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Title:

Interdisciplinary expertise in medical practice: Challenges of using and producing knowledge in complex problem-solving

Names of authors:

MIEKE BOON,[1] SOPHIE VAN BAALEN[1] AND MARLEEN GROENIER[2]

Names of the institutions at which the research was conducted:

[1] Department of Philosophy, University of Twente.

[2] Department of Technical Medicine, University of Twente

Name, address, telephone and fax number, and email address of corresponding author

Mieke Boon

Department of Philosophy,

University of Twente,

PO Box 217,

7500 AE Enschede,

The Netherlands.

Phone: +31(0)534892659

Email: m.boon@utwente.nl

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Abstract

Purpose: Clarification of *interdisciplinary expertise* as the ability to deal with the cognitive and epistemological challenges of multi- and interdisciplinary problem-solving —such as in developing and implementing medical technology for diagnoses and treatment of patients in collaborations between clinicians, technicians and engineers—, and of the *higher-order cognitive skills* needed as part of this expertise.

Method: Clarify the epistemological difficulties of combining scientific knowledge, methodologies and technologies from different disciplines in problem-solving, by drawing on recent developments in the philosophy of science.

Conclusion: We argue that *interdisciplinary expertise* involves the *cognitive* ability to connect, translate and establish links between disciplinary knowledge, as well as the *metacognitive ability* to understand and explain the role of the *disciplinary perspective* —consisting of, e.g., basic concepts, theories, models, methodologies, technologies, and specific ways of measuring, reasoning and modeling in a discipline— in how knowledge is used and produced.

Key words: interprofessional education, adaptive expertise, interdisciplinary expertise, metacognitive skills, higher-order cognitive abilities, epistemology, problem-solving, reflection, disciplinary perspectives, medical technology.

Practice Points

- Preparing health professionals for complex problem-solving tasks requires teaching interdisciplinary expertise.
- Deeper epistemological (i.e., 'knowledge theoretical') difficulties of knowledge-integration are analyzed by means of recent insights in the philosophy of science.
- This may contribute to better understanding difficulties of multi- and interdisciplinary collaborations.
- Experts may not be aware of the role of disciplinary perspectives in how they use and produce knowledge, which hampers effective teaching of interdisciplinary expertise and interdisciplinary collaboration.
- Interdisciplinary expertise involves the higher-order cognitive ability to understand and make explicit the contributions of *disciplinary perspectives* (entailing basic concepts, methods, technologies, and specific ways of measuring, reasoning and modeling) to the character of knowledge.

Introduction

Today's rapidly evolving health care systems require clinicians who are capable of meeting complex challenges (Mylopoulos et al. 2018). The increasingly central role of innovative medical technologies in many medical specialties (World Health Organization, 2010a) makes the demands on medical experts even more challenging.

Text box 1: Example of developing and implementing technology: *Proton therapy* for the treatment of cancer

The development of this therapy involves combining knowledge of the technology —including particle accelerators to produce the proton beam, imaging modalities for treatment planning, and robotics for optimal dose delivery— with biomedical knowledge of (molecular) biology and the treatment of individual cancer patients. The development of this kind of complex biomedical technologies, therefore, requires interdisciplinary collaboration between (biomedical) engineers, technicians and physicians, and once the technology has been implemented, physicians must collaborate with technicians to actually apply this technologically complex treatment and to analyze the effects on individual patients.

There has been an ongoing call to transform health education in order to prepare health professionals for the increasingly complex challenges. The overarching goal of this educational transform is to strengthen health systems and achieving excellence in patient care (World Health Organization 2010b; Frenk et al. 2010; Gilbert et al. 2010). Dealing with complex problems requires the application of medical and scientific knowledge and methods, and usually involves *interprofessional* collaborations. With the increasing role of medical technology, health professions education (HPE) also needs to prepare for interdisciplinary collaborations with technologists and engineers. This is particularly crucial for the effective *development* and *implementation* in clinical practice of novel, often complex medical technology for diagnosis and treatment of patients (see Text box 1). However, the full potential of interdisciplinary teams is not always exploited, while the integration of disciplinary perspectives in multidisciplinary teamwork can contribute to better healthcare for individual patients (Acquavita et al. 2014; Becker and Schnell 2017).

It is commonly assumed that limits to interprofessional and interdisciplinary teamwork is due to problems with communication, collaboration and cooperation (Clark 2004), linked to barriers and enablers at institutional, organizational, infrastructural, professional and individual levels (e.g., Choi & Pak 2007; Lawlis et al. 2014). Yet, in addition to these well-known aspects, limitations may also be due to inherent *cognitive* and *epistemological* (knowledge-theoretical) issues. Our focus is on professionals in medical practice who develop new knowledge in inter- and multidisciplinary collaborations for solving complex clinical problems, including those related to medical technology. We introduce the notion of *interdisciplinary expertise* as the ability to deal with the cognitive and epistemological challenges of interdisciplinary problem-solving, and suggest that developing interdisciplinary expertise requires teaching and learning specific *higher-order cognitive skills*.[1]

[1] We will use the notions 'higher-order cognitive skills' and 'metacognitive skills' interchangeably.

