LEARNING MICROSCOPIC PATHOLOGY: SCAFFOLDING THE EARLY DEVELOPMENT OF EXPERTISE IN MEDICAL IMAGE INTERPRETATION

by

Markus Nivala

From the Centre for Learning Research and Department of Teacher Education
University of Turku, Finland

Supervisors:

Professor Erno Lehtinen
Centre for Learning Research
Department of Teacher Education
University of Turku, Finland

Professor Roger Säljö
Department of Education
University of Gothenburg, Sweden
Centre for Learning Research
University of Turku, Finland

Reviewers:

Professor Henny Boshuizen
Centre for Learning Sciences and Technologies
Open Universiteit, the Netherlands

Professor Sten Ludvigsen
Institute of Health and Society
University of Oslo, Norway

Opponent:

Professor Henny Boshuizen
Centre for Learning Sciences and Technologies
Open Universiteit, the Netherlands

Abstract

Medical imaging is becoming increasingly important and omnipresent in everyday diagnostic practice. Consequently, the development of imaging technologies creates new challenges and opportunities for professional development and medical education. This thesis investigates how medical students learn to interpret medical images; what are the prerequisites and practices of learning microscopic pathology, and how learning can be scaffolded in a virtual microscopy environment. While similar themes have been studied quite extensively in regards to expert performance, surprisingly little is known about novices and the challenges they face in entering the field.

There is an ongoing debate about the role and extent of the basic sciences in medical curriculum. It has been argued that basic sciences do not play a central role in experts' diagnostic reasoning, and therefore, the emphasis of medical education should shift towards teaching and acquiring clinical knowledge. Study I examined how students' prior knowledge of basic histology and histopathology predicts early learning of diagnostic pathology. Data were collected during two preclinical courses that medical students (N=118) attended in their first and second years of medical school. The measurements included tests on biomedical and clinical knowledge and a performance test in diagnostic pathology. Second-year performance on the diagnostic pathology examinations was predicted by the students' prior knowledge of histology, but not by the students' prior knowledge of histopathology. The results confirmed the long-term value of basic science studies in the preclinical phase.

Besides prior knowledge and experience, it is often suggested that diagnostic expertise depends on innate abilities. It has been argued that students should be tested for their visual abilities to ensure that they are able to learn visual diagnostic skills. Study II explored whether visual perceptual skills, personality characteristics and/or prior knowledge predict students' performance in microscopic pathology. The Test of Visual Perceptual Skills was used to assess students' visual perceptual abilities, and The Big Five Personality Inventory was administered as a self-assessment of personality traits. Student performance in microscopic pathology was measured in the beginning (pre-test) and at the end (post-test) of the introductory course in pathology. In addition to the pre-test, histology and cell biology grades were used as a measure of prior knowledge. Furthermore, the course examination scores (microscopy examination and test of biomedical knowledge) were also used as performance measures. The results indicated that visual perceptual ability and personality characteristics have a small but detectable

effect on initial learning of microscopic pathology. However, performance in the post-course microscopic pathology tests was predicted only by prior knowledge. Therefore, the effect of innate abilities is somewhat negligible as medical students are able to learn entry-level microscopic pathology irrespective of their personality traits or visual perceptual abilities.

Study III described and evaluated an intervention that was designed to improve medical students' (N=105) recognition of normal histology in order to improve their ability to discern abnormalities and performance in diagnostic pathology. This was done by utilizing virtual microscopy for the following purposes: (1) students were provided with online materials of normal cell and tissue structures, (2) an online entrance examination, (3) digitized slides with abnormal features indicated by visual and textual cues, with normal areas for comparison, and, (4) three virtual quizzes taken in class for self-diagnostic purposes. Histological knowledge was assessed in the beginning (normal histology) and at the end of the course (abnormal histology), and compared to historical controls. Furthermore, the students completed an anonymous course evaluation of the learning environment and the different elements of the course. The experimental group significantly outperformed the historical controls in recognition of normal histology. However, while students embraced the idea of emphasizing normal histology, historical controls performed better in the abnormal histology test. Although the intervention improved students' recognition of normal histology, the results showed that this alone is not sufficient to produce applicable knowledge structures.

Study IV investigated how visual and conceptual cues can be used to scaffold students' reasoning and to elicit productive engagement with microscopic specimens. Fifteen pairs of second year medical students participated in two sessions in which the students used a virtual microscope as a diagnostic tool in the context of learning pathology. The students were presented with six authentic tissue samples with varying levels of scaffolding; 1) no cues, 2) visual cues, and 3) both visual and conceptual cues. The sessions were videotaped, and the students were required to write down the findings and diagnosis for each case. The findings reported by the students were classified into relevant, irrelevant and false. Based on the video, the false findings were further classified according to whether the students focused on the clinically relevant area or level of the sample while coming up with the findings. Finally, diagnostic episodes were analyzed qualitatively with the focus on the different difficulties the students faced and how the annotations affected their reasoning process. As expected, the number of relevant findings increased as the level of scaffolding increased, while the number of irrelevant findings decreased. Cues with both conceptual and visual information reduced false findings considerably,

but the presence of visual cues increased the number of false findings. However, without visual cues, the false findings arose mostly while the students were examining clinically irrelevant features of the slide. Although visual cues seemed to increase the number of false findings, the students made these claims while discussing and examining an appropriate part of the slide. In conclusion, the visual and conceptual cues improved students' performance, and guided the students' perception and reasoning in a manner that is productive in terms of learning to make clinically relevant observations.

Study V focused on virtual microscopy and the endogenous diagnostic practices that emerge in students' collaborative diagnostic reasoning. Fifteen pairs of medical students were asked to solve diagnostic tasks in a virtual microscopy learning environment. The students' collaborative efforts were analyzed qualitatively on the basis of approximately 20 hours of video recordings. To capture emerging problem-solving practices, episodes in which the students showed the most prominent signs of uncertainty were systematically identified and indexed. The analysis shows how the students used the technology as a mediating tool to organize and construct a shared visual field, and later, a shared understanding of the problem, through multimodal referential practices: gestures, three-dimensional manipulation of the image and paced inspection of the specimen. Furthermore, the analysis shows how the aforementioned practices coincide with students' medical reasoning in this particular learning context and how students employ a wide array of biomedical and contextual knowledge in order to produce, evaluate and crosscheck their diagnostic hypotheses. Finally, it is argued that as technologies develop, understanding the technical side of image production becomes an integral part of the interpretative process.

The results of the present work strengthen the evidence in favor of teaching basic sciences in medical curriculum. An understanding of basic sciences benefits students in two ways. In the long term, it scaffolds the learning of clinical knowledge and diagnostic skills. In the short term, it offers a coherent knowledge structure that enables students to overcome the present shortcomings of their still developing clinical knowledge. The results also show that in terms of medical image interpretation, prior knowledge is a better predictor of learning than innate abilities or personality characteristics. However, mere replicative knowledge without functional understanding of physiology is not sufficient. In order to improve diagnostic performance, the concepts of the basic sciences have to be actively applied to, and submerged into, clinical problems. Virtual microscopy can be used to introduce students to a plethora of authentic clinical cases in an accessible format. Although the mere availability of materials without pedagogical design is not an adequate incentive for students, virtual microscopy enables the use of cues and

collaboration to scaffold and challenge students' diagnostic reasoning. As shown by the present analysis, these scaffolds, in turn, enable a more meaningful engagement with the microscopic images. Visual and conceptual cues help students to avoid the most obvious pitfalls and errors and prompt students to engage with unexpected visual information in need of clarification. Collaboration elicits activities that benefit learning, that is, it reveals students' assumptions and explanations for mutual regulation, creates a sense of accountability and exposes students to alternative views and interpretations. In short, the empirical studies confirm the potential of virtual microscopy as an educational tool, but only in conjunction with appropriate pedagogical design. In order to take full advantage of virtual microscopy, more advanced, definite and explicit feedback mechanisms should be implemented. Virtual microscopy should be integrated into, not only added to, the current teaching practices.

