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Conceptual Change in the Development of Visual Expertise

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Introduction

Experts in various fields differ from laypeople in their superior ability to interpret and analyse situations as well as solve problems typical of their respective areas of expertise. The learning of these exceptional skills typically takes a long time and requires specific training (Ericsson & Pool, 2016) The learning of radically new skills is not only necessary when people are initially educated for a profession; in fact, even experienced professionals are increasingly facing new learning challenges because professions are undergoing transitions. New scientific findings and novel technical tools often result in substantial changes in traditional professions. As such, many professional fields even disappear as new develop on the borders of previous professions, while completely unique novel professions are in some cases developed as a consequence of scientific and technological development or societal demands (Palonen, Boshuizen, & Lehtinen, 2014). One field in which technological advancement opens radically new opportunities but also challenges existing opportunities is the use of visualizations in medicine. In this article, we focus on the development of visual expertise by re-analysing three earlier studies to see whether theories of conceptual change may enrich our understanding of such processes.

During the last few decades, research on professional learning and expertise development has produced many powerful theoretical approaches that have highlighted significant aspects of the processes that lead to high levels of competence and expertise in professional domains (Billet, Harteis, & Gruber, 2018). Studies that focus on experts' memory, problem solving, and knowledge restructuring as well as the role of intensive, high-level training (deliberate practice) have mainly been related to theoretical models of cognitive psychology and cognitive science (see Ericsson, 2018). In recent research on workplace or professional learning, many researchers emphasize the socio-cultural nature of professional learning as an additional level of analysis needed for understanding the complex nature of learning (Hakkarainen, Paavola, Palonen, & Lehtinen, 2005; Lehtinen, 2012; Ohlsson, 2011) that is required in a professional field (Billet et al., 2018).

In many cases, new emerging professional fields require knowledge and practices that are so radically different from conventional forms of expertise that mere monotonic learning based on existing knowledge, skills, and practices is not sufficient for coping with these requirements (Lehtinen, Hakkarainen, & Palonen, 2014; Ohlsson, 2011; Rasmussen, 1983).

These new fields resemble situations that students in general education or university face while learning new scientific concepts. In professional and science learning some concepts and phenomena are particularly difficult to learn because they are counterintuitive and radically conflict with professionals' or students' initial thinking and everyday conceptions. It is also typical that many people do not see the novel challenges in the situation but continuously try to interpret and solve them by using old routines (Merenluoto & Lehtinen, 2005; Tripsas & Gavetti, 2000). Such conceptual incommensurabilities indicate that adequate learning does not solely refer to the integration of new knowledge into existing knowledge structures, but also involves conceptual change in the underlying framework theory in which the prior concepts are embedded (Carey, Zaitchik, & Bascandziev, 2015). These kinds of cases wherein an initial conception is embedded in a larger theory-type framework are often resistant to teaching attempts (Carey, 1986). Researchers within the research tradition of conceptual change have extensively studied learning challenges faced while learning scientific and mathematical concepts and developing well-established theoretical models that describe and explain various learning trajectories. Some trajectories are leading to an adequate scientific understanding, whereas some others result in various misconceptions or synthetic conceptions that integrate some aspects of the correct concepts with initial conceptions (; Vosniadou, 2014).

However, theories of conceptual change, which have been successfully applied to describe prerequisites of radical changes in scientific knowledge, are not widely employed in research on professional learning and expertise development (Lehtinen et al., 2014). Most studies of conceptual change focus on the development of scientific and mathematical concepts in early childhood or within formal education.. Some professional tasks are more difficult to learn than others, and these differences cannot be explained by the mere complexity of a task. The manner of thinking needed in advanced professional practice is often based on a completely different framing of the task and corresponding situation than laypeople would assune What is also typical for professional learning is that some misleading beliefs are resistant to instructional efforts (e.g., Chalofsky, Rocco, & Morris, 2014; Leana & Barry, 2000). This article summarizes some of the findings of our research project—which focussed on the development of expertise and professional practices in interpreting medical images—and discuss whether theories of conceptual change would help to understand the nature of these individual level change processes. The empirical cases are based on a reanalysis of previously published results. When conducting the original studies the analyses relied on theories of expertise and visual perception and the conceptual change theories were not applied.

Theories of Conceptual Change

Theories of conceptual change originally developed in science education as an attempt to more thoroughly understand frequently observed misconceptions of scientific phenomena (Posner, Strike, Hewson, & Gertzog, 1982). The concept is rooted in developmental theories that emphasize the role of prior mental structures in interpreting new situations, on the one hand (e.g., Piaget, 1974), as well as in the philosophy of science—particularly in the Kuhnian method of describing scientific revolutions (Kuhn, 1970)—on the other hand. Several researchers have elaborated upon further theories of cognitive processes related to the situations in which learners' prior knowledge and conceptions are incongruent with the new concepts they are learning.