The HPE literature approaches the development of professionals who are able to deal with complex challenges through various relevant themes. Interdisciplinary collaboration is addressed in the literature on *interprofessional education*, while the ability to use and produce knowledge and methods in solving (novel) problems is called *adaptive expertise*, which encompasses topics such as clinical reasoning, integrating basic and clinical sciences, transfer of knowledge, and preparation for future learning (PFL). Building on this literature, we will clarify epistemological and (meta)cognitive aspects of interdisciplinary collaborations in complex problem-solving by using recent insights of the *philosophy of science*.

Interprofessional education (IPE)

The need for interdisciplinary and interprofessional (multidisciplinary) health care teams has been promoted since World War II as a means for providing comprehensive and continuous care (De Witt 1996). Problems with communication, collaboration, and cooperation are seen as endemic (Clark 2004) and spark calls for the development of new programs to teach health professions students how to work together collaboratively and more effectively in interdisciplinary teams (Knebel & Greiner 2003). This has resulted in a strongly developed educational research tradition called *interprofessional education* (IPE). Currently, the broader societal aim of IPE is to align interprofessional health care education and healthcare system transformation. Interprofessional *education* occurs when students from two or more professions learn about, from and with each other to enable effective collaboration and improve health outcomes (WHO 2010b). Accordingly, IPE aims at training effective communication across multiple healthcare disciplines and professions, which is considered critical to ensure the delivery of safe and efficient care (see e.g. the literature review by Abu-Rish et al. 2012). Once students understand how to work interprofessionally, they are ready to enter the workplace as a member of the collaborative practice team. IPE, therefore, is also called educating for collaborative practice (Hudson & Croker 2018).

It is remarkable, however, that in specifications of interprofessional learning competences there is usually no reference to the specific knowledge-theoretical (i.e., epistemological) difficulties and the required higher-order cognitive skills that play a role in *interdisciplinary collaborations*. The professional aim of IPE is high-quality, patient-centered, team-based (collaborative) care, which requires learning specific concepts, competencies and skillsets (e.g. Becker & Schell 2017). Knebel and Greiner (2003) promote a *competency-based* approach to medical education and list core competencies, such as the ability to provide patient centered care, work in interdisciplinary teams, employ evidence-based practice (i.e., integrate best research with clinical expertise and patient values), apply quality improvement, and utilize informatics (i.e., communicate, manage knowledge, mitigate error, and support decision making using information technology). Similarly, based on reviewing international interprofessional competency frameworks, O'Keefe et al. (2017) have identified a (single) set of common, assessable interprofessional learning outcomes. In medical education research, it is argued that these competencies and skillsets are best trained by means of interprofessional experiences in practice-based setting in medical education that are professionally supervised (e.g., Shrader & Zaudke 2018).

In our view, the competencies aimed at in interprofessional education commonly focus on what can also be called *professional responsibility* regarding the patient, the team and other stakeholders. This responsibility encompasses aspects such as a professional attitude (including respect and ethics), the professional ability to manage situations, to communicate and collaborate, and to recognize the relevance of other disciplines to solving a problem. In order to highlight the *epistemological* requirements in clinical decision making, Van Baalen & Boon (2015, 2017) have introduced the concept of *epistemological responsibility* of clinicians for their clinical decisions, which focuses on the responsibility to collect, critically appraise, interpret and fit together heterogeneous information relevant to the diagnosis and treatment of a specific patient in a specific situation – for instance, the individual patient's clinical record, on the one hand, and more general scientific and clinical knowledge, on the other hand. Based on the collected heterogeneous, and usually incomplete or incoherent information, clinicians must construct a coherent (mental) 'picture' or 'story' that enables further reasoning about the patient's condition (see Text box 2). In other words, acting as an epistemologically responsible professional involves using and producing knowledge in a reliable and relevant manner such as to arrive at good quality diagnosis and treatment, for which health professionals can be held accountable.

Text box 2: Knowledge integration: Constructing a 'picture' of the patient.
Van Baalen & Boon (2017, 2015) have analyzed the discomfort of medical doctors with the role of evidence based medicine (EBM) in decision-making regarding the diagnosis and treatment of patients. They argue that, rather than simply following EBM guidelines, the epistemological challenge of doctors involves gathering and integrating relevant, yet heterogeneous pieces of information, such as scientific-medical knowledge of diseases and treatments (including EBM guidelines), diagnostic data on the patient and also contextual information (e.g., the patient's situation, goals and values, the availability of specific medical equipment and expertise, and the constraints of the medical system), in order to construct a coherent 'picture' ('story' or 'model') of a specific patient's disease and possible treatments. Constructing this 'picture' and using it in clinical decision-making crucially requires the *expertise* of doctors, rather than being a rule-based activity guided by one or another algorithm.

From an epistemological perspective, the professional task of clinicians is therefore already inherently interdisciplinary in the sense of bringing together, integrating and reasoning on the basis of local information and general (scientific) knowledge from different sources. This is a complex epistemic task, and collaborations with experts from other disciplines such as (biomedical) engineering will only increases the epistemic complexity. That is why the valuable ambitions of educating interdisciplinary health professionals require reflection from an epistemological perspective on the kind of expertise needed in interdisciplinary problem-solving.

Our conception of epistemological responsibility is taken as the basis for defining *interdisciplinary expertise*: it requires the ability to collect relevant information from different disciplinary sources, and to combine these heterogeneous bits of information into a coherent, adequate and relevant 'story,' 'picture' or 'model' that helps in understanding, reasoning and decision-making about the clinical problem. In more complex cases this also requires *interdisciplinary collaborations*. Our purpose is to further clarify this notion of interdisciplinary expertise and the higher-order cognitive skills crucial to actually exercise it.