The theoretical and methodological implications of the present work illustrate the importance of examining learning on multiple levels of explanation and emphasize the difference between acquiring expertise and applying expertise. Therefore, theories, models and descriptions of expert practices should not be implemented uncritically as pedagogical models or guidelines in early training. Research should focus on revealing the learning trajectories behind expertise, as each stage of development may also require qualitatively different pedagogical solutions. Finally, the ongoing development of imaging technologies changes and permeates the diagnostic process, and thereby creates new methodological challenges. As diagnostic work becomes increasingly embedded in, and enacted through, technology, it becomes more and more important to design naturalistic experiments in which the manipulation of the technological, and even social environment, is not only allowed, but understood as a central competence in the interpretation process.

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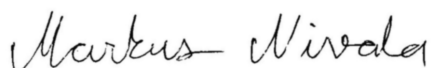
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Markus Nivala

Turku, Finland

List of original publications

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Study II Helle, L., Nivala, M., Kronqvist, P., Ericsson, K. A., & Lehtinen, E. (2010), Do prior knowledge, personality and visual perceptual ability predict student performance in microscopic pathology?. *Medical Education*, 44, 621–629. doi: 10.1111/j.1365-2923.2010.03625.x

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Study III Helle, L., Nivala, M., & Kronqvist, P. (2013). More Technology, Better Learning Resources, Better Learning? Lessons from Adopting Virtual Microscopy in Undergraduate Medical Education. *Anatomical Sciences Education*, 6(2), 73-78. doi: 10.1002/ase.1302.

LH contributed to the study conception and design; and to data collection, analysis and interpretation. MN contributed to the study design and data collection, and was responsible for the methodological and pedagogical adaptation of the virtual microscopy software. PK participated as a content-specialist, contributing to the design of the study, learning materials and tests. All authors revised the manuscript and approved the final version for publication.

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1.   Introduction

> "*[I]t is no surprise that start of the scientific revolution 'coincides'*
> *with the development of the telescope and the microscope.*"
>
> (Gribbin, 2002).

Medical imaging is becoming increasingly important and omnipresent in everyday diagnostic practice (Dikshit, Wu, Wu, & Zhao, 2005; Krupinski, 2010). Simultaneously, the development and diversification of imaging technologies is creating new medical knowledge and reshaping the nature of medical expertise, and thus poses new challenges for professional development and medical education (Miles, 2005; Ziai & Smith, 2012). At the same time, novel representational technologies such as virtual microscopy are creating new possibilities for education and learning. These advances, in turn, raise both theoretical and pedagogical questions regarding medical education.

This thesis investigates how medical students learn to interpret medical images; what are the prerequisites and practices of learning microscopic pathology, and how learning can be scaffolded in a virtual microscopy environment. While medical image interpretation has been studied quite extensively since the early 1980s, only a few studies have focused on the early development of these competencies. This becomes especially apparent if one takes into account the varying definitions studies employ for "novice" or "beginner". The definitions range from naïve controls (Nodine, Kundel, Lauver, & Toto, 1996) or medical students (Crowley, Naus, Stewart, & Friedman, 2003; Krupinski et al., 2006) to residents who are already specializing in the field (e.g. Wooding, Roberts, & Phillips-Hughes, 1999). The present work focuses on what could be referred to as "real novices", that is, students who are studying to become doctors (as opposed to naïve controls), but have little, if any, experience in interpreting microscopic images.

Furthermore, much of the research on medical imaging and education has been done in regards to technological implementation and the subsequent student perceptions and participation (Harris, Leaven, Heidger, Kreiter, Duncan, & Dick, 2001; Shapiro, Ko, & Jacobson, 2002; Kumar, Velan, Korell, Kandara, Dee, & Wakefield, 2004; Dee, 2009). While these studies have demonstrated the technological and pedagogical viability of web-based imaging solutions such as virtual microscopy, less is known about the preconditions and pedagogical arrangements that are advantageous for learning (Hamilton, Wang, & McCullough, 2012).

The domain of the thesis, pathology, is the study of the causes, development, morphology and clinical manifestations of diseases (Robbins, 2010). However, only a small minority of the medical students will pursue pathology as their main specialty; the majority of medical professionals do not examine pathological samples in their everyday work. Nevertheless, understanding the underlying principles of diseases is arguably important for practitioners of any medical specialty (Burton, 2005). As Brass (2009) argues, "[T]he ability to use new discoveries to rationalize clinical decision making is rapidly expanding. Understanding the scientific foundations of medical practice and the ability to apply them in the care of patients separates the physician from other health care professionals" (p. 1251).

1.1   Expertise in medical image interpretation

Although the educational aims and challenges of undergraduate pathology courses remain at least partly different from the professional development of specialists, expertise research offers valuable insights into the nature and prerequisites of medical image interpretation. Previously, expertise in medical image interpretation has been studied especially in the field of radiology (Norman, Coblentz, Brooks, & Babcook, 1992; Krupinski, 2010). Both pathology and radiology require the ability to combine visual information with clinical information and scientific knowledge. Therefore, the diagnostic process and expert reasoning are typically investigated in terms of cognitive or perceptual factors. Another often used, and overlapping, distinction is between the analytical and non-analytical processing of information.

1.1.1 The role of basic sciences in expert medical reasoning

Expert reasoning is often described as rapid, intuitive, automated, tacit, and characterized by a non-cognitive or non-analytical response to the available information (Eva, 2005; Norman, 2010; Pelaccia, Tardif, Triby, & Charlin, 2011). Despite their biomedical knowledge, diagnosticians seem to mainly rely on their clinical knowledge in routine diagnosis (Norman, 2005; Norman, Young & Brooks, 2007). However, even experts revert to the basic sciences and analytical reasoning in the most complex and difficult cases, as a failure to critically assess the intuitive diagnostic hypotheses may, for example, lead to premature closure and increased number of diagnostic errors (Norman et al., 1994; Eva, 2005; Kaufmann, Yoskowitz, & Patel, 2008). Nevertheless, as Norman (2007) argues, "basic science teaching is, occupying as it does a huge proportion of the preclinical curriculum, under constant assault" (pp. 401–402). For example, the hours allocated for histology teaching have been in slow, yet steady, decline since the 1950s (Drake,

McBride, Lachman, & Pawlina, 2009; cf. Bergman, van der Vleuten, & Scherpbier, 2011; Kaufman et al., 2008). This may be at least partly due to the aforementioned perception of basic sciences as somewhat invisible and even unnecessary in the everyday diagnostic work of clinicians.

Furthermore, both clinical teachers and medical students sometimes fail to see a clear connection between basic biomedical sciences and clinical work (Custers & ten Cate, 2002; Wilhelmsson, Dahlgren, Hult, Scheja, Lonka, & Josephson, 2010). Koens, Custers, & ten Cate (2006) reported that while basic science teachers and clinical teachers agree about the value of clinical knowledge in the medical curriculum, clinical teachers rate basic sciences as less important, especially when it comes to knowledge on microscopic and molecular levels. Moreover, Bhangu and colleagues found that only 28 per cent of second year medical students perceived that anatomy teaching prepared them to interpret medical images (Bhangu, Boutefnouchet, Yong, Abrahams & Joplin, 2010; cf. Kirschner & van Merriënboer, 2013). However, learning new diagnostic skills and knowledge is arguably a different phenomenon from using pre-existing skills and knowledge. For example, in a study by Fischer and Muller-Weeks (2012), 42 per cent of the physicians reported that they do not use basic science knowledge frequently in everyday diagnostic work. Physicians reported that they utilize basic science especially while reading scientific articles (84 per cent of the respondents) and training students (89 per cent). Thus, the fact that experts do not consciously use or externalize their basic science knowledge in their everyday diagnostic practice does not mean that basic sciences are irrelevant to learning and the development of expertise.

