Expertise development and scientific reasoning

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Abstract

Expertise research is closely related to issues of learning and professional development. In professional contexts, the focus is on exceptionally advanced performance in professions which require long academic – and at least partly scientific – education before entering into work. Surprisingly, only a few studies have systematically examined the role of scientific reasoning in expertise development. Many researchers have shown that initial scientific knowledge seems to disappear or at least lose its importance during the course of expertise development. This conclusion was challenged by Boshuizen and Schmidt (1992) in their studies on expertise development in medicine. They presented the theory of encapsulation, which describes how formal scientific knowledge is integrated with practical knowledge during clinical experience. However, these studies focused on the role of scientifically developed concepts, not how scientists themselves reason about concepts within a larger theoretical and methodological framework. In professional practices, reasoning about knowledge is often based on criteria that do not clearly match with scientific reasoning processes. For university studies, preparing for future professionals, the question of different forms of reasoning about knowledge and practices in professional knowledge domains is highly important. The aim of this chapter is to summarize existing findings about the relationship between expertise development, practical epistemologies, and scientific reasoning.

Introduction

Studies aimed at enhancing scientific thinking and research skills are important in all fields of university studies. However, only a small part of university graduates will continue as researchers, whereas a majority will begin work in professions that are not predominantly scientific . This raises the question of the relevance of students learning scientific research skills (Murtonen, Olkinuora, Tynjälä, & Lehtinen, 2008). Do they gain access to the competences which professional researchers need? What is the role of the knowledge of research methods and scientific thinking skills in other professions where highly educated people work?

Advanced knowledge is a crucial driver for the functioning and the development of contemporary economies and societies. Because of that, the role of scientific research findings is becoming more and more important in all professional fields. Professionals in various fields should develop the expertise needed in using scientific evidence in their daily work. Additionally, it is increasingly important that researchers develop the high-level expertise that makes scientific breakthroughs possible. In this chapter our aim is to deal with the nature and development of scientific thinking in the field of research and other high-level expert professions and discuss what could be the contribution of expertise research in understanding the development of these scientific reasoning competences.

What is expertise?

Exceptional performers in many fields, including craftsmanship, science, sports, music, and medicine, have long interested researchers and the public. Investigations have helped in understanding why some individuals reliably outperform others, explaining underlying reasons and mechanisms, predicting individuals' development of expertise, studying their influence on the societal communities they are part of, and supporting people in developing successful professional performance. Accordingly, some scientific explanations of human excellence have emerged while others have disappeared (Ericsson, Hoffman, Kozbelt, Williams, 2018).

The Dutch psychologist de Groot (1946) initiated a novel line of scientific endeavor, as the first to inspire a completely new perspective on the nature of outstanding performance. In particular, he was the first to focus on domain-specific aspects of performance and in contrast to domain-independent aspects. De Groot focused on the differences between the best chess players' cognitive processes, in particular their problem-solving, and those of lesser performers. This problem-solving was captured using think-aloud protocols to gain verbal reports (Ericsson & Simon, 1993). De Groot found that (a) the best players had qualitatively different representations of chess positions than weaker players, (b) they had more and better information about problem situations, (c) crucial patterns and critical situations were more easily recognized, and (d) their analyses and action proposals of given chess positions were closely related. These qualities appeared crucial for finding the best chess moves in short time.

Later, the role of knowledge in information-processing theories has been emphasized. This was initiated in the early 1970s spurred by the inadequacy of using search processes to model complex human behaviour and the clearer evidence of prior knowledge's role in solving problems. It was at this stage that de Groot's work was finally acknowledged, once increasing evidence confirmed his notion that even basic information-processing is affected by prior experience (Chase & Simon, 1973a, 1973b)

Since then, empirical evidence had confirmed that the advantages held by exceptional performers' are not based on a general supremacy, but are instead limited to the domain. A new theoretical view around the concepts of "expert" and "expertise" was thus designated. These theories about the acquisition of expertise explained performance as domain-specific, "hand-made", and based on the growth of routines, skills, and abilities gained though extended, carefully designed practice ("deliberate practice"; Ericsson, Krampe, & Tesch-Römer, 1993). Additionally, theories about the restructuring of expert knowledge based on experience emerged (Boshuizen & Schmidt, 1992; Kolodner, 1983), and support for the acquisition of expertise was considered important in instruction (Brown, Collins, & Duguid, 1989). These studies confirmed the immense plasticity of human cognitive performance. Expertise was demonstrated to be the most appropriate adaptation to the requirements and constraints within a domain (Ericsson & Lehmann, 1996; Gruber, Jansen, Marienhagen, & Altenmüller, 2010), leading to changes in neural, physiological, cognitive, and perceptual-motor parameters.

Deliberate practice

The process of knowledge restructuring describes how experience leads to changes in domain-specific cognitive representations of individuals. Not just any experience leads to knowledge restructuring as such. Instead, relevant cases are needed for preparing to act appropriately in the domain and meet professional requirements. The core idea of deliberate practice is that such processes must be fostered and guided in practice activities. Performance levels of professional musicians was not related to the amount of domain-related activities in total, according to Ericsson et al. (1993). Instead, the total amount of solitary practice was most closely associated with performance levels. This solitary practice involved training specific aspects of performance, as recommended by teachers. "Part of the practice is to gradually embed the trained task in its natural context with regular time constraints and less predictable occurrences." (Ericsson, 2009, p. 417). This focus on improving performance differentiates deliberate practice from playful engagements and routine, mindless performance. These latter forms of activity are less impactful on performers' current levels.