Research on the difficulties associated with learning scientific and mathematical concepts has resulted in a few well-established theories of the development of students' conceptual understanding, such as ontological shift (Chi, 2008; Chi, Slotta, & de Leeuw, 1994), 'knowledge-in-pieces' (diSessa, Gillespie, & Esterly, 2004), and framework theory (Vosniadou, 2014). The framework theory approach, proposed in the 1980s and 1990s and later elaborated upon by Vosniadou (2013), is widely applied in research on conceptual change in learning scientific and mathematical concepts, although it can also be perceived as a promising model for dealing with some challenges arising in professional learning. In early studies, researchers reported that children tend to develop relatively coherent, theory-like, mental models for physical phenomena based on their everyday experiences. These frameworks connect concrete experiences and ontological and epistemological beliefs that then make sense of and explain those phenomena. The most widely cited example of these frameworks is children's attempts to develop mental models of the Earth and the day/night cycles. Based on their daily experiences, children develop framework theories for explaining physical phenomena they encounter in their environments. In a similar way, early experiences in learning numbers and using numbers to count result in a framework theory of numbers. This framework theory comprises features of numbers typical for natural numbers; for instance, each number is represented by one symbol, the size and order of the numbers are immediately visible, and each number has a successor. These beliefs are adequate in the field of natural numbers but often cause difficulties in children's learning of rational numbers (Van Dooren, Lehtinen, & Verschaffel, 2015) or real numbers (Lehtinen, Merenluoto, & Kasanen, 1997).

A more recent development in conceptual change research questions the original belief that conceptual change always indicates that scientific concepts would be replaced with initial or naïve conceptions. Several studies have demonstrated that, in many cases, the learning of advanced scientific concepts does not result in the replacement of the initial concepts; rather, the scientific and initial concepts coexist (Vosniadou, 2013), which is quite often the case in situations in which initial conceptions are strongly established. This phenomenon has been studied by comparing tasks wherein both scientific and initial conceptions lead to correct answers (congruent tasks) as well as tasks in which initial concepts would lead to incorrect answers if the activation of the initial conceptions was uninhibited (incongruent task). For example, the size of two fractions in congruent tasks means that in bigger fractions the whole number elements (numerator and denominator) are larger than those of the smaller fractions, whereas in incongruent tasks, the smaller fractions have larger whole number elements. Research reveals that, even among highly mathematically educated participants, their reaction times for incongruent tasks are longer than those for congruent tasks (Obersteiner, Van Dooren, Van Hoof, & Verschaffel, 2013). The explanation for a longer reaction time is that, in the case of a fraction comparison, the initial conception implies that the natural number-based size comparison is automatically activated and that the participant must inhibit his/her inadequate reasoning before providing an answer.

These findings regarding the coexistence of initial and scientific concepts are related to Kahneman's (2011) description of fast and slow thinking and dual process theory (Evans & Stanovich, 2013; Gillard, Van Dooren, Schaeken, & Verschaffel, 2009). People tend to use automatized routines when quickly reacting to tasks they encounter, which normally leads to adequate responses; reflective thinking is thus exclusively activated if they notice the presence of something unfamiliar within those tasks.

If initial and scientific conceptions co-exist, practical reasoning and problem solving therefore require the meta-conceptual awareness and ability necessary to regulate the use of different conceptions according to situational requirements. For example, in most daily activities, naïve physical conceptions work sufficiently but may lead to inaccurate conclusions in complex situations. In mathematics, this regulation is clearly visible in advanced thinking because all number systems (e.g., natural, rational, and real numbers) are mathematically correct and required in different situations (Merenluoto & Palonen, 2007). In less self-evident reasoning situations, regulation is difficult and subject to cognitive biases (Kahneman, 2011).

Novel findings concerning the co-existence of initial and more advanced (scientifically correct) concepts have raised new opportunities for applying theories of conceptual change in professional situations. An important topic that research on professional learning should investigate is whether or not it is typical for people to possess widely shared initial conceptions that are incompatible with more advanced professional knowledge when learning professional knowledge and skills. In addition, if one's initial and more advanced concepts can co-exist, research must determine whether or not there exist situations in professional contexts in which the possible initial concepts are triggered and applied even though one would already possess more advanced and relevant concepts.