The role of biomedical knowledge, or basic sciences, in diagnostic expertise has also been debated in the field of cognitive psychology and expertise research (Rikers, Schmidt, & Moulaert, 2005). The "two-worlds" theory postulates that biomedical knowledge and clinical knowledge, while interconnected, constitute two separate knowledge bases and, therefore, support different forms of clinical reasoning (Patel & Kaufman, 1995). It is argued that as expertise develops, clinical knowledge replaces biomedical knowledge at least in routine diagnostic reasoning (Patel, Kaufman, & Arocha, 2002). According to encapsulation theory, which offers an alternative and more integrative view of the phenomenon (e.g., Schmidt, Norman, & Boshuizen, 1990; Boshuizen & Schmidt, 1992; Charlin, Tardif, & Boshuizen, 2000; Rikers et al., 2005), acquired biomedical knowledge becomes integrated with practical experience and encapsulated into clinically relevant, high-level, summarizing concepts (Boshuizen & Schmidt, 1992; Schmidt & Rikers, 2007). Rikers et al. (2005) exemplified encapsulation with the concept of "acute myocardial infarction", which, for an experienced physician, integrates anamnesis

(medical background), symptoms (e.g., chest pain, shortness of breath) and clinical findings (e.g., hypotension) into a coherent diagnostic explanation. In their seminal study, Boshuizen and Schmidt (1992) demonstrated how experienced physicians use encapsulated concepts that, indeed, abbreviate the underlying pathophysiological processes. According to Schmidt and Rikers (2007), the final stage of expertise development occurs when encapsulated knowledge is restructured into illness scripts, i.e., narrative cognitive entities that contain "a wealth of clinically relevant information about the *enabling conditions of disease*, as a product of growing experience with how disease manifests itself in daily life" (p. 1135). In any case, it seems evident that basic sciences serve different functions during the advancing stages of expertise development. While basic sciences do not necessarily translate directly into better performance in each phase of development, it may serve a "stepping stone" function in the acquisition of future expertise. Study I investigates the long-term effect histology and histopathology have on the learning of diagnostic pathology.

1.1.2 Expertise, innate abilities and medical image interpretation

In addition to biomedical and clinical knowledge, the interpretation of medical images requires visual acuity as well as task-appropriate adaptation and fine-tuning of perceptual processes. The extremely fast, effective and seemingly effortless expert performance has sometimes been interpreted as a sign of exceptional innate abilities. Consequently, there seems to be a largely held belief that expert performance in, for example, pathology, is at least partly due to "having a good eye" (Crowley, Naus, & Friedman, 2001; cf. Lesgold, 1984). Yet, it is arguable whether "having a good eye" depends on having better than average general or innate visual skills, or whether it is "merely" a domain specific set of skills accrued from experience (see e.g., Nodine, Kundel, Mello-Thoms, Weinstein, Orel, Sullivan, & Conant, 1999). For example, Nodine and Krupinski (1998) compared radiologists and laypeople on generic visual search tasks and concluded that "radiologists do not possess superior visual skills compared with laypeople" (p. 603). In fact, the ability to recall and recognize human anatomy seems to be domain specific and dependent on selective processing of clinically meaningful information. Myles-Worsley, Johnston and Simons (1988) showed that experience correlates with radiologists' ability to recognize abnormal radiographs, but not with face recognition. Furthermore, recognition accuracy of clinically irrelevant, normal, radiographs decreased as radiological experience increased. On the other hand, Wanzel et al. (2002) found that visual-spatial ability relates to *initial* competence in spatially complex surgery. Thus, while experience may even out the performance differences in the long run, differences in innate or pre-existing visual abilities might affect the (initial) rate of learning, an idea that has sparked off discussions

about aptitude testing in the more visual domains of medicine (e.g., Smoker, Berbaum, Luebke, & Jacoby, 1984; Rigby, Warren, Diamond, Carter, & Bradfield, 1991; Cross, 2005; Hamilton, van Diest, Williams, & Gallagher, 2009). Following this debate, Study II explores if visual perceptual skills, personality characteristics and/or prior knowledge predict students' performance in microscopic pathology.

1.1.3 The visual and cognitive components of medical image interpretation

Extending the discussion beyond innate or general abilities to the development of expertise, it is debatable, whether the learning of pathology is more dependent on, or limited by, visual or cognitive development and to what extent visual and cognitive processes guide each other (Lesgold, Rubinson, Feltovich, Glaser, Klopfer, & Wang, 1988; Nodine et al., 1996; Crowley et al., 2003; Brazeau-Lamontagne, Charlin, Gagnon, Samson, & Van Der Vleuten, 2004). Again, the sheer speed at which experts conduct and conclude their visual search suggests that the inspection and recognition of abnormalities are hardly guided by conscious cognitive strategies (Wooding et al., 1999). Indeed, bottom-up theories of image interpretation postulate that a diagnostic hypothesis results from a rapid extraction and combination of visual features of the image (Kundel & Nodine, 1983) and that, consequently, the development of expertise depends largely on perceptual learning (i.e., increases in the sensitivity and specificity of a perceptual system) (Sowden, Davies, & Roling, 2000). Yet, it has been shown that prior knowledge or hypotheses about the image influence what is seen in medical images (Norman, Coblentz, Brooks, & Babcook, 1992; Fandel, Pfnür, Schäfer, Bacchetti, Mast, Corinth, Ansorge, Melchior, Thüroff, Kirkpatrick, & Lehr, 2008). Kundel and Nodine (1983) used eye tracking to demonstrate that the distribution of visual attention depends on the meaning assigned to the picture. This finding would suggest a more cognition-guided image perception. In fact, it seems that expertise in medical image interpretation is associated with flexible and adaptive shifting between the non-analytic and analytic cognitive and perceptual systems (Eva, 2005; Schmidt and Rikers, 2007; Pelaccia et al., 2011). However, much of the research about medical image interpretation has been done in the field of (traditional) radiology and is therefore not necessarily directly applicable to pathology, especially when it comes to entry-level pathology.

Compared to the interpretation of traditional chest radiographs, for example, pathologists' work is more dynamic in terms of visual search. As a disease can manifest itself on several morphological levels (organ, tissue, cell and molecular level) (Engel, 2008), pathologists have to make conscious choices with regards to what areas of the specimen, and on what level of magnification, to pay attention to. Indeed, "the detection of objects and structures

(nuclei, cells, epithelium, glands, etc.), their locations, and their background'' (Hamilton et al., 2009, p. 286) is a serial process (Crowley et al. 2001) guided by conscious choices. The first step of the visual search is to identify ''something that does not belong'', and thus, ''merits further investigation'' (Crowley et al. 2003, p. 49). As Marton and Pang (2006) argue, "to discern an aspect, the learner must experience potential alternatives, that is, variation in a dimension corresponding to that aspect, against the background of invariance in other aspects of the same object of learning" (p. 193). This suggests that, in terms of visual diagnosis, recognizing the diagnostically relevant areas, ''something that does not belong'', requires knowledge of normal histology (Pelaccia et al., 2011). Abnormalities are to be compared and contrasted with the relative invariance of normal histology. For a novice, even the task of discerning the diagnostically relevant features in the specimen is sometimes overwhelming (Rikers, Schmidt, & Boshuizen, 2000; Patel, Arocha, & Zhang, 2005). In contrast, experts' superior performance seems to be largely based on their ability to quickly find and focus on the diagnostically relevant information (e.g., Elstein, Shulman, & Sprafka, 1978; Kundel, Nodine, Krupinski, & Mello-Thoms, 2008). Study III describes and evaluates an intervention that was designed to improve students' recognition of normal histology in order to improve their ability to discern abnormalities and their performance in diagnostic pathology.