Years of practice often do not lead to development beyond local levels of competition in sports, as can be easily recognized in many athletes. Instead, deliberate practice – sustained, conscious, and goal-oriented training – is required for outstanding high-level expert performance. Such active learning requires continuous effort to overcome barriers to performance and improve levels of performance, as noted by many others (Bloom, 1985; Cleveland, 1907; Dreyfus & Dreyfus, 1986).

Already early in their careers, experts' learning processes differed from their peers, as noted in the retrospective interviews of Ericsson and colleagues (1993). Future experts had more dedicated coaches and teachers, were more efficient in their practise, and demanded higher achievement. Experts training activities were, for a long time-period, solely aimed at improving their performance. Even if they know it may improve their performance, individuals rarely spontaneously engage in deliberate practice. Instead, they engage in typical activites based on external rewards or inherent enjoyment (Lehmann, 2002). It is crucial for those who engage in deliberate practice to have teachers or mentors who offer targeted feedback and explicit teaching goals, which provides the possibilities for improvement through error correction and repetition.

Deliberate practice and teacher-guided instruction and closely connected. A teacher's ability drives the performance improvements that come from the gradual development gained from deliberate practice implies (Lehmann & Ericsson, 2003). This ability is driven by the accumulation of artefacts and knowledge that has occurred in complex domains. Teachers share this accumulated knowledge with learners with an understanding of future skill requirements and can thus support learners' enculturation into expert communities of practice.

The theory of knowledge encapsulation

The theory of knowledge encapsulation stems from medical expertise development research (Hobus, Schmidt, Boshuizen, & Patel, 1987; Lesgold et al., 1988; Patel & Groen, 1986). The theory denotes three processes that characterise expertise development: knowledge accretion and validation, knowledge encapsulation, and illness script formation (Boshuizen & Schmidt, 2008). The theory has roots in de Groot's (1965) paradigmatic case processing research. It is a theory on knowledge restructuring, which is useful in explaining the positive relation between expertise and recall precision in chess. However, in medical case processing research the relation between expertise level and recall is inconsistent, sometimes positive (Norman, Feightner, Jacoby, & Campbell, 1979) and sometimes negative (Patel & Medley-Mark, 1986). These inconsistencies suggest that the relation between the level of expertise and case recall in medicine is curvilinear. An inverted U-shape curve appears that is described as an “intermediate effect” (Schmidt & Boshuizen, 1992). Practitioners experience recall performance improvements during early training (up to six years) followed by falling performance with additional experience. This decrease in performance is associated with (1) increasing use of macro-concepts, (2) increasing reorganisation in recall in comparison with the initial case structure, and (3) a decreasing dependence of item recall on perceived importance of the item (Claessen & Boshuizen, 1985; Schmidt & Boshuizen, 1993a). Additionally, written case explanations and diagnostic think-aloud protocols of the underlying mechanisms follow an inverted-U-shaped relation between the use of biomedical knowledge and expertise (Boshuizen & Schmidt, 1992; Schmidt & Boshuizen, 1993a; van de Wiel, Boshuizen, & Schmidt, 2000; see also Patel & Groen, 1986).

In this context, the concept of “knowledge encapsulation” was first introduced (Boshuizen & Schmidt, 1992; Schmidt & Boshuizen, 1992). It referred to experts use of macro-concepts in case recall (Schmidt & Boshuizen, 1993b). Although intermediates used a great deal of detailed biomedical knowledge, both experts and novices used very little. Despite this, experts used a great deal more macro-concepts that integrated biomedical and clinical knowledge than novices.

Given this integration, the drawn-out process of knowledge encapsulation appears to both shorten lines of reasoning and use umbrella terms to integrate new knowledge parts (Boshuizen, Schmidt, Custers, & van de Wiel, 1995). The complexity of the encapsulations used by experts and novices appeared to differ. Novices had incomplete concepts that affected their diagnostic performance. They treated certain crucial symptoms as unrelated and inexplicable, which contributed to incomplete case representations (Boshuizen & van de Wiel, 1998).

Repeated processing of domain-relevant cases appears crucial for learning and gaining experience (Prince et al., 2003; Schmidt et al., 1996). The typical task (e.g., diagnosis), which structures the process as well as the outcome, is inherent in this case processing. However, extant research relies on cross-sectional designs, limiting the surety of this assumption. A recent longitudinal study improves on these previous studies, but still has too short a time-frame to move beyond previous cases (Boshuizen, van de Wiel, & Schmidt, 2012). Students compared their knowledge with cases and compared consequences and enabling conditions with different expressions of a disease. Relevant resources were needed to debug faulty knowledge.

On the role of scientific thinking when experts use evidence in their work

In many professions, high-level experts are not researchers themselves. Yet, they need to understand the nature of scientific research to make crucial decisions. Most professional expert practices are based explicitly or implicitly on research evidence. In some fields, particularly in medicine, the use of research evidence is well organized by consensus bodies, which help individual professionals make use of research findings in their practical work (West, 2000). However, in most other professional fields, there is no organized system for the use of research findings in practical work. Instead, it is the responsibility of individual professionals to find and interpret existing evidence. The use of evidence is, however, not a trivial issue (Reed et al., 2005). During the last decades evidence based practices have been enhanced in many professions and the ideas originally developed in medicine are spreading to other professional fields, such as education (Slavin, 2002). In spite of the popularity of the evidence-based approaches, only a few studies have critically focused on the skills and knowledge needed when professionals evaluate scientific evidence and make use of it in developing, conforming, or changing professional practices.