The first question raised in this study regards what triggers non-monotonic learning processes beyond prior experience (Ohlsson, 2011) and which require "some kind of reorganization of the ways on represents one's world" (Strauss, 1982, p. 2) The early conceptual change studies within the science education tradition highlight the role of cognitive conflict as the driver that triggers conceptual change processes (Posner et al., 1982). Later studies, however, indicate that cognitive conflict is a complex phenomenon that does not always lead to the type of conceptual change that overcomes incompatible prior knowledge (Limon, 2001; Merenluoto & Lehtinen, 2004). In science teaching, it is often possible to make clearly visible the conflict between beliefs and new concepts, which is however not necessarily the case in more complex and possibly somewhat messy working life situations. Thus, it is important that researchers pay attention to the condition that makes it possible for people to notice when their prior knowledge and skills are insufficient or irrelevant for coping with new challenges.

Based on their studies on teacher students' attempts to learn conceptually challenging pedagogical content knowledge, Merenluoto and Lehtinen (2004) proposed a theoretical model of the dynamics of motivational, metacognitive, and cognitive processes in experiencing cognitive conflict and conceptual change. The perception regarding the demands of a new situation or task is influenced by a student's cognitive, metacognitive, and motivational sensitivity to the situation's novelty. From a cognitive point of view, sensitivity refers to noticing the fundamental difference between one's prior knowledge and a new task's cognitive demands as well as one's meta-conceptual awareness of this difference. Motivational sensitivity refers to an individual's tendency to look for novel and surprising features during working or learning activities (Merenluoto & Lehtinen, 2004). Low sensitivity indicates that, even in situations wherein a person is confronted with tasks in which his/her prior knowledge and skills are not sufficient for an adequate performance, the person nevertheless does not feel the need to develop new skills or acquire new knowledge that would more efficiently enable him/her to manage new situations. In the case of high sensitivity, a person possesses sufficient prior knowledge and the metacognitive skills necessary to understand that the cognitive demands of new tasks extend beyond his/her current competences, and he/she is disposed to pay attention to the unknown aspects of the tasks that may lead to learning that subsequently overcomes the constraints of his/her prior knowledge (Merenluoto & Lehtinen, 2004).

The co-existence hypothesis has raised an additional question related to sensitivity. Studies on cognitive biases in several domains reveal that people do not always apply their most advanced knowledge in problem-solving or decision-making situations (Kahneman & Tversky, 1996), which relates to the findings of one's non-monotonic development of expertise (Patel & Groen, 1991). At a certain phase of expertise development, people might possess although be unable to apply the necessary knowledge in a complex practical situation (Jaatinen, Palonen, & Lehtinen, in press).

A lack of sensitivity to novel challenges is also related to the many professional development trajectories. Ericsson (2018) demonstrates that even in professions that require long and demanding professional training (e.g., medicine), only some people continuously focus on improving their performance to reach higher levels of expertise, whereas many forfeit their engagement in deliberate practice, thereby leading to premature automation and arrested expertise development.

Conceptual Change and Complex Professional Practice

The framework theory approach of conceptual change research is perceived as a promising approach in professional learning (Achtenhagen, 1995; Tillema & Orland-Barak, 2006; Tynjälä, Nuutinen, Eteläpelto, Kirjonen, & Remes, 1997), although it is not widely applied in empirical research on professional or workplace learning. Most research on conceptual change focusses on situations in which learners struggle to acquire a scientifically correct understanding of a new concept in a situation in which their initial conceptions of the phenomenon conflict with this new concept. One may assume that, in professional learning, these kinds of situations typically exist during pre-service training. For example, medical students' initial concepts can result in misconceptions that affect their development of clinical skills (Södervik, Vilppu, Osterholm, & Mikkilä-Erdmann, 2017). Nevertheless, the learning challenges people face in the workplace are not necessarily related to individually well-defined concepts; rather, new technologies and work processes require learning within a complex system of diverse types of knowledge and skills (Boshuitzen & Schmidt, 2008;

Lehtinen et al., 2014; Ohlsson, 2011). Lehtinen and his colleagues (2014) summarized the findings of studies on scientific reasoning and professional practices in research groups. They concluded that the knowledge needed in advanced scientific practices can be described as layers of various types of knowledge, including general knowledge related to principles of scientific reasoning, domain-specific theoretical and methodological knowledge, and knowledge related to disciplinary epistemic cultures and situated practices (Lehtinen, McMullen, & Gruber, 2019).