Adaptive expertise

Interdisciplinary expertise requires the cognitive ability to integrate or combine knowledge from different sources and to transfer knowledge from one domain to another such as to generate *new* knowledge for novel problems. This notion is very much similar to the concept of *adaptive expertise* (e.g., Schwartz and Bransford 2005; Mylopoulos & Regehr 2007, 2011), which assumes that the quality of diagnostic reasoning requires the cognitive ability to integrate, combine and transfer knowledge by which new knowledge is generated. Examples are: the ability to integrate knowledge from different sources (Kim & Lee, 2001), to integrate basic sciences and clinical science in order to understand the causal mechanisms of diseases (Woods 2007; Woods et al. 2007; Goldszmidt et al. 2012; Kulasegaram, Martinianaks et al. 2013; Mylopoulos & Woods 2014; Kulasegaram, Manzone et al. 2015; Woods & Mylopoulos 2015a,b; Lisk et al. 2016, 2017; Bandiera et al. 2018; Cheung et al. 2018), to integrate one's expert knowledge with the knowledge gathered from the patient narrative (Mylopoulos et al. 2018), and to apply previously learned knowledge, concepts and methods to solve new problems in another (future) context, which is referred to as *transfer* (Castillo et al. 2018; Kulasegaram, Min et al. 2015; Liv and Tolsgaard 2018).

Interdisciplinary expertise broadens the concept of adaptive expertise which was introduced by Hatano and Inagaki (1986) as an extension to so-called *routine expertise*. Routine experts, according to Hatano and Inagaki, have learned to perform procedures effectively, which involves knowledge and skills, such as decision rules, executive strategies, and the skills necessary to apply that knowledge. These skills and knowledge are acquired through direct observation, verbal instructions, corrective feedback, and/or supervision. *Adaptive experts*, on the other hand, also *understand* the meaning of the procedural skills. Mylopoulos and Woods (2009) explain the concept of adaptive expertise as follows: "Adaptive expertise is an evolving construct, broadly understood as encompassing all the core competencies of routine expertise, as well as *additional cognitive and metacognitive processes*. Efficiency in practice [based on routine] is not eliminated, but, rather, is complemented, which allows adaptive experts to *interpret* and respond to new situations in a way that recognises the *assumptive nature of knowing* and the importance of *reflective practice*. As a result, rather than viewing problems solely as platforms to which to apply knowledge, adaptive experts are able to approach problems as opportunities to innovate, to *construct new ideas*, learn and improve practice" (Mylopoulos & Woods 2009, 409, our emphasizes).

HPE researchers have aimed to develop and operationalize this enriched notion of expertise in educational programs to train professionals who are capable of *generating new knowledge* and tackle new problems in their field. Much research has been carried out to investigate and test which abilities are crucial to adaptive expertise, how these abilities can be trained, and also, to understand particular cognitive and metacognitive processes underlying features of expert performance. Examples of such cognitive and metacognitive processes are: mechanisms and key competencies by which integration is achieved (e.g. Mylopoulos et al. 2017; Kulasegaram, Manzone et al. 2015), mechanisms that facilitate transfer of basic science (Kulasegaram et al. 2017), cognitive structures and mechanisms by which experts versus novices organize knowledge (Mylopoulos & Woods 2009), and mechanisms by which new understandings and ideas are generated (Mylopoulos & Regehr 2011).

Interdisciplinary expertise can be taken as an extension of the concept of *adaptive expertise*, firstly by extending the scope of problems in medical practice beyond diagnostic problems or clinical reasoning to the development and implementation of medical technology. Secondly, by including the cognitive ability to participate in interdisciplinary collaborations with other, unfamiliar, (scientific) disciplines. In order to develop the notion of interdisciplinary expertise, we will first aim to explain in more depth the cognitive and epistemological aspects of adaptive expertise.

A model of the relationship between cognitive abilities and knowledge-structures

A finding that stands out in most of the mentioned educational research is that the processes through which learners develop the ability to combine, integrate and transfer knowledge —which includes knowledge of basic scientific concepts and mechanisms, clinical signs and symptoms, case examples and technical skills— requires that knowledge becomes more and more *organized* in the expert's mind (Castillo et al. 2018; Mylopoulos & Woods 2009).

The way in which authors conceptualize the development of adaptive expertise can be summarized in a model that distinguishes the development of (meta-)cognitive skills and understanding from the development of (cognitive) knowledge-structures.[2] Adaptive experts organize, access, combine and produce knowledge in ways that may fundamentally differ from that of the novice (Mylopoulos & Regehr 2007, 2011; Mylopoulos & Woods 2009), which is attributed to the cognitive ability to *structure* and *integrate* ('in their minds') knowledge and concepts (e.g., of basic and clinical science), thereby achieving *cognitive integration* (Kulasegaram et al. 2013). This specific cognitive ability enables them to build knowledge-structures and improve their conceptual understanding (e.g., of a disease) (Lisk et al. 2016, 2017; Bandiera et al. 2018), which in turn, enables them to *transfer* their knowledge to applications in unprecedented problems (Castillio et al. 2018; Kulasegaram et al. 2013, 2017). The cognitive abilities are needed to structure knowledge and integrate it into knowledge-structures, which generate conceptual understanding. This conceptual understanding further supports the cognitive ability to use and produce knowledge-structures when solving complex problems. But then, how does the resulting knowledge-structure add to the cognitive ability to use and produce knowledge? This process may be better grasped by also interpreting it from an *epistemological* point of view, in which an expert's ability to use and produce knowledge also depends on features of the knowledge-structure that she has developed.