The first question is what kind of evidence professionals are looking for. Critical scientific thinking requires a deeper understanding that scientific research does not give direct answers to practical or societal questions. Seeking out evidence and afterwards combining and evaluating evidence dealing with different aspects of a question requires advanced professional skills. For instance, the in medical field there is a distinction between two types of sources of research providing evidence for practice: (a) comparative effectiveness research, which considers both costs and benefits and (b) evidence based research, where the aim is to find best evidence to maximize best outcomes independently of cost. Expert practitioners must be able to take into account the differing goals of these approaches when weighing the evidence. However, these alternative sources of scientific evidence are not so explicitly available in all fields.

The second demanding expert practice in using research evidence is to evaluate the usefulness and trustworthiness of the findings coming from different forms of research (Bowen & Zwi, 2005). To evaluate and make use of this variety of possible scientific sources in sophisticated way requires well-developed knowledge and skills to reason about affordances and constrains of different research methods and designs. Informative findings can be found from case studies, small-scale experiments, surveys, large-scale (randomized) experiments, reviews and meta-analyses (Nutley, Walter & Davies, 2007; 2009). However, the methods of data collection, sample sizes, sample qualities, quality of experimental design, type of statistical analyses etc. are different in studies, which must be taken into account in evaluating the suitability and relevance of research findings in informing practice. For instance, in medicine, evidence based recommendations are normally based on meta-analyses. However, individual large randomized experiments are also often used as basis for recommendations for policy and practice. Small-scale experiments and qualitative studies can provide insight into new phenomena in a way that is not possible to find from aggregated evidence. (Flather, Farkouh, Pugue & Yusuf, 1997)

However, recent trends in meta-science have clarified the difficulties facing even researchers in interpreting scientific findings (Ioannidis, 2005). For instance, meta-analyses are widely seen as most reliable sources of experimental evidence, although they are easily misleading without adequate methodological knowledge. The very idea of aggregating a large amount of experimental results from several studies is to overcome the biases of individual studies. They help to deal with inconsistencies in research, and make it possible to analyze moderating and mediating variables (Stone & Rosopa, 2017). However, meta-analyses can also have weaknesses that limit the reliability and validity of the results, which must be taken into account when the findings are used in political decisions or developing professional practices. For example, publication bias results from authors being more willing and able to publish statistically significant results. This means that even though meta-analyses cover findings from a large number of studies, the results can be positively biased because of this distorting tendency in publication. Furthermore, only some meta-analyses include original studies that have replicated the same treatment. More often meta-analyses summarize findings from varying study designs and treatments and it may be difficult to say that what the results exactly mean. All these features of meta-analyses mean that interpretation of them can be challenge for practitioners.

While these specific challenges require explicit expertise in methodological areas, perhaps the biggest challenge in the use of scientific evidence in professional practice and political decision making is related to the need to combine very different types of knowledge or epistemic cultures (Knorr Cetina, 1999). Studies have shown big differences between epistemic cultures of various research fields and professional practices making use of findings of these fields. There are differences for example in terms of contextualization or dealing with complexity and uncertainty (Kastenhofer, 2007). This means that evidence coming from the scientific literature should be combined with other forms of knowledge used in practical work situations (Bowen & Zwi, 2005). For understanding the challenges of evidence-based policy and practice, the relationship between scientific and other types of knowledge is a crucial, but inadequately addressed, question in studies of evidence-based practice and policy. However, in studies of expertise development, the relationship between theoretical and practical knowledge has been extensively studied. The situation is similar than the processes dealt with in studies on knowledge-encapsulation describing how formal knowledge is integrated with practical and situational scripts (Boshuizen & Schmidt, 1992). Formal knowledge of scientific evidence and even deeper knowledge of methodological constrains of the available evidence is not necessarily beneficial for the expert performance, if the person is not able to create macro-concepts integrating various forms of scientific knowledge and situated knowledge developed in practice.

Experts in science – do they think differently?

There is a rich research tradition focusing on the development of scientific thinking in children and adolescents. These studies have mainly focused on how students of different levels of schooling learn to understand the scientific control-of-variables strategies or how students' epistemic beliefs about the nature of scientific knowledge are develop. Some studies, however, have analyzed students' scientific thinking more broadly. These studies highlight that scientific thinking is a more complex phenomenon, which requires varying skills and knowledge. Kuhn and her colleagues (Kuhn, Iordanou, Pease, & Wirkala, 2008) distinguished three aspects of scientific thinking that are more advanced than just controlling variables. The first is related to variable control but refers to the strategic ability to coordinate effects of multiple causal influences on an outcome. The second aspect is a mature understanding of the epistemological foundations of science, in particular understanding scientific knowledge as human constructs. The third aspect is the skilled argumentation typical to scientific domains, including the ability to coordinate theory and evidence.

These skills can be considered as standards of the scientific thinking, which university graduates should have learned during their studies. However, they are demanding. People typically consider only one hypothesis at a time, pay attention to the superficial similarity when using analogies, and often ignore information that would be important in reasoning about possible causal effects (Dunbar, 2001a). Many middle school students failed in tasks requiring this type of advanced scientific thinking (Kuhn et al., 2008), although some of the students managed to gradually learn to deal with these aspects of scientific thinking.