Visual Expertise and Conceptual Change

Technological development continuously offers new methods of producing images and visualizations that facilitate existing professional practices and in some cases deeply reshape professionals' opportunities to observe, diagnose, or interpret phenomena important in their respective fields. The skills needed to make use of these new visual tools are becoming important in many professions, and new professional fields are emerging based on novel visual tools. Radiologists have traditionally interpreted x-rays of the human body, but recent technological developments have provided radiologists with powerful new methods that extend their opportunities for viewing phenomena yet simultaneously challenge their existing expertise (Bertram, Helle, Kaakinen, & Svedström, 2013). Meteorologists, air traffic controllers, big data analysts, and pathologists all interpret images, and an important part of their expertise involves visualizing important phenomena with the help of this visual material (Van Meeuwen, 2013). In some visualizations, professionals are not only more qualified to draw conclusions based on those images, but they also truly see things that laypeople cannot see. From the perspectives of professional learning and expertise development, it is interesting to analyse the initial learning when novices or laypeople learn the skills typical among professionals in addition to the process when experts of diagnosing certain images extend their expertise to novel visualizations relevant in their field.

These situations call into question the role of learning new conceptual knowledge and professional practices as well as the kinds of conceptual change processes that are related to initial learning and the subsequent extension of expertise.

Some studies demonstrate that experts' knowledge bases and the automaticity of knowledge can result in inflexible methods of coping with novel task demands. In expertise research, these methods have been described as functional fixedness or reductive bias (Feltovich, Spiro, & Coulson, 1997), which generally refers to evidence of rigidifying the effects of long-term practice. Based on this evidence, we therefore expect that expert performance must primarily be considered domain-specific.

Aims of the Study

This study aims to both present the findings of three earlier studies on medical image diagnosing and analyse whether and how theories of conceptual change may explain their findings. All three studies describe situations in which people must learn new diagnostic skills. In the first study, a group of novices participated in a short training session aimed at helping them notice diagnostically important features of x-rays, which are difficult to see. In the second study, experienced specialists in one imaging technology analysed cases using different imaging systems (i.e., near and far transfer). In the third study, experienced specialists in another imaging technology and medical students received eye movement modelling-based training to analyse cases with a new imaging technology.

In their seminal studies, Boshuizen and Schmidt (2008) describe how formal biomedical knowledge and practice-based knowledge—that is, 'illness scripts'—were integrated during professional development. Studies on the use of medical visualizations highlight two additional layers of necessary knowledge. In this very technical field, a deep understanding of the affordances and constraints of a particular technology is an important aspect of expertise (Lesgold et al., 1988). In addition, professional communities that work with a specific technology possess typically developed and shared professional practices that have proven helpful for diagnosing (Rystedt, Ivarsson, Asplund, Johnsson, & Båth 2011). When medical students and residents are studying to acquire the skills necessary to use a particular imaging technology, they must develop their expertise in all these layers; these students evidently face the greatest conceptual change challenges in learning theoretical biomedical knowledge. It is also possible that these students possess naïve ideas that conflict with the practical illness scripts shared with their experienced colleagues. As newcomers to the field, they are not likely to possess strong prior knowledge of either the technologies' specific features or of the professional practices typical in the field.

Thus, we can hypothesize that when novices learn the skills needed to interpret certain types of medical images, they may face conceptual change challenges related to the basic theoretical knowledge underlying the diagnosis process. However, they must also learn other layers of knowledge in which theories of conceptual change in their original forms (describing changes in well-defined scientific concepts) may not be as relevant as is the case of describing the challenges associated with learning scientific concepts.

When an expert in one imaging technology extends his/her expertise to other technologies and visualizations, the conceptual change challenge is mainly due to the possible conflict between his/her prior knowledge of the features of imaging technology and the affordances and constraints of the new technology. A possible conflict can also be identified between the professional practices and knowledge cultures of the familiar and the new field, respectively. Based on expertise studies (Feltovich, Spiro, & Coulson, 1997), two competing hypotheses emerge. Extensive experience with one technology has created strong framework theories that lie behind interpretations of the affordances of imaging technologies and professional practices, and thus changing the interpretations and professional practices is difficult. The alternative hypothesis is that, due to their extensive practice with another visualization technology, these experts already possess well-developed and flexible underlying theories that are adequate in the new field as well, and, thus, no conceptual change is required. In this case, professionals are quick to learn how to diagnose in the new field if they receive guidance on effective professional practices with the novel technologies.

Sub-Study 1: How Novices Learn to See Features in X-Rays that They Previously Failed to Notice

This case study describes team members of an international, interdisciplinary research project who participated in a half-day training session in x-ray diagnosis (Gegenfurtner, Lehtinen, Helle, Nivala, Svedström, & Saljö, 2019). The project focussed on learning and medical imaging, and the trainer was one of the project's radiologist experts. None of the team members who participated in the training session had received any medical education, and all were untrained in the language and practices of diagnostic radiology. In order to help the education researchers plan experiments for medical image expertise, the course aimed to offer them experience in producing diagnoses from chest x-ray pictures.