Fundamental epistemological questions

Focusing on features of the intricate and coherent knowledge-structures that experts build up 'in their mind' and how this allows for different types of reasoning by adaptive and interdisciplinary experts about complex and interdisciplinary problems, raises several fundamental epistemological questions whose answers may further our grasp of how to develop it, such as: (1) What is the nature of knowledge-structures, (2) How do knowledge-structures enable an expert's thinking and reasoning, (3) What is interdisciplinary problem-solving, (4) Why is expertise in using and producing knowledge so difficult to

[2] The notions 'knowledge-structure' and 'conceptual structure' are used interchangeably.

acquire, and (5) Are there ways to mitigate this learning process? Section numbers below refer to these five questions.

(1) The nature of knowledge-structures: Epistemology, or, Beliefs about knowledge

Castillo et al. (2018) suggest that the ability to apply basic knowledge to a (new) problem (i.e., to 'transfer-out') requires a *deep conceptual understanding*. It involves identifying the similarity between the problem and the basic scientific concept that is part of the deep (conceptual) structure. Novices, however, when encountering a new problem, are more likely to compare it with his or her mental representations based on surface-level cues ('it is what it is'), whereas an expert 'sees' the problem in terms of an underlying principle.

From a philosophical perspective, the difficulty of applying knowledge that one is not already familiar with, may have to do with the conviction that (scientific) knowledge objectively and literally describes (underlying) aspects of the world. This belief about the nature of objective knowledge is called *empiricism* or *positivism*. Thomas Kuhn (1970), based on historical and philosophical studies of the development of science, argued that scientific knowledge is not objective in this sense. More fundamentally, Immanuel Kant (1781) argued against the empiricists of his days that objective knowledge is not generated by passive observations. 'The world does not speak for itself' in the sense that observations create impressions in our minds that automatically generate objective 'bits of knowledge.' Instead, the human cognitive system plays an inherent and indelible role in generating knowledge based on observations and experiences of the world.

By structuring and interpreting 'impressions,' or 'raw data' as we would call it now, the human mind generates bits of *meaningful knowledge*. How does such structuring work? According to Kant, humans inevitably employ and invent all kinds of *concepts* to structure and interpret raw, unorganized and uninterpreted impressions. In other words, concepts that sprout from the human mind are needed to see and describe something. Even at the most basic level, concepts such as 'objects,' 'properties,' 'causal relationship,' 'interactions,' 'functions,' 'chance' and 'necessity' *structure* impressions, thereby generating knowledge. Also at more complex levels, organizing, interpreting and drawing meaningful links between bits of knowledge happens all the time, such as when we formulate sentences to describe observations, craft mathematical formulae to connect measured data, and construct pictures, schemas and models to represent and systematize observations and ideas.

In this manner, researchers and experts also create *new* concepts (such as categories for specific diseases) and *new* relationships (such as causal relationships or correlations to explain or predict that disease). Although there is much freedom in how this is done, both the (physical) world and concrete (disciplinary) practices set limits to what is accepted (cf. Kuhn 1970). In professional and research practices, this is where epistemic and pragmatic criteria come into play, such as the *adequacy*, *consistency*, *coherency*, *simplicity* and *intelligibility* of knowledge (including concepts, descriptions, causal relationships, correlations, generalizations, explanations and mechanisms) (Boon 2012, 2017).

Without these kinds of cognitive activities, that is, without employing and inventing concepts to *interpret, structure and systematize information*, there is no knowledge – not even at the most basic level of immediate experiences. This implies that the cognitive and epistemological parts of an expert's understanding are inextricably linked. A better understanding of the higher-order cognitive abilities that both adaptive and interdisciplinary experts need in order to use and generate knowledge-structures, therefore, must take into account this philosophical insight about knowledge generation 'in the mind of an expert' (Boon 2012).

(2) Knowledge-structures in the expert's mind: Knowledge as epistemic tool

How does the proposed notion of a 'knowledge-structure' in problem-solving and clinical reasoning differ from the idea of knowledge as *objective descriptions of facts* and of *rules that connect facts*? And why does it fit better with adaptive and interdisciplinary experts who use and produce knowledge in complex problem-solving tasks? Philosophically, the suggested alternative view of knowledge is called *epistemological constructivism*. This alternative view does not only transcend positivist but also so-called social constructivist notions of knowledge. The idea that knowledge is not objective in the positivist sense does not force us to believe that knowledge is merely subjective —i.e., socially constructed based on communication and negotiation only— since it is also epistemological in the sense of striving to meet epistemic criteria such as adequacy and coherence (Boon 2017), which is grasped by the idea that experts bear epistemological responsibility (Van Baalen & Boon 2015, 2017).