1.2   Using virtual microscopy to scaffold the learning of pathology

Technological advancements in medical imaging are changing medical practice and education (Weinstein, Graham, Richter, Barker, Krupinski, Lopez, Erps, Bhattacharyya, Yagi, Gilbertson 2009; Hamilton et al., 2012). In pathology, virtual microscopy creates both new affordances and challenges for learning and teaching. Virtual microscopy refers to increasingly ubiquitous technologies that enable multiple users to view microscopic specimens online simultaneously. Glass slides are digitized at a very high resolution, and users are able to view and zoom in at any part of the slide up to 40x magnification (Lundin, Lundin, Helin, & Isola, 2004; Hamilton et al, 2012). Therefore, virtual microscopy replicates the functionality of optical microscopes, while also adding new functions and possibilities (see below). Furthermore, the recognition ''that decision makers are not solitary thinkers, but live in a social world thick with artifacts and populated by other agents who jointly determine the decision processes and outcomes'' (Patel et al., 2002, p. 60) highlights the importance of both the technological and social organization of diagnostic work (Kushniruk, Kaufman, Patel, Lévesque, & Lottin, 1996). Technology (and social organization) serves a dual function: while it is something to adapt and become accustomed to, it can also be used as an aid, a scaffold,

for developing medical expertise and understanding. In terms of virtual microscopy, the latter function is especially important. While experienced pathologists use a light microscope as a ''direct extension of their perceptual process'' (Crowley et al. 2003, p. 49), for novices even the mechanical use of a light microscope can be very challenging when, for example, incorrect settings of the eyepiece cause problems in focusing and extensive strain on eyes. Not only does virtual microscopy offer physically comfortable access to microscopic specimens, but it also makes the specimens available outside the confines of microscopy laboratories.

Furthermore, the pedagogical possibilities of virtual microscopy go beyond simple ease of access or economies of scale. Features such as annotations can be used to scaffold students' visual and cognitive processes. This enables them to work in a Vygotskyan "zone of proximal development" (Vygotsky, 1978) to overcome the limitations of their still developing expertise and to avoid the most obvious and unproductive errors. As exemplified by Kundel and colleagues (1978), most errors of visual diagnosis fall into three categories: scanning or search errors, recognition errors and decision-making errors. To put it differently, students have to know where to look, be able to recognize the abnormalities and, finally, be able to combine the morphological clues into a coherent diagnosis (Crowley et al., 2001; Engel, 2008; Hamilton et al., 2009; Elizondo-Omaña, Morales-Gómez, Morquecho-Espinoza, Hinojosa-Amaya, Villarreal-Silva, Garcıa-Rodríguez, & Santos Guzmán-Lopez, 2012). Visual cues can be used to guide students to inspect relevant areas of the learning material (De Koning, Tabbers, Rikers, & Paas, 2010; Kriz & Hegarty, 2007) and, therefore, reduce scanning or search errors. While this certainly gets the students to the next level, recognition errors might still hamper practising higher-level diagnostic reasoning, "because there are a vast number of patterns that must be recognized and because many patterns are infrequent, requiring an extended training interval to accrue sufficient exposure" (Crowley et al., 2001, p.125). Recognition and conceptual understanding can be scaffolded by using textual cues in addition to the visual cues (for a review, see De Koning, Tabbers, Rikers, & Paas, 2009). On the other hand, it should be noted that not all errors are unproductive; on the contrary, making errors is a necessary for understanding the limitations of one's knowledge and skills (Bransford & Schwartz, 1999; Eva, 2009; Gartmeier, Lehtinen, Gruber, & Heid, 2011). Study IV investigates how visual and conceptual cues can be used to scaffold students' diagnostic reasoning and to elicit productive engagement with microscopic specimens.

The effect virtual microscopy will have on the learning of pathology is ultimately defined by how the technology is adopted and adapted into the social and pedagogical practices of medical education. On one hand, users adapt to new technology as it shapes

and transforms the available actions and information. Although this reshaping of the intellectual and physical landscape does not necessarily yield immediate changes in performance, it can have potentially long-lasting effects on future learning and clinical work (Kushniruk et al., 1996; Kuutti & Kaptelinin, 1997; Bransford & Schwartz, 1999; Schoultz, Säljö, & Wyndham, 2001; Säljö, 2010; Ritella & Hakkarainen, 2012). On the other hand, technology is not introduced into a vacuum, but into pre-existing practices and conventions that co-determine how it is adopted and adapted (Overdijk, van Diggelen, Kirschner, & Baker, 2012; Arnseth & Ludvigsen, 2006; Crook & Light, 2002). Therefore, successful implementation and development of any new technology requires critical analysis of the actual emerging learning practices (Arnseth & Ludvigsen 2006; Säljö 2010; Lehtinen 2012). Study V focuses on virtual microscopy and the endogenous diagnostic practices that emerge in students' collaborative diagnostic reasoning.

2. Aims

The general aim of the present dissertation is to explore how medical students learn to interpret medical images, the prerequisites and practices of learning microscopic pathology, and how learning can be scaffolded in a virtual microscopy environment. The specific aims of the five studies are as follows:

1. The aim of Study I is to examine if prior knowledge of basic sciences, especially histology and histopathology, predicts early learning of diagnostic pathology.

2. The aim of Study II is to investigate if visual perceptual skills, personality characteristics and/or prior knowledge predict students' performance in microscopic pathology.

3. Study III aims to describe and evaluate an intervention that was designed to improve students' recognition of normal histology in order to improve their ability to discern abnormalities and their performance in diagnostic pathology.

4. Study IV examines how visual and conceptual cues can be used to scaffold students' reasoning and to elicit productive engagement with microscopic specimens.

5. The aim of Study V is to analyze the endogenous diagnostic practices that emerge in students' collaborative diagnostic reasoning.

3.   Methods

3.1   Participants and context

Participants were medical students at the Faculty of Medicine, University of Turku, Finland, who were attending an introductory course in pathology. Participation in the studies was voluntary and informed consent was obtained. The data were collected between years 2007 and 2011 and consist of three different student cohorts.

The introductory course in pathology is part of students' preclinical training and its main learning objectives are: (1) to learn about the prevalence and risk factors of the most common diseases, (2) to understand how cell-level disorders manifest themselves in clinical findings, and (3) to recognize the cell and tissue abnormalities related to the most common diseases. Although microscopy is introduced already during the first year curriculum (e.g., histology), in this course the emphasis of microscopy teaching is targeted towards diagnostic skills and knowledge.

While studies I and II focus on the predictors of learning pathology, studies III, IV and V deal with the adoption and adaptation of virtual microscopy into the teaching of pathology. The particular technology in question is called the WebMicroscope, a web-based application that allows users to view a microscopic specimen on a computer screen (Lundin et al., 2004). In practice, a student can view a pathological slide anywhere, anytime and from any computer with an Internet connection. The specimens are digitized at a very high resolution that enables the users to view any part of the slide up to 40x magnification. In addition to general controls (zoom, contrast and brightness), slides can be enhanced with visual and textual cues (i.e., annotations), which appear as links on the user interface. Each annotation link leads to a predetermined view (area and zooming level), and it may contain further cues such as text, arrows or circles. WebMicroscope was first adopted into undergraduate medical training at the University of Turku in 2007, and its use has been expanding ever since.