What about expert scientists? Does their work rely on the same skills? Are these skills more automatized and fluid? Or is there something more in their cognitive processes that makes professional scientists' thinking qualitatively different from the general scientific thinking required from university graduates (Murtonen, 2015)? There are only a few studies that have directly compared novices' and experts' abilities to apply general scientific thinking skills needed in research. The results of Schunn and Anderson (2001) show that university students have learned relatively advanced knowledge and skills related to scientific thinking in methodology courses, but they have difficulties to apply this formal methodological knowledge and general scientific thinking in concrete research tasks. Experts, using this knowledge in their daily work are much better than students in applying general methodological knowledge when they have to design experiments for studying complex effects and relationships. These findings can be interpreted as evidence that university graduates and expert scientist basically share the same methodological knowledge and skills but expert scientist are more fluent and skillful in applying this knowledge base.

However, in the Schunn and Anderson (2001) study there were also some findings showing differences between experts. The expert participants were selected so that one group were specialists in the particular scientific content (memory research) used in the experiment and the other group were researchers of other psychological contents. When planning experimental designs in the study, the experts of other domains applied a general rule to keep experimental design as simple as possible, whereas the content experts applied more complex designs. These findings indicate that expert performance on demanding scientific tasks can only partly be explained by domain general formal principles of scientific reasoning. Actual scientific practice is also based on expert scientists' rich domain knowledge which can mediate and facilitate the way how general scientific thinking can be applied in particular tasks.

Schunn and Anderson (2001) conducted their study in a computer-based environment, the Simulated Psychology Lab, where participants had to plan experimental designs according the instructions given by the researchers. As such, this was a representative scientific task of the field. However, completing the tasks took place outside the real research contexts in which experts were doing their normal work. This raises the question of the role of context in expert performance. Previous studies have highlighted the role of abstractions and generalizations in experts thinking but, at the same time, the crucial role of particular cases and conditions in concrete activity contexts (Feltovich, Ford & Hoffman, 1997).

Scientific expert communities: Situated practice and epistemic cultures

Along these lines are also influential sociological and anthropological studies on the functioning of scientific communities. Knorr Cetina (1999) has studied the knowledge creation processes in high-level scientific groups. These studies have highlighted the big differences between disciplines and groups in terms of criteria of empirical evidence, ways to deal with object relations, and relationship between theory and empirical research. These domain specific features of scientific disciplines, called epistemic cultures by Knorr Cetina, challenge the notion of a unified scientific method. The differences between epistemic cultures can be seen in many aspects of scientific reasoning. For instance, molecular biology and ecology differ in terms of temporal/spatial scale, de-contextualization and recontextulization of research objects, and dealing with complexity and uncertainty. (Karstenhofer, 2007). From this point of view expertise in science cannot be explained merely as a proficiency of a general scientific method or knowledge about the concepts and methods typical for a domain (Mieg & Evets, 2018). Instead, these must be considered as necessary but not sufficient skills needed in real research work. In addition to the advanced proficiency of general scientific thinking, experts in science are a part of the epistemic culture of their field.

A more radical view highlighting the nonformal aspects of professional scientific practices was presented by Latour and his colleagues (Latour & Woolgar, 1979), who carried out anthropological studies in science laboratories and argued that a typical experimental study results in mixed and inconclusive findings. In the real research processes, there is a continuous attempt to find out possible failures in the designs or measurement methods and selection of useful and non-useful data. From this point of view, expertise in science would mean ability to combine general and domain specific scientific knowledge and thinking, and to cope with the messy and unexpected situations in research practices.

These sociological and anthropological studies indicate that explanations about the nature of scientists' expertise has to go beyond knowledge of general scientific methods and scientific thinking. However, neither the studies of Knorr Cetina nor the investigations of Latour offer a basis for more detailed analysis of the nature of scientific expertise and cognitive processes used by experts in these contexts. More detailed analyses of the cognitive demands, which researchers face in real research contexts can be found from the few cognitive science studies focusing on science experts' work in real research situations. In series of studies Dunbar (2001b; 2002; Dunbar & Fugelsang, 2004) used an approach that combines the detailed analysis of researchers and research groups scientific reasoning in real situations in science laboratories and in-depth analysis of the same reasoning processes in decontextualized testing settings. "Rather than using only experiments, or observing only naturalistic situations, it is possible to use both approaches to understanding the same phenomena." Dunbar, 2001, p. 117).

Findings of these studies are in line with the sociological and anthropological findings: "Much of the time the scientists have unexpected findings, ambiguous results, and uninterpretable data." (Dunbar 2001b, p. 121). One crucial cognitive activity is the reasoning about these ambiguous results, which sometimes leads to novel scientific discoveries. Skills to reason about these situations in a way, which is on the same time creative and scientifically solid, and the use of various cognitive and scientific reasoning strategies, characterize the scientific expertise in action. The protocols of high level research groups, presented in Dunbar's (2001a; 2002) studies highlight the advanced cognitive strategies to use analogies and to reason about causalities within real research work contexts. Importantly, these strategies are not affected by the typical biases people have in decontextualized experiments on analogical and causal reasoning.

On the other hand ambiguous findings in real research situations are often a starting point for methodological innovations aiming at controlling possible sources of errors. The term "scientific uncertainty" has been used to describe typical situations in real research context. No measure can be 100 percent correct and there is practically always a lack of information (Smith & Stern, 2011). Deep knowledge about this uncertainty and rich well-developed strategies to deal with errors and missing information are central to science expertise.