How does this alternative view of knowledge work? Let's take the 'picture' of a specific patient (see Text box 2) as an example of a small, more or less confined knowledge-structure. The epistemological issue is that this 'picture' must not be understood as a *literal description* of (aspects of) the patient. Instead, the 'picture' has been *constructed* by the clinician such that it can be used in her clinical reasoning about the patient. An expert can *reason* upon this 'picture' in many different kinds of ways, such as, explaining symptoms in terms of a possible disease, or explaining a disease in terms of basic knowledge, or inferring from diagnostic tests to a disease, or drawing analogies with other known cases, etc. Another example is the confined knowledge-structure that a clinician has about a *disease*. Similar to the 'picture' of the patient, it consists of heterogeneous aspects that are coherently linked together, such as knowledge about signs and symptoms that indicate the disease, knowledge of how to diagnose the disease, scientific explanations of the disease, knowledge about possible treatments of the disease including their (side-) effects, and knowledge about the workings of relevant medical technologies. Clearly, these two different kinds of knowledge-structures, about the patient and about the disease, may need to be linked together as well in order to allow further reasoning processes. Hence, smaller knowledge-structures can become mutually connected and generate (parts of) the broader knowledge-structure that the expert has 'in her mind.' Conversely, the construction of confined knowledge-structures such as 'pictures' of the patient or of a disease is enabled and guided by this broader knowledge-structure, which thereby expands all the time.

The question remains how knowledge-structures enable an expert's reasoning. We envision such reasoning as being enabled and guided by the *links* in the knowledge-structures. The links —which can also be called more formally, *relationships* between A and B— may be of many different kinds, such as correlations (A correlates with B), statistical relationships (if A is the case, also B may be the case or happen), causal relationships (A causes B), explanations (A explains B), properties (A is a property of B), categories and classifications (A is of kind B), signs or signals (A implies that B is the case), meanings (A must be understood as B), similarities (A is similar to B), and interpretations (A is usually interpreted as being a B). It is through these links in the knowledge-structure that reasoning based on it is possible. Conversely, based on learning new (scientific and clinical) knowledge, as well as on observations and experiences in practice, experts draw (new) links between *heterogeneous* bits of knowledge. This is not always an entirely rule-based, algorithmic or deductive reasoning process —as for instance in the deductive uses of rules to infer to a conclusion, or in causal or mechanistic reasoning to link basic and clinical knowledge. Usually, it also involves creative, interpretative and imaginative reasoning processes in the sense suggested by the philosophical (Kantian) view on knowledge generation, grasped by the notion *epistemological constructivism* outlined in the previous section. As a consequence, the resulting new knowledge-structures are not 'obvious' for non-experts and novices, which may be one of the reasons why becoming an expert is difficult (Khushf 1999; Procee 2006).

Summing up, the knowledge-structure 'in the mind of an expert' encompasses and links together heterogeneous bits of knowledge, consisting of phenomenological, experiential, empirical, clinical and scientific knowledge about an object (e.g., a kidney). The expertise of clinicians consists in the ability to construct these 'pictures' of objects by skillfully gathering and coherently linking together these pieces of knowledge, and to utilize the resulting 'pictures' for thinking and reasoning about the object, which is enabled and guided by the *links* created between the pieces of knowledge in the 'picture' (i.e., a knowledge-structure). The proposed alternative epistemology suggests that this 'picture' must not be understood as a *literal description* or *representation* of the object (as in a photo), but rather as a *tool for thinking* about the object. More formally, knowledge about objects that enable thinking about these objects, such as concepts, 'pictures,' knowledge-structures and models, are called *epistemic tools* (Boon & Knuuttila 2009; Boon 2017a,b; Boon and Van Baalen forthcoming). Experts have developed the cognitive ability to expertly use the knowledge-structure as a tool for thinking about an object (i.e., as an epistemic tool), first to classify or interpret a problem, and then to expertly reason about it by combining deductive, inductive, abductive (explorative and investigative) and creative ways of reasoning.

(3) Interdisciplinary expertise

Disciplinary experts excel in their domain because they can rapidly detect relevant information, are successful at self-monitoring, have effective problem-solving strategies and are capable of generating the most satisfactory solutions (Chi, 2006). However, Chi (2006) notes that there are also drawbacks to being an expert. Expertise is highly domain-specific and disciplinary experts might apply pre-existing knowledge to non-routine or unfamiliar situations without the ability to see new possibilities or greater complexity (also see Mylopoulos & Regehr 2007). Especially in emerging fields, *adaptive expertise* is crucial (Palonen et al. 2014). We have indicated changes in medical practices due to the increasing role of technology as a prominent example. Participating in these innovations requires the ability to use knowledge more flexibly and to collaborate with other, unfamiliar disciplines.

We suggest that, similar to the cognitive ability to *apply* one's extensive knowledge base and to *create* new knowledge aimed at the patient's needs and context in adaptive expertise in the sense outlined by Myopoulos et al. (2018), *interdisciplinary problem-solving* requires the cognitive ability to also connect or integrate knowledge and methods from different disciplines. Interdisciplinary collaborations, therefore, require a specific type of expertise, which expands on adaptive expertise and which we call *interdisciplinary expertise*. Nonetheless, we side with Palonen et al. (2014) that the ability of knowledge creation in new environments is deeply dependent on the *disciplinary* knowledge bases, and equally important to interdisciplinary expertise. In interdisciplinary collaborations between clinicians, technicians and engineers who aim at developing and implementing novel medical technology, interdisciplinary expertise involves effectively integrating or combining knowledge and methods of different types of disciplines (medical and technological) into solutions that are both technologically sound and medically appropriate.