3.2   Materials, data collection procedures and analysis

The empirical studies build on four different data sets. Table 1 summarizes the methods used in each study. Please note that due to the journal conventions and intended target audience some test and course titles come in slight variations in the original publications.

3.2.1 Study I

During the first semester of medical school, the participants (n = 118, representing 91 per cent of the full student cohort) had completed a course in histology, which also included an introductory module in histopathology, with respective tests in the course examination. The histology test had 10 multiple-choice questions (MCQs) measuring factual knowledge, along with 10 visual tasks (also MCQs). The MCQs measuring factual knowledge included questions such as, "Which of the following is a contracting cell?" The visual tasks tested recognition of cell types and tissues. The histopathology test included 10 multiple-choice tasks, of which six tested students' knowledge of central pathological concepts (such as apoptosis and mechanisms of cell damage). The rest were visual tasks in which the students inspected tissue samples and were asked to identify appropriate morphological changes or abnormalities from a list of choices.

At the end of the second year introductory pathology course students took two official examinations: (1) a microscopy examination (six diagnostic tasks) and (2) a test of biomedical knowledge. The microscopy examination consisted of six microscopic specimens with concise background information; students' task was to list the relevant findings, diagnoses, and prognoses. The test of biomedical knowledge had three parts: 1) multiple-choice questions comprising 36 items concerning, for example, pyothorax, signs of inflammation, and causes of cardiomyopathy, 2) two essays (of four possible choices) on topics such as nephrotic syndrome and melanoma, and, 3) two patient cases consisting of written anamnesis and clinical information), that is, a description of symptoms and various test results. For both cases, students were asked to provide a diagnosis with medical justification and elaborate on the pathogenesis.

Structural equation modeling (SEM) was used to examine the relationships between histological knowledge and performance in diagnostic pathology and biomedical knowledge.

3.2.2 Study II

Student performance in microscopic pathology was measured in the beginning (pre-test) and at the end (post-test) of the introductory course in pathology. Furthermore, the course examination scores (microscopy examination and test of biomedical knowledge) were also used as performance measures. Both pre- and post-tests lasted for 45 minutes and consisted of six authentic tissue samples presented using WebMicroscope software. For each of the six images, the students were asked to indicate the type of tissue and identify and list the present cell types.

In addition to the pre-test, histology and cell biology grades (combining scores in histology, histopathology, molecular biology and genetics examinations) were used as a measure of prior knowledge. Finally, the Test of Visual Perceptual Skills (TVPS-3) (Martin, 2006) was used to assess students' visual perceptual abilities, and The Big Five Personality Inventory was administered as a self-assessment of personality traits (conscientiousness, extroversion, agreeableness, neuroticism, openness).

Due to some relatively minor deviations from a normal distribution, the data were analyzed by multinomial logistic regression analysis using four categories (quartiles) of the dependent variable. Significant results were also confirmed using standard linear regression analysis whenever possible.

3.2.3 Study III

The experimental design of the study aimed at improving students' recognition and understanding of pathological abnormalities through emphasizing the contrast between normal and abnormal tissue and cell structures. This was done by utilizing the WebMicroscope for the following purposes: (1) students were provided with online materials of normal cell and tissue structures, (2) an online entrance examination, (3) digitized slides with abnormal features indicated by visual and textual cues, with normal areas for comparison, and, (4) three virtual quizzes taken in class for self-diagnostic purposes. Before the pathology course started in 2010, students (n = 105) were asked to review the online materials on normal cell and tissue structures and complete the online course entrance examination. The entrance examination consisted of 24 slides from which the students were to recognize the cell and tissue structures. As the online entrance examination was designed to merely promote revision of normal histology, it was not a strictly controlled examination. During the course, three virtual quizzes with immediate feedback on correct answers were taken in conjunction with histology laboratory sessions.

Students' evaluation of the annotated virtual slides was compared to the same information from the previous year. In addition, 20 volunteers (2010) and 61 historical controls (2007) participated in assessments of histological knowledge. Independent sample T-tests were used separately for the normal histology and abnormal histology test with class (2007 vs. 2010) as the grouping variable. Furthermore, the students completed an anonymous course evaluation on the learning environment and the different elements of the course. Finally, four (of 20) volunteers were interviewed about the use of the provided digital sources.

3.2.4 Studies IV and V

The participants (n = 30) took part in two problem-solving sessions, one at the beginning and one at the end of the course. The tasks were performed in pairs (15 pairs altogether). The decision to observe students working pair-wise was partly a practical choice (as it ''forced'' students to externalize their thinking to each other) but also an issue of ecological validity, as this mode of organizing student work was utilized in the course the students were attending.

WebMicroscope was used to present students with six authentic tissue samples with varying levels of scaffolding. To make sure that the varying case difficulty would not distort the results in one way or another, three partly different slide sets (A, B, C) were used. Each set had the same slides but the order of the slides was rotated. Thus, the pairs with different slide sets had different levels of scaffolding in each case. Scaffolding was organized so that the first two cases had no cues, the next two had visual cues, and the last two had visual and conceptual cues. Visual cues were annotation links that took the students to a predetermined view (area and zooming level) with varying amounts of further cues such as arrows or circles. In this experiment, conceptual cues were written with a higher level of abstraction than is typical in learning materials. For example, in the gastritis case, one conceptual cue pointed out inflammation, but not whether the cells in question were evidence of acute or chronic inflammation.

Students were requested to write down their clinical findings and diagnosis using a pre-structured form. Written answers were assessed by an experienced pathologist who was not aware of which slide set each pair had been assigned and, therefore, if the students had had visual/conceptual cues in each case or not. The diagnostic accuracy was rated on a scale from 0 to 2 points so that partially correct diagnoses were given one point (e.g., if only 'metastasis' was given as a response in the case of adenocarcinoma metastasis). Furthermore, the students' interactions were videotaped from two angles: from behind (capturing the computer screen and the students' gestures) and from the students' left side (capturing their actions and facial expressions). The videos were synchronized and analyzed in ELAN, a multimedia analysis tool developed at the Max Planck Institute for Psycholinguistics.

For the analysis in study IV, the findings reported by the students were classified into three classes: 1) *relevant* in terms of the correct diagnosis, 2) *irrelevant* only in terms of arriving at the correct diagnosis, including, for example, a general description of the specimen, and 3) *false*, as in features that were not present in the slide. These were then indexed into the video files. This index was used to further classify *false* findings

according to whether the students focused on the clinically relevant area or level of the sample while coming up with the findings. The frequencies of reported findings (relevant, irrelevant and false) were cross tabulated with different levels of scaffolding (no cues, visual cues, conceptual cues). The Pearson's Chi-square test was used to analyze if the patterns of observed frequencies differed from the patterns of expected frequencies. In addition, standardized residuals were used to examine what were major contributors to the differences. Analysis of the video files was used to examine why students missed certain key findings and the effect of annotations.

Study V utilizes a subset of the same data set as used in Study IV, but is a purely qualitative analysis of students' reasoning in the WebMicroscope learning environment. With our interest in emerging learning and problem-solving practices, we systematically looked for and marked episodes in which the students showed the most prominent signs of uncertainty, that is, for example, when they expressed explicitly that they did not know what they were looking at or when they disagreed upon what they saw. As uncertainty was less frequent in cases with both visual and conceptual cues, these cases were excluded from the analysis. The discontinuities, or moments of uncertainty, triggered episodes in which the students engaged in the most observable, deliberate and interactive reasoning, making them both analytically interesting and methodologically accessible. Because of the visual and dynamic nature of the data, the analysis was kept as close as possible to the original data for as long as possible. Thus, instead of analyzing transcripts, episodes of interest were indexed, analyzed and themed in ELAN. The video analysis was performed collaboratively by researchers at the University of Turku, Finland, and the University of Gothenburg, Sweden, (one of the recruited pairs was Swedish speaking) in multiple iterative cycles. After an independent analysis at both universities, researchers compared and refined notes on the general description of the students' strategies. The episodes were given short written descriptions and organized into common themes based on the dominant strategies.