The training session was videotaped. During the meeting, the radiology expert provided background information on the diagnosis and demonstrated what kinds of visual practices he typically employed to diagnose x-rays. The course focussed on learning to differentiate between chest x-rays of normal lungs and x-rays of patients with a pneumothorax—a potentially mortal injury wherein air pours into the pleural cavity. X-rays offer two indicators of a pneumothorax: an extremely thin white line called the pleural line and a minor unbalance of the chest. The visual practices the expert demonstrated in the course aimed to scaffold the newcomers into 'seeing' the pleural line and the collapsed rib spaces on the studied chest x-rays to decide whether or not a pneumothorax was present.

The training session commenced with a lecture on the relevant aspects of human anatomy, and the expert explained the condition's aetiology. He then continued by displaying a number of x-rays side by side in the light box. The expert asked participants to make a diagnosis based on the presented x-rays, and none of them were able to see the pleural line in any x-rays. Only after this phase, the expert provided technical information regarding the meaning of each colour (i.e., white, levels of grey, and black). In addition, he offered practical tips of some professional practices, such as zooming, and concrete scaffolding by highlighting where the thin line is positioned. After these interventions by the expert, the participants were gradually able to see the line and later notice it in new x-rays.

The participants experienced difficulty in determining whether or not an unbalance of the chest was present in the x-rays. Thus, the expert again presented a few professional practices to facilitate the task. For example, by turning an x-ray upside down, the visual appearance changed, and this novel presentation of the lungs and rib cage made visualizing the unbalance between the two halves of the chest easier.

A radical change in participants' ability to visualize diagnostically relevant features of the x-rays evidently occurred during the training session. This means that the participants had to construct a system model of how this particular part of the body works and to connect it to the real-world experience of handling bodies. This happened with the help of imaging technology (x-ray) that mediated the connection between abstract concepts and the physical situation. This, in turn, required that participants familiarized themselves with the affordances of this particular technology. In addition, certain professional practices were needed to support the connection of all these elements.

When analysing whether or not theories of conceptual change are relevant for describing this change, we must first discuss how extensively the change in seeing relevant features of the x-rays is based on new conceptual knowledge acquired during the session and whether or not this new knowledge conflicts with some typically held beliefs. The conceptual knowledge of the pneumothorax acquired during the training session's initial theoretical introduction was completely novel to some participants and enriched the prior knowledge of others.

Crucial information involved the knowledge that there is a pleural cavity between the lung surface and chest. Lungs and chest are not interlocked but the partial vacuum in pleural cavity holds the surfaces close to one another when people are breathing by the muscles of the chest area. A pneumothorax implies that due to a hole in the chest, air can flow into the pleural cavity. This knowledge made it possible for the participants to imagine how a chest injury can lead to a collapsed lung. This mental model supported the visual search of chest x-rays. The second question in this theoretical analysis inquires into how easily one may acquire this knowledge as well as whether the enriching of existing knowledge is sufficient or whether changes in some commonly held belief systems among lay people are required. To our knowledge, no systematic studies have yet analysed the beliefs lay people typically hold regarding the anatomy of the lungs, but we can assume that the fact that the lung surface is separated from the chest, and that it is the partial vacuum in the pleural cavity which keeps lungs in their form, might be counterintuitive. In this sense, we may observe an instance of conceptual change that is somewhat similar to the examples of science learning; however, judging by the participants' experiences in the training situations, the possible initial 'theory' was not strongly resistant to change.

It was also necessary for the novice participants to get some basic understanding of how elements of the body are visible in x-rays which show boundaries between regions of different density rather than boundaries between body components. It is hard to notice the pneumothorax in a radiographic image because the air in the lungs has the same density as air that entered to produce the pneumothorax situation, and the contour is seldom apparent. Through experience, one can also learn to detect that the overall shape of the air-filled portion of the chest is abnormal.

This acquired anatomical and x-ray specific knowledge alone did not lead to experienced changes in participants' ability to visualize the indicators of a pneumothorax; rather, the expert needed to provide more extensive guidance on the associated professional practices. These kinds of methods that are typical for experienced professionals in areas that require the interpretation of visual information have been studied in the research tradition of professional vision (Goodwin, 1994). In his seminal work on professional vision, Goodwin (1994) analysed practices and meaning-making procedures that are developed and socially shared within communities of professionals. Professionals apply situated practices, category systems, material tools, and embodied acts that make possible the visualization of objects in their work in such a way that is impossible for laypeople who are unfamiliar with these practices of professional vision. In this case study, for example, the zooming in and turning of x-rays upside down as well as detailed guidance for visualizing the pleural line are visual practices similar to those reported in previous studies in other fields (e.g., archaeology) (Goodwin, 1994).