Several authors have argued that adaptive expertise requires *metacognitive* skills (e.g., Carbonell et al. 2014; Lajoie 2009). Authors in the literature on learning and teaching interdisciplinarity also claim that interdisciplinary thinking is a higher-order or metacognitive skill, which involves the ability to search, identify, understand, critically appraise, connect, and integrate theories and methods of different disciplines and to apply the resulting cognitive advancement together with continuous evaluation (e.g., Ivanitskaya et al., 2002; Lourdel et al. 2007; DeZure 2010; Zohar & Barzilai 2013; Goddiksen & Andersen 2014). However, this literature remains largely silent on what these skills consist in, how they can be taught, and why it is difficult to teach and learn (Boon & Van Baalen forthcoming). We argue that the ability to recognize the workings of *disciplinary perspectives* is an important metacognitive skill of interdisciplinary experts, and additionally, that *understanding* the meaning of this ability (in the sense of Hatano & Inagaki outlined above) may be obstructed by general (positivist) beliefs about knowledge, which we aim to clarify and overcome by philosophical reflection and an alternative view of knowledge.

(4) The role of disciplinary perspectives in interdisciplinary problem-solving

MacLeod and Nersessian (2013) and MacLeod (2016) have studied scientific research in biomedical and engineering labs in order to better understand why interdisciplinary research is so difficult. They show that each discipline consists of a coherent body of specificities —MacLeod (2016) calls this *domain-specificities*— that determine how a discipline approaches (scientific) problems. These specificities cannot be easily communicated, which makes the effective collaboration across disciplines[3] difficult. We use the notion 'disciplinary perspectives' to explain these difficulties from an epistemological perspective. What are disciplinary perspectives and how do they work?

Kuhn (1970) expands on Kant's epistemology by claiming that knowledge is not only shaped by concepts 'in the mind,' but also by practical, technological and intellectual aspects that constitute a discipline These other aspects have been historically established by partly contingent, practical, technological and intellectual developments of a specific (scientific) practice. Kuhn's major contribution was to emphasize the indelible role of this 'hidden' background —called *paradigms* by Kuhn and *disciplinary perspectives* by us— in the construction of knowledge (Andersen 2013, 2016; Boon 2017a,b; Boon & Van Baalen forthcoming). This philosophical insight thus rejects positivist ideas about (scientific) knowledge even more thoroughly. Nonetheless, positivism is still deeply ingrained in many scientific and professional

[3] The notions 'discipline,' 'domain,' 'specialization,' and 'specific practice' are used interchangeably.

practices and it supports metaphors about knowledge integration that hide inherent problems of interdisciplinary problem-solving. One is that pieces of knowledge from different disciplines are fitted together as in a jig-saw puzzle. On this metaphor, linking and integrating knowledge from different disciplines is more or less straightforward.

A disciplinary perspective is a cognitive framework that an expert has developed by being educed within a certain discipline. The basic epistemological idea is that knowledge in a discipline is indelibly shaped by the specificities of the discipline, such as basic concepts, (scientific and clinical) knowledge, methods, technologies, and specific ways of measuring, reasoning and modeling. These specificities form the disciplinary perspective, which in that sense is a cognitive framework that experts need to acquire. The important point is that experts cannot use or produce knowledge without it – they cannot look 'behind' the perspective, and therefore, knowledge is not objective or literal or 'obvious' in ways suggested by a positivist view of knowledge. Instead, the disciplinary perspective enables her to 'see' specific aspects of an object (e.g., in terms of specific categories), to interpret or explain these 'observations' in specific ways (e.g., in terms of scientific knowledge), to ask specific types of questions about these 'observations' (e.g., about other, not yet manifested symptoms or signals), to come up with possible interventions (e.g., specific treatments fitting to the disease), and to generate novel hypotheses (e.g., drawing new connections or interpretations when faced with new information, for instance from other disciplines).

Experts in different disciplines have become acquainted with the perspective specific to their discipline, and they are usually not aware of 'having a perspective.' However, their disciplinary perspective typically determines how they see and approach a problem, which in our view is an important reason why interdisciplinary problem-solving is so difficult. Therefore, our notion of interdisciplinary expertise entails that experts must, at a metacognitive level, be able to understand the working of their disciplinary perspective and to explain how this guides and enables their different ways of reasoning about problems. The ability to make the disciplinary perspective explicit is a metacognitive skill. This idea may be taken as an elaboration on Mylopoulos and Scardamalia (2008), who argue that *processes of knowledge production*, in which adaptive experts transfer and translate their knowledge, must become an object of reflection and collaborative formation of ideas on how to improve the ways in which solutions to problems in health care practices are generated. Our analysis may provide a vocabulary to facilitate this.

Hence, important for understanding interdisciplinary collaboration is the realization that disciplinary experts will 'look at' their object through their *disciplinary perspective* (as through a technological instrument that shows specific aspects, but not others). They will 'see' or 'filter-out' aspects that can be dealt with in their own discipline (Chi 2006). Text box 3 gives an example of research in which several disciplinary perspectives need to be combined. Having *interdisciplinary expertise* therefore not only involves the *cognitive ability* to effectively gather and establish links between heterogeneous pieces of knowledge about an object (to produce a specific knowledge-structure that enables further reasoning). In interdisciplinary collaborations it also involves the *metacognitive ability* to recognize and deal with the role of disciplinary perspectives – firstly by understanding that knowledge cannot be understood as literal or 'obvious,' because knowledge generated in a discipline is indelibly interwoven with its basic concepts, methods, technologies, and specific ways of measuring, reasoning and modeling, and secondly, by being able to analyze or explain how the disciplinary perspective shapes knowledge in their discipline.

