, metacognition is merely mentioned a handful of times in passing and never receives separate treatment (Bammer, 2013; Frodeman, Klein, Mitcham, & Holbrook, 2010; Hirsch Hadorn et al., 2008).[36]

Of course, it is true that some forms of self-reflection and critical thinking are heralded as necessary components of interdisciplinary work. Particularly in the context of education, critical thinking does receive attention. Critical thinking skills enable students to weigh evidence, to analyze and evaluate reasoning and arguments, and to identify when scholars are lacking in this area. Due to confrontation with the methods and contents of various disciplines, interdisciplinary learners are continuously challenged to develop such skills (Ivanitskaya, Clark, Montgomery, & Primeau, 2002).[37] Critical thinking skills are also said to contribute, together with collaboration and reflection skills, to the process that yields interdisciplinary understanding (de Greef, Post, Vink, & Wenting, 2017). In the context of interdisciplinary research that takes place outside of education, though, it is neither metacognition nor critical thinking that is considered to be of crucial interest; rather philosophy is considered most necessary to guide critical self-reflection by scholars. The question is, though, whether philosophy can sufficiently cover the functions of metacognition.

Philosophy has been put center stage in the context of interdisciplinary and transdisciplinary research as it is the designated discipline for reflection upon disciplinary matrices and, in that context, disciplinary assumptions.[38] It is these assumptions that need addressing, being potential barriers to interdisciplinary collaboration and integration. Indeed, they are the barrier "that has been most emphasized in the literature on interdisciplinarity: the differences in epistemology and hence in specific methods, notions of adequate proof, and other fundamental assumptions of different fields" (Lélé & Norgaard, 2005, p. 968). In accordance with that observation, contributors to the *Handbook for Transdisciplinary Research* suggest that "[u]sing

[36] It should be noted, though, that Bammer comes close when she devotes an interesting analysis to "appreciating different kinds of unknowns," one of which concerns "tacit knowledge" and another "meta-ignorance." Yet she relates these to disciplines and stakeholders and doesn't treat them as topics for "thinking about thinking" more generally (Bammer, 2013, p. 69).

[37] Worth noting is that at the highest level of interdisciplinary learning, the student is assumed to use metacognitive skills as well, according to the authors' model (Ivanitskaya, et al., 2002).

[38] It is especially because of the theoretical and methodological pluralism that is involved in interdisciplinary research–mentioned earlier here–that reflection on assumptions is necessary, as I argued in Menken and Keestra, 2016.

an interdisciplinary approach to the research topic requires the sustained communication of explicit and implicit assumptions related to specific subject areas." They continue by stating the potential benefits of such communication of assumptions: "This leads to the specifying and clarifying of concepts, research questions, and interpretations within and between disciplines at every stage of the project" (Simoni, Perrig-Chiello, & Büchler, 2008, p. 268). It is commonly considered a philosophical task to foster the articulation of and communication about these assumptions, yet given what we have expressed in this article so far we should doubt whether such reflection as philosophy promotes is sufficient for the required monitoring and regulation of the–often implicit–representations and processes.

Being very explicit about the value of philosophy for interdisciplinary research is the Toolbox Project or Toolbox dialogue method.[39] According to this method, interdisciplinary collaboration is facilitated by identifying individually and collaboratively the epistemological, metaphysical, and also normative assumptions team members hold and then exploring the differences. A set of questions helps this process along, targeting researchers' thoughts about their motivation for research, their ideas about appropriate methods, their views about normative bias, and their beliefs about context-free research, for example (Eigenbrode, et al., 2007). In essence, the method aims to remove communication barriers by addressing disciplinary assumptions with the help of philosophy, contributing to the integration of different disciplinary research worldviews. The Toolbox reaches for this aim via two or three steps: First, team members respond to a set of epistemological and metaphysical questions; second, the members participate in a facilitated dialogue workshop on their responses; and third, they again fill in the questionnaire (O'Rourke & Crowley, 2013).

Important and useful as these steps are for improving interdisciplinary collaboration, according to the analysis provided here, successful collaboration requires more than such mitigation of the "opacity problems" that threaten team communication that are at the focus of a philosophical approach like this (MacLeod, 2016 ). A similar conclusion was drawn after the case of representational "misalignment" mentioned earlier: "Even important philosophical alignments–as in participants' agreement that an inductive

[39] Michael O'Rourke participated in the ICPS 2015 panel session that is the origin of this Special Section of *Issues in Interdisciplinary Studies* with a presentation on "Philosophical Technology and Transdisciplinary Integration: Adapting to Climate Change in West Michigan." The presentation covered the Toolbox approach after a brief discussion of "values-informed mental models" that inform researchers' ethical and epistemical thinking.

approach was necessary–did not mitigate the conflict in points of view. The negative impact of misalignments related to implementation appeared to overcome apparent agreements" (DuRussel & Derry, 2005, p. 217). So when this philosophical process is not accompanied with a process facilitating metacognitive knowledge and skills at the individual and team level, the impact of such reflections upon the team members' worldviews and the subsequent team research process is likely to be minimal or temporary. First, individual experts must recognize and learn to regulate the manifold cognitive processes and representations that can contribute to but also impede their expert cognition and behavior, at times even leading to suboptimal or inconsistent performance. Second, an interdisciplinary team must engage in metacognition as a team in order to adjust intra-personal as well inter-personal representations. In so doing the team can improve the affective, cognitive, behavioral, and social processes that enable it to bring its project adequately to an end while being prepared to respond to unknowns in a way that might be expected of an interdisciplinary team. Figure 3 represents the process by which a team engages adequately in both metacognition and philosophical reflection and in so doing produces a more comprehensive interdisciplinary understanding.