According to Dunbar (2001b), researchers have conventional procedures, distinct from the formal models of scientific methods. These procedures resemble the practical scripts described in studies on professional practices in medicine (Boshuizen & Schmidt, 2008). For example, dealing with unexpected results seem to follow a kind of practical script of phases, which are consistently repeated in similar situations (Dunbar 2001b). These procedures cannot be found in formal methodological texts, but they are effective ways to recognize errors and to find genuinely novel theoretical explanations in cases when errors are not sufficient explanations for the unexpected results. It is likely that these procedures are also dependent on the epistemic cultures of different fields.

Short term studies of research groups and science laboratories can give insight of the epistemic cultures and situated practices but do not necessarily show how successful scientists create the outstanding methodological and theoretical capacity for themselves and for their research groups. Retrospective studies unraveling the different phases of careers of high-level scientists indicate that strategic networking is a key activity, which make it possible to get access to emerging theoretical ideas and novel methodologies (Gruber, Lehtinen, Palonen & Degner, 2008).

On the basis of this analysis it is possible to present a model of high-level professional skills of scientists in which expertise consists of several layers. The first layer refers to domain general scientific thinking and skills including advanced epistemological cognition and abilities to control multiple variables and draw causal conclusions. This knowledge is basically learned by most university students in the methodology courses, but professional scientists who need these skills frequently can apply these general skills and scientific thinking on more advanced level than university students.

The second layer is a rich and well-organized domain specific knowledge base, which researchers have acquired during basic studies and researcher training, and further developed as a part of their research practices. Because of the integration of general scientific thinking and domain specific knowledge base, scientific experts can comprehend more complex designs, better interpret unexpected results and draw more adequate causal conclusions in their own field than in other fields they do not know so well.

The third layer refers to disciplinary epistemic cultures and situated practices. These challenge the notion of unified scientific thinking and clearly go beyond the formal models, principles, and rules of "standard" scientific thinking and methods. These are the aspects of scientific expertise that are learned through participation in daily work and discourses of scientific communities of practice.

These multiple levels of scientific expertise already explain why it typically takes a long time to become a highly recognized researcher. The model describes the different aspects, which can constitute expertise in science. However, as in other forms of expertise, the level of the scientific expertise of an individual depend on the amount and quality of deliberate practice focusing on these different aspects.

How do expert researchers get their superior skills?

There is no single model of expert level scientific thinking. Instead, expert scientists' exceptional performance is based on a large variety of competences developed during formal studies and work experiences. Some of these competences are domain-general and often learned in formal education; some are domain specific, partly mediated by formal curricula; and some are situationally-developed in research practice within research groups and laboratories. General competences are partly the same higher order cognitive processes that people also use outside of science, such as induction, deduction, analogical reasoning, and problem solving. Some of these general scientific reasoning processes are closer to the research context, such as thinking about experimental designs. However, most of the scientific thinking and reasoning is domain-specific, focusing on particular concepts and theories or domain-specific methods (Dunbar & Klahr, 2012). In addition, several researchers have shown, that domain and situation specific informal practices of research groups and laboratories and scientific reasoning related to them are a crucial part of competences of expert scientists (Dunbar, 1995; Knorr Cetina, 1999; Latour & Woolgar, 1979).

Scientists' ability to create new knowledge and discover novel phenomena have raised the question about the functioning of scientists' minds (Dunbar & Klahr, 2012). Most earlier research has tried to explain the exceptional achievement of top scientists through general innate or early developed personal traits such as intelligence, conscientiousness, autonomy, openness, flexibility, and cognitive complexity (Barrett, Vessey, Mracek & Mumford, 2014). Later empirical research has recognized some personality features typical for successful researchers, but the predictive value of these background variables is low. For example, openness was the only personality component of the Big Five Inventory which somewhat correlated with scientific creativity (Grosul & Feist, 2014).

Instead, the experiences researchers have had during their academic career and the contexts in which they have worked seem to be stronger predictors for their successful research careers than any personal traits (Barret et al., 2014). This is in line with the general findings of expertise research. Abilities and other background variables may play a role in the beginning of the expertise development, and certain threshold levels may be needed, but their effect is weaker or disappears among the higher levels of expertise development (Ericsson, 2014). On the other hand, extended practice as researcher does not mean that all experienced researchers would gradually become superior scientific thinkers. This is also in line with the findings of expertise research in varying professional fields, which has shown the difference between routine experience and deliberate practice (Ericsson, 2018).

There are a few studies that have analyzed the nature of experience and practice in the development of expertise in science. Barret et al. (2014) used bibliographic data of 93 historically eminent scientists and Mumford and colleagues (2005) used obituaries of 499 more recently deceased highly respected researchers in studies aimed at analyzing the impact of different aspects of their careers on the quality of scientific achievement. Both studies highlighted some features of the careers leading to exceptional achievement that are similar to findings of expertise research in sports, music, and other professional fields. As well, they found some other aspects that might be more specific for the development of scientific excellence. Scientists seldom start to systematically prepare for their career at early ages, in contrast to top athletes and musicians. However, early engagement in the research field and early contact with an important mentor was also found to predict exceptional performance during the later career (Mumford et. al, 2005). In both of these studies, scientific activities during earlier phases of the career, which were strong predictors of later success, parallels with deliberate practice (Ericsson, 2018). For example, deliberate early practice was one of the strongest predictor of later creative scientific achievement (Mumford et al., 2005).

Additonally, focused collaboration within their own research group and with researchers from outside has been strongly highlighted in studies about the career development of successful researchers (Barret et al., 2014: Dunbar, 2001b; Dunbar & Klahr, 2012; Gruber, et al., 2008; Mumford et al., 2005).