Table 1. Summary of methods

Study	Participants	Data	Analysis
Study I	Medical students, n = 118	1st year course examinations: histology, histopathology	Structural equation modeling
		2nd year course examinations: microscopy examination, biomedical knowledge	
Study II	Medical students, n = 150	1st year course examinations: histology and cell biology	Regression analysis
		2nd year course examinations: microscopic pathology and biomedical knowledge	
		Test of Visual Perceptual Skills	
		The Big Five Personality Inventory	
		Pre- and post-test in microscopic pathology	
Study III	2010 2nd year medical students, n = 105	Online entrance exam Assessment of histological knowledge in the beginning and at the end of the course	Independent sample T-test
	2007 Historical controls:	Course evaluation	Correlation analysis
	2nd year medical students, n = 61	Interviews	Qualitative content analysis
Study IV	2nd year medical students, n = 30	Students written reports, including findings and diagnosis	Chi-square test, analysis of standardized residuals
		Video recordings	Qualitative analysis
Study V		Video recordings	Qualitative analysis
		Students written reports, including findings and diagnosis	

4.   Overview of the empirical studies

4.1   Study I

Over the years, the role and extent of the basic sciences in medical curricula have been challenged by expertise and learning research as well as by the development of the medical curricula. Firstly, experts seem to rely mostly on their clinical knowledge in routine diagnosis, reverting to the basic sciences only in cases of uncertainty. Secondly, advancing medical sciences and technological development are constantly creating new content and skills to be incorporated into the curriculum. Increasing emphasis is also put on ethical knowledge and managerial skills of future doctors, limiting the amount of time available for learning the basic sciences. Finally, medical students do not always perceive the basic science courses taken during the preclinical phase as especially relevant.

The aim of this study was to examine how prior knowledge of basic histology and histopathology among students predicts early learning of diagnostic pathology. Histology deals with the normal histological structures and major functions of the constitutive cells, whereas histopathology is more concerned with abnormalities at the cell and tissue level. Therefore, both are highly relevant subjects in terms of diagnostic pathology.

Participants (N = 118, representing 91 percent of the full student cohort) were medical students at the University of Turku, Finland. Data were collected during two preclinical courses that students attended in their first and second years of medical school. The measurements included tests on histology, histopathology, a performance test in diagnostic pathology and a test of biomedical knowledge. Structural equation modeling (SEM) analysis was used to examine the relationships between prior knowledge (first year) and performance in diagnostic pathology (second year).

Second-year performance on the diagnostic pathology examinations was predicted by the students' prior knowledge of histology, but not by the students' prior knowledge of histopathology. Furthermore, knowledge in diagnostic pathology (microscopy examination) seemed to mediate the effect histology had on later learning of biomedical knowledge. This would suggest that, for biomedical knowledge to become useful, it has to be integrated into clinical knowledge. The fact that histopathology test scores did

not predict diagnostic performance suggests that the relationship between histology and the microscopy examination is not only a consequence of general cognitive skills, as those would also have affected success on the histopathology test. It is possible that the extent of the histopathology instruction may have been insufficient for the students to build up knowledge structures and illness scripts that are applicable to new knowledge. Moreover, meaningful learning of abnormalities may require a relatively stable point of reference, that is, normal histology, which students did not yet have at that point of time.

Although earlier research has demonstrated similar results in studies with shorter longitudinal designs, the present study demonstrates that the effect remains even after a considerable time delay (a year) between the measurements, thus confirming the long-term value of basic science studies in the preclinical phase.

4.2   Study II

Helle, L., Nivala, M., Kronqvist, P., Ericsson, K. A., & Lehtinen, E. (2010). Do prior knowledge, personality and visual perceptual ability predict student performance in microscopic pathology? *Medical Education, 44*, 621–629. doi: 10.1111/j.1365-2923.2010.03625.x

There has been long-standing controversy regarding aptitude testing and selection for medical education. Visual abilities are considered particularly important for detecting signs of disease as part of diagnostic procedures in, for example, microscopic pathology, radiology and dermatology, and as a component of perceptual motor skills in medical procedures such as surgery. The aim of the study was to explore possible predictors of performance in microscopic pathology in the context of an undergraduate pathology course.

A pre- and post-test of diagnostic classification performance, test of visual perceptual skill (Test of Visual Perceptual Skills, 3rd edition [TVPS-3]) and a self-report instrument of personality (Big Five Personality Inventory) were administered. In addition, data on academic performance (performance in histology and cell biology, a compulsory course taken the previous year, in addition to performance on the microscopy examination and final examination) were collected.

The results indicated that one personality factor (conscientiousness) and one element of visual perceptual ability (spatial relationship awareness) predicted performance in the pre-test. The only factor to predict performance in the post-test was performance in

the pre-test. Similarly, the microscopy examination score was predicted by the pre-test score, in addition to the histology and cell biology grade. The course examination score was predicted by two personality factors (conscientiousness and lack of openness) and the histology and cell biology grade.

Visual spatial ability may be related to performance in the initial phase of training in microscopic pathology. However, from a practical point of view, medical students are able to learn basic microscopic pathology using worked-out examples, independently of personality characteristics or visual perceptual ability. This finding should reassure students and clinical teachers about students' ability to improve through training independently of their scores on tests on basic abilities and personality.

4.3 Study III

Helle, L., Nivala, M., & Kronqvist, P. (2013). More Technology, Better Learning Resources, Better Learning? Lessons from Adopting Virtual Microscopy in Undergraduate Medical Education. *Anatomical Sciences Education, 6*(2), 73–78. doi: 10.1002/ase.1302.

The adoption of virtual microscopy at the University of Turku, Finland created a unique real-world laboratory for exploring ways of reforming the learning environment. The purpose of this study was to evaluate the students' reactions and the impact of a set of measures designed to boost an experimental group's understanding of abnormal histology through an emphasis on knowledge of normal cells and tissues. The set of measures included: (1) digital resources to review normal structures and an entrance examination for enforcement, (2) digital course slides highlighting normal and abnormal tissues, and, (3) self-diagnostic quizzes. The performance of historical controls was used as a baseline, as previous students had never been exposed to the above-mentioned measures. The students' understanding of normal histology was assessed in the beginning of the module to determine the impact of the first set of measures, whereas that of abnormal histology was assessed at the end of the module to determine the impact of the whole set of measures.

The students' reactions to the instructional measures were assessed by course evaluation data. Additionally, four students were interviewed. Results confirmed that the experimental group significantly outperformed the historical controls in understanding normal histology.

The students held favorable opinions on the idea of emphasizing normal structures. However, with regards to abnormal histology, the historical controls outperformed the

experimental group. In conclusion, allowing students access to high-quality digitized materials and boosting prerequisite skills are clearly not sufficient to boost final competence. Instead, the solution may lie in making students externally accountable for their learning throughout their training.

4.4 Study IV

Nivala, M., Säljö, R., Rystedt, H., Kronqvist, P. & Lehtinen, E. (2012). Using virtual microscopy to scaffold learning of pathology: A naturalistic experiment on the role of visual and conceptual cues. *Instructional Science, 40*(5), 799-811.