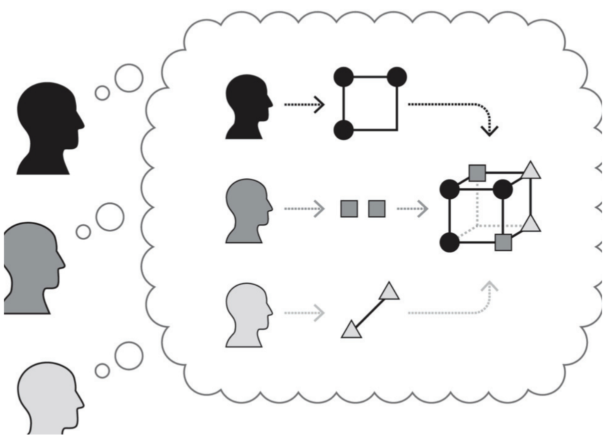

Figure 3. An interdisciplinary team of experts develops together a more comprehensive understanding of a phenomenon – represented by the three-dimensional cube composed of different elements each of them contributes. Their joint or team metacognition and philosophical reflection upon their interdisciplinary collaboration facilitate the process of their development of an interdisciplinary integration of their distinct mental representations of the phenomenon.

## § 3. Concluding Remarks: Interdisciplinary Expert Teams and Their Limitations

In light of the complexity of problems such as interdisciplinary teams attempt to solve and the methodological and theoretical pluralism involved in investigations of these problems, how is it possible that so many of these problems have been solved? How is it possible at all that the cognitive representations experts have been developing about these phenomena have been successfully integrated with each other and implemented into technologies, insights, policies, and understandings that have at least in part fulfilled the aims for which they were developed? The question can invite a metaphysical approach, yet here I've focused on its epistemological nature, partly motivated by the recognition that experts can also be incorrect or err, leading to disasters like the Challenger accident, for which the team's failed handling of a fatal unknown was responsible. After summarizing this article's cognitive-scientific and philosophical insights pertaining to the question, I will close with a brief discussion of a method that seems to me promising in providing a process that helps in the integration of different expert contributions while acknowledging these background conditions and the constraints on the integrative results stemming from these conditions– the process of Reflective Equilibrium.

The first section of this article describes the cognitive processes underlying individual cognition, in which both implicit and explicit mental representations play important roles. Learning and the development of expertise entail that an individual develop not just one but multiple mental representations. Compared to those of a beginner, the representations of experts are much more extensive and complex. Thanks to their assembling a rich "collection" of such complex mental representations pertaining to their field of expertise, experts are able to recognize complex phenomena quickly and respond to them flexibly. New representations develop by way of Representational Redescription of previously developed ones. To a large extent, this occurs implicitly and without requiring experts' conscious efforts. However, experts also devote considerable amounts of time to deliberate practice in which they are repeatedly practicing, monitoring, and evaluating their performance while applying new strategies for correcting or improving it and for further modifying their representations. Such practice implies that experts are learning to engage in metacognition: They have learned to observe and regulate some of their own cognitive processes and representations, which can explain their improving performances. Metacognition is according to this analysis complementary to the philosophical reflection on disciplinary assumptions that is often recommended as an important precursor to interdisciplinary integration of insights. Such reflection on epistemological, metaphysical, and normative assumptions is related to metacognition as these assumptions form in some sense the background conditions for the chunks, patterns, and structures that characterize expert mental representations. However, metacognitive knowledge and skills contribute in a special way to the acquisition and performance of expertise and cannot be replaced by such philosophical reflection.

These insights into cognitive processes and representations and the metacognition supportive of them are brought to bear on interdisciplinary collaboration in section two of this article. In addition to handling the processes and representations involved in expertise, experts functioning in interdisciplinary teams have to coordinate their contributions with those of colleagues from other disciplines. To that end they develop also team mental representations in which task-related, team-related, process-related, and goal-related information about the team project are integrated. I have argued that for interdisciplinary team cognition to be developed adequately, team members need to engage in both individual and team metacognition. Assisted by metacognition, team members coordinate their contributions both in an implicit and in an explicit way, modifying the team mental representations accordingly while adjusting their individual expert representations in parallel. Again, team philosophical reflection on assumptions underlying the disciplinary perspectives of team members does complement team metacognition, yet it does not completely overlap with the team's metacognitive monitoring and regulation of individual and collective cognitive processes and representations. Psychological, affective, and social influences are just a few important factors for team cognition and behavior that deserve to be monitored and regulated with team metacognition.