For archaeologists, Goodwin (1994) identified that the visual practices of coding, highlighting, and producing material representations are central to the activity of analysing post moulds. More specifically, an expert archaeologist and her student interacted while learning how to use a coding scheme to classify the colour of soil (i.e., the coding practice), how to make a post mould perceptually salient against an amorphous background (i.e., the highlighting practice), and how to make a profile map of an excavation site (i.e., the practice of producing material representations).

With the help of the professional practices we observed, the participants clearly experienced a radical change in their ability to visualize diagnostically important features in the chest x-rays. Nevertheless, this case study is not an instance of conceptual change similar to that as described in dominating theories and empirical findings that concern the difficulties associated with learning scientific concepts. Increased conceptual knowledge and possible conceptual change regarding the anatomy of the lungs were part of the developed diagnostic skills. However, it is difficult to perceive that any particular initial belief or habit would be incommensurable with the professional practices needed to visualize the relevant aspects of the x-rays. These were merely new practices with which the participants were unfamiliar prior to their training. Changes that led to more advanced visual perceptions could be understood in terms of layers of the cognitive and activity systems, including enriched anatomic conceptual knowledge, detailed technical knowledge of the grey levels depicted in x-rays, and professional visual practices used by radiologists to diagnose these kinds of x-rays.

Sub-Study 2: Horizontal Transition of Expertise

In many cases, technological and organizational changes indicate that professionals who have acquired a high level of expertise in one specific field must extend the scope of their expertise into new fields, such as new technologies that offer opportunities to enrich their repertoires of tools and alternative methods of dealing with the work objects. In some cases, this horizontal extension of expertise (Gegenfurtner, Nivala, Säljö, & Lehtinen, 2009) implies the mere enriching of one's existing knowledge and skills; in other cases, however, this extension can be more difficult and require deeper changes that at least appear similar to those of conceptual structures required for learning new scientific concepts that are incommensurable with previous conceptual frameworks (Lehtinen, et al., 2014).

Through a series of studies, our group focussed on the horizontal changes among medical experts when they were asked to diagnose patient cases using use new imaging technologies. In the first study, the participants were nine medical professionals from a university hospital (Gegenfurtner & Seppänen, 2013), five of whom had backgrounds in PET diagnosis and four in CT diagnosis. All participants conducted diagnoses on a daily basis via the methods of their specializations. In this study, they diagnosed images of patient cases in three different ways: firstly via their familiar method (PET or CT), secondly via a method with which they were unfamiliar (PEY or CT), and thirdly via a method that combined their familiar and unfamiliar methods (integrated PET/CT). During the process, participants thought aloud, and their eye movements were recorded.

The results in their diagnostic accuracy revealed a significant difference between the familiar and unfamiliar conditions although no difference between the familiar and combined conditions. These experts could not directly transfer their skills to new methods, as the horizontal transition rather required some new knowledge or skills. In all conditions, participants performed more and longer fixations in task-relevant than task-irrelevant areas. In the number of fixations, no difference was identified between the conditions, although a significant difference was identified in fixation times between the familiar task and the two other tasks. In the semi-familiar combined task and unfamiliar task, participants had longer fixation times than those in the familiar task. Participants' ability to recognize task-relevant areas in the unfamiliar task indicated that they possessed the conceptual knowledge needed to focus their attention on diagnostically relevant aspects of the visualizations. The finding that they spent more time analysing the relevant aspects in unfamiliar conditions refers to the scarce experience and professional practice required to use that particular technology.

Think-aloud protocols afforded some additional information about the work processes. In diagnosing unfamiliar visualizations, the participants tended to apply the working methods, such as the order of looking at the images when working with their familiar methods. Think-aloud protocols also referred to the problems experts encountered when dealing with the unfamiliar visualizations. These difficulties were not due to the differences in their underlying biomedical knowledge, but were rather based on the completely different ways whereby the images represented the human body. A CT image is an analogical presentation of a patient's anatomical structure, whereas a PET scan is a digital construct of statistical data that describes the concentration of radioactive tracers, which are typically indicators of the sugar levels in different organs. All participants were familiar with the basic principles of the two methods although nevertheless encountered substantial difficulty in beginning to diagnose the unfamiliar visualizations. Even in the combined visualizations, the participants often experienced cognitive overload and hoped to remove the unfamiliar layer from the images. In diagnosing unfamiliar visualizations, the participants tended to apply the working methods they used when working with their familiar methods.