Text box 3: Example of disciplinary perspectives in interdisciplinary collaboration
Developing an MRI imaging technology for the diagnoses for kidney diseases (Van Baalen et al. 2017) involves several disciplinary perspectives, such as: (1) MRI physics, which enables reasoning about the mechanism of producing and recording the signal in interaction with tissue, (2) image-processing, which enables reasoning about the parameters that can be obtained from this signal and how these parameters can be visualized, and (3) nephrology, which enables the deduction of how certain pathologies will affect kidney tissue. Understanding how changes in kidney tissue affect the MRI signal and how that can be visualized by the imaging technology requires *effectively combining* knowledge, methods and technologies of these disciplines. Effective interdisciplinary collaboration requires awareness of having a distinct disciplinary perspective in each discipline and the ability to explain how it provides knowledge.

(5) Learning and teaching interdisciplinary expertise

Summing up, several reasons can be given of why learning and teaching interdisciplinary problem-solving is difficult (i.e., our fourth question). Firstly, we have suggested that the 'picture' of a patient, and confined knowledge-structures more generally, must not be understood as a *literal description* of an object but rather as *epistemic tools* that enable different kinds of reasoning about the object. However, this may be a view about knowledge that does not easily fit with common intuitions. Secondly, we have argued that *disciplinary perspectives* determine how experts use, produce and understand knowledge-structure(s). However, the disciplinary perspective is usually not explicitly taught, but gets internalized as an inherent dimension of their expertise to the extent that experts are not even aware of having a specific perspective. What they actually 'see' or describe may even be experienced by them as a kind of literal picture or description. Experts may therefore experience difficulties in understanding why novices do not just 'see' and understand their profession. Third, it seems generally accepted that becoming an expert is difficult, and that someone's expertise can best be developed by taking part in that practice. This approach can work well enough within the disciplines, but can be a cause of epistemological difficulties in interdisciplinary problem-solving.

How do these insights help to develop interdisciplinary expertise and are there ways to mitigate the learning process? We suggest that a first step towards acquiring the higher-order cognitive skills needed to participate in interdisciplinary collaborations —such as in developing and implementing medical technology— is to make students aware of the role of *disciplinary perspectives* in the generation of knowledge (e.g., as in Text box 3). For example, students can be trained to recognize how a disciplinary perspective shapes what experts within a certain discipline 'see' when they study a certain object, and how they have constructed knowledge-structures about objects. Experts in one discipline (e.g., clinicians) will 'see' different aspects of the object to experts in another discipline (e.g., engineers). Not only will they 'see' different aspects, they will also formulate different problems, ask different questions in order to understand the problem, refer to discipline-specific experiential and theoretical knowledge, invoke different methods (e.g., for retrieving additional information) and technologies (e.g., for diagnostic purposes), and form hypotheses and explanations typical of the discipline, which is how discipline-specific knowledge-structures about objects get constructed. In this manner, teachers can illustrate and make explicit to students how disciplinary experts deal with an object from their disciplinary perspective – in other words, what question they ask, how they perform measurements, how they draw conclusion about the object, etc. in order to craft a 'picture' or 'model' of an object. A recently published general methodology for constructing models can help in learning how to do this in a systematic manner (Boon forthcoming).

With these suggestions, we have not given a specific proposal for curriculum design for teaching interdisciplinary expertise, but we have provided some basic strategies for acquiring the higher-order cognitive skills required for interdisciplinary problem-solving.

Summary and Conclusions

The rapidly evolving and increasingly (technologically) complex health care system generates complex challenges, which requires medical professionals who have the cognitive ability to collaborate effectively with experts from other disciplines, for which HPE needs to prepare them. Interdisciplinary collaborations between clinicians, technicians and engineers who aim at developing and implementing novel medical technologies is used as an example. We argue that these kinds of interdisciplinary collaborations require *interdisciplinary expertise*, which is the ability to deal with the cognitive and epistemological challenges of interdisciplinary problem-solving, and we suggest that developing interdisciplinary expertise requires teaching and learning specific *higher-order cognitive skills*.