These insights into the cognitive processes and representations involved in interdisciplinary collaborations, potentially facilitated by metacognition and philosophical reflection, go a long way in explaining how interdisciplinary team cognition is possible. Yet this explanation of how the interdisciplinary integration of insights is possible does not amount to its full explanation. For the realization of an interdisciplinary integration of insights we still need an additional process, a process that bears similarities to both metacognition and philosophical reflection and that takes the pluralism from which we started seriously, while maximizing the coherence among the disciplinary contributions.[40] This requires a reflective balancing act of the team, in which disciplinary contributions are weighed against the team's goals and norms, while acknowledging the uncertainties and incompleteness inherent in knowledge production. Thinking in a similar way, John Rawls has proposed a Reflective Equilibrium process that helps to bring moral convictions, principles or rules, and other relevant beliefs into maximum coherence. Assuming that it is impossible to offer absolute foundations to truths and norms, reaching coherence by balancing elements against each other and refining or revising them where it seems fit is the best option available (Rawls, 1974). Extending this iterative balancing process, it can also include various background theories or assumptions that humans implicitly adhere to while developing considered judgments, theories or assumptions that deserve explicit attention as well (Daniels, 1979).

Taking into account that interdisciplinary team collaboration requires team members to bring their distinct insights to bear on a joint project, while acknowledging that these insights rest upon–often implicit–assumptions and norms, I argue that a similar process can support their efforts. Indeed, applying such a process would render interdisciplinary learning as "the construction of systems of thought in reflective equilibrium" (Boix Mansilla, 2010, p. 298).[41] The account of interdisciplinary team cognition proposed here advises a team and its members to engage in metacognition and in philosophical reflection, helping them to explicitly articulate and deliberate about their individual and team representations, assessing, evaluating, and adjusting them together. For their maximally coherent interdisciplinary integration, Reflective Equilibrium offers a promising method that could play a role as a third component in optimal team process. Particularly when applied in an interdisciplinary team context in which empirical data are taken seriously, it can further assist in problem solving while discouraging self-justification and biased judgments that easily taint disciplinary perspectives (De Vries & Van Leeuwen, 2010).

In other words, interdisciplinary understanding or problem solving requires both individuals and teams to make their disciplinary contributions

[40] There are alternative options available for such a "reflective balancing act" by interdisciplinary teams, each with its own merits, characteristics, and conditions of applicability. Many of these have been presented in Bammer, 2013; Frodeman, et al., 2010; and Hirsch Hadorn, et al., 2008.

[41] In the context of the Toolbox Project's approach to interdisciplinary research, discussed here in § 2.3, Reflective Equilibrium has been suggested as well, enabling the balancing between a priori and a posteriori insights that mutually influence each other in a feedback loop (O'Rourke, 2013).

while also engaging in metacognition, philosophical reflection, and a process of Reflective Equilibrium, the latter being meant to assist in the integration of disciplinary contributions in a maximally coherent and justifiable way. With both individuals and teams adopting these practices, one may hope that a novel unknown, such as that that destroyed the Challenger, will be not only recognized and appreciated by individual experts but also sufficiently and reflectively balanced against other considerations and insights by them and by the team as a whole so as to prevent other such disasters and promote successes in the problem-solving process instead.

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## Appendix: Prompts or Questions for Metacognition

Below is a variety of prompts or questions that elicit metacognition in interdisciplinary individuals or teams. They can target metacognitive knowledge (MK), metacognitive monitoring (MM), or metacognitive regulation (MR).

- How would you rank the value of humanities/social scientific/scientific research or explanations? What value does each type have for you in your work? (MK)
- Based on what properties do you categorize the relevant objects of your research? Would other categorizations be possible? If you use statistics, could you apply another threshold value for finding correlations? If not, why? (MM; MR)
- How does this metaphor or this model of the research topic help you to make connections to experience or knowledge you've gathered previously? Would it be helpful to make some adjustments to the metaphor or model? (MM; MR)
- When you last performed a task like this, what did you do that you should do differently this time? What should you do again this time because it worked well before? (MK; MR)
- Given the interdisciplinary context of your task, how could you modify your usual strategy in performing it? What would perhaps be lost in that case? (MK; MR)
- Do you think it possible confusion about results so far might require you to reconsider some basic assumptions or definitions regarding the problem at stake? (MM; MR)
- Might learning the insights into the problem of other team members prompt you to realize that your initial insights were lacking in some sense? (MM)
- Why do you think that the task you proposed to perform is optimal for solving the problem at stake? Would an alternative route be possible? (MM; MR)
- What goals have you as a team determined and what plan for reaching those goals? What are the issues that might arise with the current plan? Do your answers to these questions vary? (MM; MR)
- When you compare your visual representations of the complex system under scrutiny with those of other team members, can you identify differences among the representations. What features have

been lost or been fore- and back-grounded, for example? (MM)

- Of all the features of the problem under scrutiny, what does and what does not make sense from your disciplinary perspective? Or what is especially difficult to understand? What would you like to know more about? (MM; MR)
- Are you ready to use novel problem-solving strategies or are you inclined to apply those that have worked in the past and avoid others? (MK; MR)

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