Based on the results, we may conclude that the participants were able to flexibly adapt their biomedical knowledge to new situations (see Feltovich et al., 1997). Based on these findings, we can conclude that, in the case of horizontally transitioning from one visualization method to another, the challenge in diagnosis seemed to be in the method-specific knowledge and working conventions (see Lesgold et al., 1988), which means there was no need for conceptual change in the underlying biomedical concepts. A somewhat similar challenge was encountered in changing the professional practices; in these no-guidance situations, participants tended to apply the practical methods of their own specializations to new situations even though these methods were not the most efficient in the new areas. However, based on the comparison, it is impossible to determine whether these working habits were based on larger framework theories and thus were resistant to change, or whether adequate professional guidance was absent. A limitation in this design was that no novice control group was included, which would have made possible an evaluation of whether or not expertise in one technology assists experts' diagnosis in unfamiliar tasks more so than among novices who possess no prior experience with imaging technologies. Another limitation was the absence of an intervention that would have been necessary for studying experts' possible resistance to change when learning professional practices used in a novel imaging technology.

Sub-study 3: Intervention with eye-movement modelling

In a typical workplace learning situation, a newcomer observes how an experienced worker performs tasks specific to the profession (Billett, 2014). In a demanding diagnosis that involves complex visualizations, merely observing a professional's work produces scarce information. In a few recent studies, eye movement modelling examples were employed as a training tool in visually challenging situations. Our intervention study aimed to compare experts and novices and study the effects of eye-movement modelling on their learning to diagnose unfamiliar visualizations (Gegenfurtner, Lehtinen, Jarodzka, & Säljö, 2017). In addition, we focussed on the differences among participants' diagnoses of patient cases with separate PET and CT images as well as integrated PET/CT visualizations.

The novice group involved fourteen first-, second-, and third-year medical students, while the expert group involved nine PET and CT specialists, who were peer nominated as highly respected experts in their field. The expert participants were specialists in either PET or CT diagnostics although possessed no experience using the integrated PET/CT. In the eye-movement modelling intervention, participants watched a video in which an expert in PET/CT diagnosis conducted a typical diagnosis procedure. The video included eye movements, think-aloud recording, and screen captures of actions the expert performed with the device.

The participants' task was to diagnose patient cases with the help of a PET/CT visualization comprising 275 PET scans and 275 CT scans that presented dynamic, three-dimensional PET/CT visualizations. The participants were first asked to diagnose a patient case (baseline task). During the second phase, they watched an eye movement modelling example prepared by an expert of integrated PET/CT diagnosis. In the eye movement modelling, a 158 second long digital video was presented to the participants in which an expert modelled a typical procedure used in solving this kind of tasks. The video showed the expert's eye movements, the think-aloud protocol and the actions performed (key strokes and mouse clicks). Eye movements were presented in red dots indicating eye movements in real time. The size of the dots indicated how long the expert looked at a particular spot. In the third phase, participants were asked to diagnose the same case on their own (retention task), and in the final phase, they diagnosed a novel case (transfer task).

The diagnostic accuracy differences between the groups revealed that the PET and CT experts outperformed the student group on all measurement points, which was expected because the integrated PET/CT included a technology component familiar to the expert participants. However, the experts' baseline performance was not optimal because a substantial improvement was identified in the diagnoses after the eye-movement modelling. Interestingly, after the students watched the eye-movement modelling example, their accuracy improved in the retention task although remained constant in the transfer and baseline tasks. However, experts' performance improved substantially in retention and remained at a constantly higher level in the transfer task.

Experts' generally higher accuracy levels indicate that their conceptual biomedical knowledge and illness scripts (Boshuizen & Schmidt, 2008) necessary for diagnosis were originally more advanced than those of the student participants prior to the intervention. In addition, experts possessed strong professional backgrounds in one of the technologies integrated into this new tool. Both groups gained knowledge from the eye-movement modelling from the baseline task to the retention task, which indicates that eye-movement modelling is a potentially effective training method for visual diagnosis. However, the most important finding is that the expert participants were able to apply the skills they had learned during the intervention in the novel task. Many possible explanations exist for the strong difference identified between experts and novices in the transfer task. The short eye-movement intervention would likely not have been sufficiently effective to result in substantial changes in general biomedical or clinical knowledge. Experts more likely learned professional practices relevant for the diagnosing process with the new technology by watching the modelling examples, which indicates that acquiring new professional practices in these tasks was relatively easy and did not involve conceptual change challenges. The well-established professional practices in their familiar technologies were not harmful when learning useful strategies with a new technology; on the contrary, it is possible that prior knowledge in another visualization, including conceptual biomedical knowledge, knowledge of the technology's affordances, and professional practices (see Lesgold et al., 1988), made benefitting from the eye-movement modelling and learning to use the new technology easier for the expert group, thus attesting to the experts' flexibility (Feltovich et al., 1997).