New representational technologies, such as virtual microscopy, create new affordances and challenges for medical education. In this article, a study on the following two issues is reported: (a) How does collaborative use of virtual microscopy shape students' engagement with, and learning from, virtual slides of tissue specimen? (b) How do visual and conceptual cues scaffold students' reasoning?

Fifteen pairs of medical students participated in two sessions in which the students used a virtual microscope as a diagnostic tool in the context of learning pathology. The students were presented with six authentic tissue samples with varying levels of scaffolding. Tissue samples were ordered so that the first two cases had no cues, the next two had visual cues, and the last two had both visual and conceptual cues. The sessions were videotaped, and the students were required to write down the findings and diagnosis for each case.

The students' written answers (findings and diagnoses) were assessed by an experienced pathologist. Findings reported by the students were classified into relevant, irrelevant and false and indexed into the video files. Based on the video, false findings were further classified according to whether students focused on the clinically relevant area or level of the sample while coming up with the findings. Finally, diagnostic episodes were analyzed qualitatively with the focus on the different difficulties students faced and how annotations affected their reasoning process.

At a general level, the results show that students engage actively in this kind of virtual learning environment. As expected, the number of relevant findings increases as the level of scaffolding increases, while the number of irrelevant findings decreases. Yet the number of false findings does not follow this pattern. The presence of visual cues did not reduce the number of false findings; on the contrary, cues with conceptual and visual

information reduced false findings considerably. However, without visual cues, the false findings arose mostly while the students were examining clinically irrelevant features of the slide. Although visual cues seemed to increase the number of false findings, students made these claims while discussing and examining an appropriate part of the slide. Furthermore, although the level of scaffolding seemed to have an effect on the diagnostic accuracy at the beginning of the course, the effect seemed to diminish during the course.

In conclusion, the visual and/or conceptual cues improved students' performance, and guided the students' perception and reasoning in a manner that is productive from the point of view of learning to make clinically relevant observations. Scaffolding students' reasoning process through cues furthermore assisted the students in avoiding the most obvious pitfalls such as overlooking critical areas of a specimen. Overall, visual and conceptual cues improve students' reasoning in perceptual and cognitive terms, while still allowing space for the making of ''relevant mistakes'' that may induce learning.

4.5   Study V

Nivala, M., Rystedt, H., Säljö, R., Kronqvist, P., & Lehtinen, E. (2012). Interactive visual tools as triggers of collaborative reasoning in entry-level pathology. *International Journal of Computer-Supported Collaborative Learning, 7*(4), 499-518.

While the emergence of novel imaging technologies offers new opportunities, many pedagogical questions remain. In the present study, we explore the use of a new tool, a virtual microscope, for the instruction and collaborative learning of pathology.

Fifteen pairs of medical students were asked to solve diagnostic tasks in a virtual microscopy learning environment. The students' collaborative efforts were analyzed qualitatively on the basis of approximately 20 hours of video recordings.

The analysis was conducted in ELAN, a multimedia analysis software tool that allows synchronous viewing and annotating of multiple video files. To capture emerging problem-solving practices, we systematically looked for and marked episodes in which the students showed the most prominent signs of uncertainty. Discontinuity, or uncertainty, triggered episodes in which the students engaged in the most observable, deliberate and interactive reasoning. Therefore, these episodes were both analytically interesting and methodologically accessible.

The analysis shows how students used the technology as a mediating tool to organize, manipulate and construct a shared visual field, and later, shared understanding of the

problem and solutions. Organization of the visual field is done through multimodal referential practices: gestures, three-dimensional manipulation of the image and paced inspection of the specimen. Furthermore, we analyze and describe how the aforementioned practices coincide with students' medical reasoning in this particular learning context.

The analysis of medical students' diagnostic work illustrates the collaborative potential of the virtual microscopy environment and how such interactive tools render the traditional distinction between collaborating around or through computers irrelevant, as even face-to-face collaboration becomes enacted through technology. Finally, we argue that as technologies develop, understanding the technical side of image production, or any representation, becomes an integral part of the interpretative process. How this knowledge is communicated to the students may play a substantive role in how students learn to interpret medical images.

5.   Main findings and discussion

The aim of the present work has been to explore and investigate how medical students learn to interpret medical images such as microscopic specimen, that is, what are the prerequisites and practices of learning and how learning could be scaffolded in a virtual microscopy environment.

Considering the prerequisites of learning microscopic pathology, the results (Study II) confirm that visual perceptual ability and personality characteristics have a small but detectable effect on initial learning (cf. Wanzel et al., 2002). However, from a practical and educational point of view, this effect is somewhat negligible as medical students are able to learn entry-level microscopic pathology irrespective of their personality traits or visual perceptual ability. This is in line with past research that has shown the adaptable and flexible nature of human sensory systems; experience and training shape and improve the domain-specific visual strategies, and therefore render the initial differences in performance irrelevant (Myles-Worsley et al., 1988; Nodine et al., 1996; Wooding et al., 1999; Krupinski, 2000; Sowden et al., 2000).

The results are slightly more complicated when it comes to prior knowledge and its effects on learning. Studies I and II showed that prior knowledge of normal histology and cell biology predicted learning of microscopic pathology even after a long time delay (a year) between the measurements. On the other hand, prior knowledge in histopathology had, surprisingly, no detectable effect on performance in microscopic pathology (Study I), despite histopathology being the basic science behind microscopic pathology and pathology in general. Furthermore, the intervention that managed to improve students' recognition of normal histology in the beginning of the introductory course in pathology had no effect on students' performance in microscopic pathology (Study III). In the case of histopathology (Study I), one possible explanation is that the taught content was too case-specific, or not extensive enough, for students to form knowledge structures that could be applied to novel diagnostic tasks. In retrospect, it is also conceivable that the missing effect was due to inadequate operationalization of histopathological knowledge (the histopathology test consisted of only ten items), which sets considerable limits to the applicability of this particular finding. The fact that boosting recognition of normal histology did not translate into better performance demonstrates the necessity of active application of knowledge, or, as Norman (2007) argues, "unless students actively apply the concepts they are learning to understanding and explaining clinical problems, the knowledge will remain inert and will be soon forgotten" (p. 402). For a corroborating

example, Goldszmidt, Minda, Devantier, Skye and Woods (2012) showed that causal explanation of physical conditions related to certain lung diseases can improve students' ability to interpret clinical details. It seems that without an understanding of the functional basis of histology, the mere recognition of normal tissue and cell types, that is, replicative knowledge (Bransford&Schwartz, 1999; Eva, 2009), does not produce applicable knowledge structures.

In conclusion, the present work suggests, in line with for example Woods et al. (2005, 2006, 2007), that although experts rarely use basic science in their everyday diagnostic work (e.g. Koens et al., 2006; Woods, 2007; Finnerty, Chauvin, Bonaminio, Andrews, Carroll, & Pangaro,2010; Norman et al., 1994; Norman, 2005; Norman et al., 2007; Kaufmann et al., 2008), basic sciences offer a pivotal aid, or scaffold, in the early development of visual diagnostic skills (Donnon & Violato, 2006). Basic sciences create a coherent knowledge structure upon which students can build clinical knowledge (Woods et al., 2005). Moreover, as shown by the analysis in Study V, such knowledge helps novices to overcome the present shortcomings of their yet developing clinical knowledge. Students used a wide array of biomedical and contextual knowledge in order to produce, evaluate and crosscheck their diagnostic hypotheses. In fact, basic sciences seem to serve the same scaffolding function in expert reasoning when experts encounter a novel or extremely difficult case (Norman, Trott, Brooks, & Kinsey-Smith, 1994; Kaufmann et al., 2008; Pelaccia et al., 2011). However, as important as basic sciences appear to be for early learning, further expertise development seems to require major knowledge restructuring. While clinically inexperienced novices use basic sciences to create coherence among clinical findings, experts use clinical experience to organize and subsume biomedical knowledge into illness scripts (e.g. Schmidt & Rikers, 2007).