One of the common finding in expertise research during last few decades has been that nobody is an expert in many different fields, but rather, in relatively specific domains. The findings of scientific excellence are somewhat different. Studies of older eminent researchers has shown that transitions between research topics within broader research areas predicts exceptional scientific creativity (Barret et al., 2014). However, it is an open question is this still the case among contemporary research.

Discussion

It is a well-documented finding that increasing experience in work does not always lead to increasing expertise. On the contrary, studies show that it is typical even for highly educated professionals such as medical doctors that expertise development is arrested after a few years in practice (Ericsson, 2018). Active seeking and using novel scientific evidence in developing one's own work practices can be seen as an attempt to avoid the arrested expertise development. Because of the different epistemic cultures dominating the professions where scientific knowledge is produced and the practical work conditions where it is used as evidence, the evidence-based development of practices is far from trivial. It requires a form of professional deliberate practice, which helps to increase the awareness of these epistemic differences and to develop applied scientific thinking needed in evaluating the suitability of the evidence in concrete situations. In the expertise literature, there are many definitions of the superior skills of experts. Based on the analysis presented in this chapter we suggest that, concerning expertise in professional contexts, the advanced skills needed to use scientific evidence should be added to the differentiation of experts from novices and experienced non-experts.

It is natural to think that successful scientists are experts and particularly experts in scientific thinking. However, it is not straightforward to use the established definitions of expertise when scientists are considered. Herbert Simon, a Nobel laureate himself, described this tension by the ironic claim that "normal" science fits in the typical description of expert problem solving whereas scientific thinking needed in "revolutionary" scientific discoveries fits better with the way how novices' problem solving is defined. Scientific activity leading to revolutionary novel findings happens by trial-and-error searches, which characterizes novice problem solving. "The search may be highly selective—but it reaches its goal only after many halts, turnings, and back-trackings." (Simon, Langley, & Bradshaw, 1981, p. 5).

If expertise is defined as domain-specific, and based on the growth of routines, skills, and abilities gained though extended, carefully designed practice ("deliberate practice"; Ericsson, et al., 1993), it fits well with some aspects of high-level scientific thinking. Well-developed mental models of general standard scientific concepts of theory, control, causality, and validity are clearly aspects of competent scientific thinking where deliberate practice is needed. In the same way, acquiring the established conventions and practices belonging to domain-specific epistemic cultures and practical working of research groups and laboratories are good examples of deliberate practice.

Research on expertise has successfully unraveled important features of high achievement in the arts, sports, and many professional fields. However, expert performance and development in scientific thinking has not been extensively studied. A better understanding of the processes of producing new scientific knowledge and making use of scientific evidence in practical work would be beneficial for developing research studies in university programmes and in looking for work conditions and processes which could support continuous expertise development.

References

Barrett, J.D., Vessey, W.B., Griffith, J.A., Mracek, D. & Mumford, M.D. (2014). Predicting Scientific Creativity: The Role of Adversity, Collaborations, and Work Strategies. *Creativity Research Journal*, 26(1), 39–52.

Bloom, B. S. (Ed.). (1985*). Developing talent in young people*. New York: Ballantine.

Boshuizen, H. P. A., & Schmidt, H. G. (1992). On the role of biomedical knowledge in clinical reasoning by experts, intermediates and novices. *Cognitive Science*, 16, 153–184. doi:10.1207/s15516709cog1602_1

Boshuizen, H. P. A., & Schmidt, H. G. (2008). The development of clinical reasoning expertise. *Clinical Reasoning in the Health Profession*s, 3, 113–121.

Boshuizen, H. P. A., Schmidt, H. G., Custers, E. J. F. M., & van de Wiel, M. W. J. (1995). Knowledge development and restructuring in the domain of medicine: The role of theory and practice. *Learning and Instruction*, 5, 269–289. doi:10.1016/0959-4752(95)00019-4

Boshuizen, H. P. A., & van de Wiel, M. W. J. (1998). Multiple representations in medicine; How students struggle with it. In M. W. van Someren, P. Reimann, H. P. A. Boshuizen, & T. de Jong (Eds.), *Learning with multiple representations* (pp. 237–262). Amsterdam: Elsevier.

Boshuizen, H. P. A., van de Wiel, M. W. J., & Schmidt, H. G. (2012). What and how advanced medical students learn from reasoning through multiple cases. *Instructional Science*, 40, 755–768.

Bowen, S. & Zwi, A.B. (2005). Pathways to "Evidence-Informed" Policy and Practice: A Framework for Action. *PLOS Medicine*, 2 (7).

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researc*her, 18(1), 34–41.

Chase, W. G., & Simon, H. A. (1973a). Perception in chess. *Cognitive Psychology*, 4, 55–81.

Chase, W. G., & Simon, H. A. (1973b). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215–281). New York: Academic Press.

Claessen, H. F. A., & Boshuizen, H. P. A. (1985). Recall of medical information by students and doctors. *Medical Education*, 19, 61–67. doi:10.1111/j.1365-2923.1985.tb01140.x

Cleveland, A. A. (1907). The psychology of chess and of learning to play it. The American Journal of Psychology, 18, 269–308.

De Groot, A. D. (1946). *Het denken van den schaker* [Thought and choice in chess]. Amsterdam: Noord Hollandsche.

De Groot, A. D. (1965*). Thought and choice in chess*. The Hague: Mouton.