Students were able to repeat the modelled diagnostic process in the retention task but were unable to make use of this procedure in the transfer task. Many possible explanations may address this limited learning gain. It is possible that the students did not possess the conceptual biomedical knowledge necessary to flexibly apply the procedure in novel tasks. Eye-movement modelling involved very little explicit support and no verbal scaffolding with regard to acquiring the necessary biomedical knowledge base and overcoming possible challenges of a conceptual change nature. The students may have possessed limited skills for handling the technology and may have lacked a general understanding of the affordances of visualization technologies. As such, they were unable to adequately apply the skills they had learned during the eye-movement modelling in the novel tasks. The connection between situated professional knowledge and conceptual biomedical knowledge practiced is important for a reliable diagnostic process (Gilhooly et al., 1997). Due to this missing connection, students were only able to routinely apply the modelled professional practices in novel situations and did not absorb the very idea of these practices, which would have been necessary for their relevant use in novel tasks.

Discussion

Theories in behavioural sciences are typically developed to address certain research questions and are related to a particular set of units of analysis (Lehtinen, 2012; Säljö, 2009). Research in another domain often involves phenomena that seem to possess at least some similarities to the questions studied in a domain wherein a theory was originally developed, which raises the question of how the elsewhere-developed theory may be applied in that new domain. Theories of conceptual change were developed to describe the difficulties young children and students in formal educational settings face when attempting to understand certain scientific (and later mathematical) concepts. What is common among the concepts dealt with in the conceptual change research is that belief systems based on everyday experiences, prior learning in school, and, possibly, innate predispositions conflict with the scientific theories and explanations developed through research traditions. However, the possible cognitive (and affective) mechanisms that cause these difficulties, misconceptions, and resistance to change may be more general and applicable in a variety of domains—not only in the learning of scientific and mathematical concepts. This article aimed to re-analyse findings from a few previously published studies on professional learning and search for possible evidence about conceptual change theories that might explain some of our findings. The studies discussed herein focussed on situations in which novices learned how to diagnose medical images or in which experts of one imaging technology analysed images using another technology.

The main finding of the sub-studies was that, unlike science learning—which typically involves one clearly defined core scientific concept that challenges prior knowledge—the knowledge needed for the medical diagnosis processes analysed in this article did not exclusively consist of one or a few well-defined scientific concepts, but rather involved a system of various types of knowledge and practical skills. When novices and experts diagnosed novel medical visualizations, many layers of knowledge and skills needed to be developed, including underlying anatomical or conceptual biomedical knowledge, further practical knowledge of particular syndromes (illness scripts) (Boshuizen & Schmidt, 2008), knowledge of the particular technologies' affordances (Lesgold et al., 1988), and practices described as professional vision (Goodwin, 1994). Some of these aspects were already familiar among the participants, whereas others were easy to learn among those who already possessed relevant conceptual knowledge.

In considering this multi-layer nature of professional skills, it is important that we discuss on which of the levels the conceptual change approach can be applied. It is obvious that, in learning the anatomical and biomedical knowledge needed for diagnosis, medical students face conceptual change situations in which the sole accumulation of knowledge is not sufficient and in which a further radical restructuring of prior framework theories is required (e.g., Södervik et al., 2018). Presenting some examples of such changes was exclusively possible in the first sub-study discussed in this article. When novices learned how to visualize some diagnostically important features of x-rays, they were required to additionally learn some partially counterintuitive pieces of conceptual knowledge. The findings indicate that it is important that novices become aware that they must change their beliefs, although in this case, acquiring the scientifically correct conceptions was relatively quick. In the two other studies on horizontal transition, only indirect evidence asserted that acquiring the conceptual scientific knowledge background necessary to diagnose novel visualizations takes time.

In this study, some findings revealed that participants with a long professional history in one medical visualization field tended to prefer rigid attempts of using the practices with which they were familiar from their own field, even though they were not efficient for dealing with the new visualization types. However, this extended practice-based rigidity was less dominant in the results than were indicators of expert flexibility (Feltovich et al., 1997). Even a relatively short-term modelling of professional visual practices in a new field resulted in substantial and sustainable improvements in experts' performance.

All sub-studies included situations in which participants were not ably to continue previously learned rule-based activity (Rasmussen, 1983) and at least some non-monotonic learning (Ohlsson, 2011) was needed. The framework theory (Vosniadou, 2013) may be relevant for predicting when the changing of professional practices to adapt to new professional situations is relatively easy and when stronger resistance to change can be expected. However, the mere individual mental-level analysis of traditional conceptual change research must be expanded to cover the sociocultural analysis of professional visual practices as well as the affordances and challenges of the available technologies.

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