It is generally acknowledged that interdisciplinary problem-solving is difficult, which is usually explained in terms of professional or institutional difficulties. We focus on an *epistemological* (knowledge-theoretical) explanation. The nature of knowledge, but also misunderstandings thereof, may cause that knowledge and methods of different types of disciplines (medical and technological) are difficult to integrate or combine in interdisciplinary problem-solving. In our explanation, we make use of recent insights in the philosophy of science. We show that a positivist view of the nature of knowledge is inappropriate and supports the erroneous metaphor that integrating and combining knowledge from different disciplines is like merging pieces as in a jigsaw puzzle. We summarize an alternative (philosophical) view of knowledge (*epistemological constructivism*), which puts emphasis on the tool character of knowledge: knowledge is produced for epistemic uses, which produces new knowledge. In medical practice, clinicians skillfully gather and link relevant pieces of knowledge from different sources. In this manner, they construct a 'picture' of each individual patient. However, this 'picture' is not a literal description of (aspects) of the patient, as a positivist view of knowledge would suggest. Instead, the clinician has created a *structure* that coherently links the heterogeneous pieces of knowledge. The 'picture' of the patient, therefore, is a confined *knowledge-structure*, and we explain how the character of this knowledge-structure enables clinicians to use it as a tool (i.e., an *epistemic tool*) for further thinking and reasoning about the patient. The ability of clinicians to produce and use knowledge-structures in this very sense, suits well with the notion of *adaptive expertise*. Our epistemological analysis adds by explaining: (1) The nature of these knowledge-structures, and (2) How knowledge-structures enable an expert's thinking and reasoning that goes beyond mere deductive or inductive reasoning, and why the cognitive ability of adaptive experts to gather relevant knowledge and construct coherent 'pictures' that enables further reasoning about patients or diseases (which is also called *understanding*) is difficult to acquire.

This epistemological analysis is taken a step further by explaining the role of *disciplinary perspectives* in the construction of knowledge, in order to address the next question (3): What is the nature of interdisciplinary problem-solving. A disciplinary perspective consists of a coherent set of aspects —such as practice goals, phenomena or objects of interest, specific ways of measuring, reasoning and modelling, specific knowledge (concepts, models, theories), methodologies and instruments, practical constraints, epistemic values and professional or scientific ideals— that are conveyed and maintained in a discipline. This set of aspects constitutes the background within which an expert educated in the discipline uses and produces knowledge. The disciplinary perspective is crucial to expertise, because it enables an expert to 'see' or 'filter-out' specific aspects, ask relevant questions and give appropriate explanations, which may be 'invisible', meaningless and incomprehensible to a novice. This, however, also explains question (4): Why is expertise in using and producing knowledge so difficult to acquire. Expertise is often trained by doing. The disadvantage of this approach to education is that experts are often unaware of how their disciplinary perspective works and how this affects the way they construct knowledge and approach problems. They may consider their knowledge 'straight-forward' and 'obvious,' while exchanges with novices and experts from other disciplines would also require disclosure of how the disciplinary perspective plays a role in their approach. The crux of our argument is that disciplines do not generate bits of knowledge that can be easily combined as in a jig-saw puzzle – as a *positivist* view of knowledge suggests. Instead, knowledge generated in a discipline, such as the 'picture' (or knowledge structure) about a specific patient, is indelibly entangled with the specific *disciplinary perspective*. Therefore, we argue that interdisciplinary expertise expands on adaptive expertise, in that it involves the metacognitive ability to recognize and make explicit the role of disciplinary perspectives.

Finally, we briefly address question (5) Are there ways to mitigate this learning process? We suggest that curriculum design that aims to create professionals capable of interdisciplinary problem-solving must take into account the inherent epistemological difficulties of combining (scientific) knowledge, methodologies and technologies from different disciplines in research and problem-solving tasks. Further collaborative educational and philosophical research is needed to develop this insight and to translate it into new methods and pedagogies.

Glossary

Epistemology: Concerns (philosophical) questions of what knowledge is and how knowledge is justified. Generally speaking, epistemological theories seek to illuminate the nature, scope, and utility of knowledge. To this definition we add focus is on how (scientific) knowledge is constructed (i.e., used and produced) for specific problem-solving purposes.

Epistemological constructivism: A philosophical view of knowledge that transcends positivist, scientific realist and social constructivist notions of knowledge (Boon 2017a).

Disciplinary perspective: A cognitive framework that an expert has developed by being educated within a certain discipline. The framework enables her to 'see' specific aspects (e.g., in terms of specific categories), to interpret or explain these 'observations' in specific ways (e.g., in terms of scientific knowledge), to ask specific types of questions about these 'observations' (e.g., about other, not yet manifested symptoms or signals), to come up with possible interventions (e.g., specific treatments fitting to the disease), and to generate novel hypotheses (e.g., drawing new connections or interpretations when faced with new information, for instance from other disciplines).

Interdisciplinary expertise: The cognitive ability to collect relevant information from different disciplinary sources, and to combine these heterogeneous bits of information into a coherent, adequate and relevant 'story,' 'picture' or 'model' that helps in understanding, reasoning and decision-making about the clinical problem. It also includes the cognitive ability to participate in *interdisciplinary collaborations*, transferring knowledge, methods and technologies from one domain to another in order to generate *new* knowledge, methods and technologies for novel problems.

Notes on contributors

Mieke Boon (PhD) graduated in *chemical engineering* (cum laude) and is a full professor in *philosophy of science in practice*. Her research aims at a *philosophy of science for the engineering sciences*, addressing topics such as methodology, technological instruments, scientific modeling, paradigms of science, interdisciplinarity and science teaching. **Sophie van Baalen** (MSc) graduated in *technical medicine* and in *philosophy of science technology and society*, both cum laude. Currently she works on a PhD project in which she aims to understand epistemological aspects of technical medicine from a philosophy of science perspective, such as EBM, expertise, interdisciplinarity and technological instruments. **Marleen Groenier** (PhD) graduated in *psychology* and is a researcher in *professional learning in high tech healthcare.* In her research, she addresses topics such as simulation-based training and assessment complex technical medical skill, modelling learning curves, and psychometrics.

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