Dreyfus, H. L., & Dreyfus, S. E. (1986). *Mind over machine: The power of human intuition and expertise in the era of the computer*. New York: Free Press.

Dunbar, K. (2001a). The analogical paradox: Why analogy is so easy in naturalistic settings, yet so difficult in the psychology laboratory. In D. Gentner, K. J. Holyoak, & B. Kokinov (Eds.), *Analogy: Perspectives from cognitive science* (pp. 313–334). Cambridge, MA: MIT press.

Dunbar, K. (2001b). What scientific thinking reveals about the nature of cognition. In K. Crowley, C. D. Schunn, & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings* (pp. 115-140). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Dunbar, K. (2002). Science as category: Implications of InVivo science for theories of cognitive development, scientific discovery, and the nature of science. In P. Caruthers, S. Stich, & M. Siegel (Eds.) *Cognitive models of science* (pp. 154–170). New York: Cambridge University Press.

Dunbar, K., & Fugelsang, J. (2004). Causal thinking in science: How scientists and students interpret the unexpected. In M. E. Gorman, A. Kincannon, D. Gooding, & R. D. Tweney (Eds*.), New directions in scientific and technical thinking* (pp. 57–59). Mahway, NJ: Erlbaum.

Dunbar, K. N., & Klahr, D. (2012). Scientific thinking and reasoning. In K. J. Holyoak & R. G. Morrison (Eds.), *The Oxford handbook of thinking and reasoning* (pp. 701-718). New York, NY, US: Oxford University Press.

Ericsson, K. A. (2009). Enhancing the development of professional performance: Implications from the study of deliberate practice. In K. A. Ericsson (Ed.), *The development of professional expertise: Toward measurement of expert performance and design of optimal learning environments* (pp. 405–431). Cambridge: Cambridge University Press.

Ericsson, K.A. (2014). Why expert performance is special and cannot be extrapolated from studies of performance in the general population: A response to criticisms. *Intelligence*, 45, 81-103.

Ericsson, K.A. (2018). The differential influence of experience, practice and deliberate practice on the development of superior individual performance of experts. In . K. A. Ericsson, R.R. Hoffman, A. Kozbelt, & A.M. Williams (Eds.), *The Cambridge handbook of expertise and expert performance, second edition* (745-769). Cambridge: Cambridge University Press.

Ericsson, K. A., Hoffman, R.R., Kozbelt, A. & Williams, A.M. (Eds.). (2018). *The Cambridge handbook of expertise and expert performance, second edition*. Cambridge: Cambridge University Press.

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, 100, 363–406.

Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: Evidence of maximal adaptations to task constraints. *Annual Review of Psychology*, 47, 273–305.

Ericsson, K. A., & Simon, H. A. (1993*). Protocol analysis. Verbal reports as data* (rev. ed.). Cambridge: MIT Press.

Feltovich, P. J., Ford, K. A., & Hoffman, R. R. (Eds.) (1997). *Expertise in context*. Cambridge, MA: The MIT Press.

Flather, M.D., Farkouh, M.E., Pogue, J.M. & Yusuf, S.(1997). Strengths and Limitations of Meta-Analysis: Larger Studies May Be More Reliable. *Controlled Clinical Trials*, 18, 568-579.

Grosul, M. & Feist, G.J. (2014). The Creative Person in Science. *Psychology of Aesthetics, Creativity, and the Arts*, 8 (1), 30–43.

Gruber, H., Jansen, P., Marienhagen, J., & Altenmüller, E. (2010). Adaptations during the acquisition of expertise. *Talent Development and Excellence*, 2, 3–15.

Gruber, H., Lehtinen, E., Palonen, T. & Degner, S. (2008). Persons in shadow: Assessing the social context of high abilities. *Psychology Science Quarterly*, 50 (2) 237-258.

Hobus, P. P., Schmidt, H. G., Boshuizen, H. P. A., & Patel, V. L. (1987). Contextual factors in the activation of first diagnostic hypotheses: Expert-novice differences. *Medical Education*, 21, 471-476. http://dx.doi.org/10.1111/j.1365-2923.1987.tb01405.x

Ioannidis, J. P. A. (2005). Why most published research findings are false. *PLoS Medicine*. https://doi.org/10.1371/journal.pmed.0020124

Kastenhofer, K. (2007) Converging epistemic cultures?. Innovation: *The European Journal of Social Science Research*, 20 (4), S. 359-373.

Knorr Cetina, K. (1999). *Epistemic Cultures: How the Sciences Make Knowledge*. Cambridge: Harvard Univ. Press

Kolodner, J. L. (1983). Towards an understanding of the role of experience in the evolution from novice to expert. *International Journal of Man-Machine Studies*, 19, 497–518.

Kuhn, D., Iordanou, K., Pease, M., & Wirkala, C. (2008). Beyond control of variables: What needs to develop to achieve skilled scientific thinking? *Cognitive Development*, 23, 435-451.

Latour, B. and Woolgar, S. (1979). *Laboratory life. The social construction of scientific facts.* London: Sage.

Lehmann, A. C. (2002). Effort and enjoyment in deliberate practice: A research note. In I. M. Hanken, S. G. Nielsen, & M. Nerland (Eds*.), Research in and for music education. Festschrift for Harald Jørgensen* (pp. 153–166). Oslo: Norwegian Academy of Music.

Lehmann, A. C., & Ericsson, K. A. (2003). Expertise. In L. Nadel (Ed.), *Encyclopedia of cognitive science* (vol. 2, pp. 79–85). London: Macmillan.

Lesgold, A. M., Rubinson, H., Feltovich, P., Glaser, R., Klopfer, D., & Wang, Y. (1988). Expertise in a complex skill: Diagnosing X-ray pictures. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp. 311–342). Hillsdale: Erlbaum.

Mieg, H.A. & Evets, J. (2018). Professionalism, science and expert roles: a social perspective. In K.A. Ericsson, R.R. Hoffman, A. Kozbelt, A.M. Williams (Eds*), The Cambridge Handbook of Expertise and Expert Performance.* Cambridge: Cambridge University Press.

Mumford MD, Connelly MS, Scott G, Espejo J, Sohl LM, Hunter ST, Bedell KE. (2005). Career experiences and scientific performance: A study of social, physical, life, and health sciences *Creativity Research Journal*. 17, 105-129.

Murtonen, M. (2015). University students' understanding of the concepts empirical, theoretical, qualitative and quantitative research. *Teaching in Higher Education*, 20(7), 1470-1294.

Murtonen, M., Olkinuora, E., Tynjälä, P. & Lehtinen, E. (2008). ”Do I need research skills in working life?” – Students’ motivation and difficulties experienced in quantitative methods courses. *Higher Education*. 56 (5) 599-612.

Norman, G. R., Feightner, J. W., Jacoby, L. L., & Campbell, E. J. M. (1979). Clinical experience and the structure of memory. *Proceedings of the 18th Conference on Research in Medical Education*. (pp. 214–218). Washington, USA.

Nutley, S. M., Jung, T., & Walter, I. (2008). The many forms of research-informed practice: a framework for mapping diversity, *Cambridge Journal of Education* 38, 53-71.

Nutley, S. M., & Walter, I. & Davies, H. T. O. (2007). *Using Evidence: How Research Can Inform Public Services*. Bristol: The Policy Press.

Nutley, S., Walter, I. & Davies, H. (2009). Promoting Evidence-based Practice: Models and Mechanisms From Cross-Sector Review. *Research on Social Work Practice*, 19(5):552-559

Patel, V. L., & Groen, G. J. (1986). Knowledge based solution strategies in medical reasoning. *Cognitive Science*, 10, 91–116. doi:10.1016/S0364-0213(86)80010-6

Patel, V. L., & Medley-Mark, V. (1986). *Relationship between representation of textual information and underlying problem representation in medicine*. Cognitive Research Series, Montreal, Canada: McGill University, Centre for Medical Education. (CME86-CS1)

Prince, K. J., van Mameren, H., Hylkema, N., Drukker, J., Scherpbier, A. J., & van der Vleuten, C. P. (2003). Does problem-based learning lead to deficiencies in basic science knowledge? An empirical case on anatomy. *Medical Education*, 37, 15–21. doi:10.1046/j.1365-2923.2003.01402.x

Reed D, Price EG, Windish DM, Wright SM, Gozu A, Hsu EB, Beach MC, Kern DE, Bass EB. (2005). Challenges in systematic reviews of educational intervention studies. *Ann Intern Med*. 142(12):1080–9.

Schmidt, H. G., & Boshuizen, H. P. A. (1992). Encapsulation of biomedical knowledge. In D. A. Evans & V. L. Patel (Eds.), *Advanced models of cognition for medical training and practice* (pp. 265–282). New York: Springer. doi:10.1007/978-3-662-02833-9_15

Schmidt, H. G., & Boshuizen, H. P. A. (1993a). On acquiring expertise in medicine. *Educational Psychology Review*, 5, 205–221. doi:10.1007/BF01323044

Schmidt, H. G., & Boshuizen, H. P. A. (1993b). On the origin of intermediate effects in clinical case recall. *Memory and Cognition*, 21, 338–351. doi:10.3758/BF03208266

Schmidt, H. G., Machiels-Bongaerts, M., Hermans, H., ten Cate, T. J., Venekamp, R., & Boshuizen, H. P. A. (1996). The development of diagnostic competence: Comparison of a problem-based, an integrated, and a conventional medical curriculum. *Academic Medici*ne, 71, 658–664. http://dx.doi.org/10.1097/00001888-199606000-00021

Schunn, C. and Anderson, J. (2001). "Acquiring expertise in science: Exploration of what, when and how," K. Crowley, C. D. Schunn, & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom and professional settings.* Mahwah, NJ: Erlbaum, 351-392.

Slavin, R.E. (2002). Evidence-Based Education Policies: Transforming Educational Practice and Research. *Educational Researche*r, 31 (7), 15–21.

Simon, H. A., Langley, P., & Bradshaw, G. L. (1981). Scientific discovery as problem solving. *Synthese,* 54 , 1–27.

Smith, L.A. & Stern, N. (2011). Uncertainty in science and its role in climate policy. *Philosophical Transactions of the Royal Society*, 369, 4818-4841.

Stone, D.L. & Rosopa, P.J. (2017). The Advantages and Limitations of Using Meta-analysis in Human Resource Management Research. *Human Resource Management Review*, 27, 1-7.

Van de Wiel, M. W. J., Boshuizen, H. P. A., & Schmidt, H. G. (2000). Knowledge restructuring in expertise development: Evidence from pathophysiological representations of clinical cases by students and physicians. *European Journal of Cognitive Psychology*, 12, 323–355. doi:10.1080/095414400050114543

West, R.R. (2000). Evidence based medicine overviews, bulletins, guidelines, and the new consensus. *Postgraduate Medical Journal*;76, 383–389.,