Naturally, in order to develop their diagnostic skills, novices cannot only rely on their existing knowledge but have to engage in activities that are designed to improve and challenge their current skills, knowledge and performance (Ericsson & Lehmann, 1996; Ericsson, 2006). As shown by Study III, without pedagogical design, the mere availability of high-quality online materials is not a sufficient condition for improving students' competence. Therefore, Studies IV and V examined how virtual microscopy could be used as a pedagogical tool to scaffold and challenge students' reasoning. In general, it was apparent that virtual microscopy offers an authentic, accessible and, thus, viable environment for students to practice the interpretation of microscopic specimens. However, while virtual microscopy certainly has some advantages over traditional microscopy, and vice versa, Studies IV and V are not media-comparative research. As Cook (2005, see also Helle, & Säljö, 2012) has noted, comparisons between media are

rarely meaningful due to lack of valid comparison groups. Thus, the theoretical and methodological choices aim at revealing the optimal configurations within this learning environment. Studies IV and V demonstrated the dual function of visual and conceptual cues as scaffolds and as explicit challenges. As expected, increasing scaffolding improved students' performance especially in the beginning of the course by guiding them to focus on clinically relevant abnormalities. Visual and conceptual cues reduced both scanning/search and recognition errors (cf. Kundel et al. 1978; Elizondo-Omaña et al., 2012), helping the students to avoid the most obvious pitfalls and errors. Thus, it can be argued that cueing enabled students to practice diagnostic work on a level that would not have been possible without scaffolds. On the other hand, visual cues also considerably increased the number of false findings (or false-positives). Yet, with cues, these mistakes were made predominantly while discussing a relevant part of the specimen. Without cues, false-positives were mostly made while examining clinically irrelevant areas of the slide. Detailed analysis of students' reasoning (Study V) reveals how the visual cues especially functioned as explicit challenges that prompted students to ponder on and engage with unexpected visual information in need of clarification, thereby causing what might be classified as "relevant errors". As Eva (2009) argues, "errors are more likely to be made over the long term when too few errors are induced during learning. Not engaging with learning material in a manner that elicits errors may blind the learner to gaps in their knowledge or skill base that may never be corrected in the absence of clear feedback" (p.75).

In addition to visual and conceptual cues, virtual microscopy provides students with a convenient shared domain of scrutiny, making it possible to choose, highlight, compare and discuss microscopic specimens without having to take turns at the eyepiece of the microscope. Studies IV and V illustrate how the aforementioned possibility of effective and effortless collaboration can be used to engage students in diagnostic work that mimics the dynamics and complexities of work tasks in clinical settings (Alac, 2008; cf. Kumar, 2004). Moreover, collaboration around the virtual microscope elicited activities that have been previously found beneficial for learning (Study V), i.e. "explanation, argumentation/negotiation and mutual regulation" (Dillenbourg, Järvelä, & Fischer, 2009, p. 6; cf. Chi, de Leeuw, Chiu, & LaVancher, 1994; Berardi-Coletta, Buyer, Dominowski, & Rellinger, 1995; Atkinson, Renkl, & Merrill, 2003). Discussing the available visual/clinical information and the underlying biomedical phenomena revealed students' assumptions and explanations for mutual regulation. This, in turn, created a sense of accountability in which uncertainty and disagreement had to be solved by visual evidence or biomedical knowledge. Furthermore, the process of building a shared understanding of the phenomenon exposed the students to alternative views and

interpretations provided by their peers. Therefore, collaboration functioned also as a rudimentary feedback loop that helped students avoid premature closure (e.g., Berbaum et al. 1990; Eva 2009). However, in order to take full advantage of virtual microscopy, more advanced, definite and explicit feedback mechanisms should be implemented (Studies III, IV and V).

In short, using visual cues and collaboration as scaffolds enable a more meaningful engagement with the microscopic images. Additionally, virtual microscopy will arguably alter, or has already altered, the way both medical students and pathologists interpret microscopic specimens (Weinstein et al., 2009). These emerging practices were explored in Study V. This analysis demonstrated how applications such as the virtual microscope dissolve the traditional distinction between collaborating around and collaborating through computers (Lehtinen 2003), as even face-to-face collaboration becomes embedded in, enacted through and contingent on the technology (cf. Alac 2008). Working online naturally extends the available resources, allowing students to, for example, draw on multiple presentations of the same phenomenon. On the other hand, as technologies develop and create images that are more and more removed from our everyday experiences, the interpretation process is becoming even more dependent on students' "contextual knowledge" (Study V), that is, understanding of said technology and the procedures of medical image production (Dikshit et al., 2005). They have to become accustomed to new presentation styles (for example, different stainings in pathology) and be aware of how these images are produced and what kind of distortions, or artifacts, the medical images may contain (Lesgold, 1988). Finally, Study V demonstrates how students employ their prior biomedical knowledge in an authentic diagnostic task. Students use biomedical knowledge to initially frame the diagnostic process and later, if necessary, to extend the frame of reasoning. The former refers to practices in attempt to establish a coherent framework for the diagnostic reasoning by fixing the fundamental parameters between the anamnesis and the origin, orientation and major dimensions of the pathological sample. In cases of uncertainty, students used biomedical knowledge to extend their frame of reasoning by comparison (normal vs. abnormal), creation of working hypothesis and crosschecking of facts. Crosschecking could be described as primitive and yet highly conscious form of knowledge encapsulation (cf. Boshuizen & Schmidt, 1992), that is, students attempt to justify their diagnosis by integrating information from different sources and different levels of clinical findings.

In summary, the results illustrate how students' skills and prior knowledge of basic sciences affect learning of diagnostic pathology, and how prior knowledge and medical reasoning can be activated and challenged in a virtual microscopy environment.

5.1   Theoretical and methodological implications

While medical image interpretation has been studied quite extensively in the past, only a few studies in the domain have concentrated on the early development of these competencies. The results of the present work offer a multifaceted view into the early development of expertise in medical image interpretation, demonstrating how the prerequisites for early learning seem to differ from the prerequisites of expert reasoning, and how the shortcomings of students' knowledge and skills can be overcome with pedagogical and technological scaffolds. The apparent theoretical and methodological diversity that underlies the five studies is reflected in the results, which illuminate the phenomenon from multiple angles and highlight the complexities of the learning process. Indeed, the diverse methodological and theoretical choices attest to the fact that effective learning of complex skills cannot be attributed to a single factor, theory or panacea.

However, the multitude of theoretical perspectives that the present work builds on make it challenging to systematize and simplify the results, as studies that rely on different theoretical frameworks are not necessarily easily, or sensibly, comparable. Furthermore, using various methods across the studies does not allow for systematic development of methods. While mixing theoretical perspectives and methodologies within studies might be ill-advised, a cross-theoretical approach has its advantages as it illuminates how different explanations translate into different levels of explanation (for commentary, see Ludvigsen, 2012). For example, Norman and Schmidt (Norman & Schmidt, 2000; Norman, 2003) argue for reductionism, that is, studying the underlying cognitive mechanisms, such as transfer, in order to identify effective teaching strategies. On the other hand, as diagnostic work becomes increasingly embedded in, and enacted through, technology (Study V, see also, Alac, 2008), it becomes more and more important to design naturalistic experiments in which the manipulation of technological, and even social, environment is not only allowed, but understood as a central competence in the interpretation process (Rystedt, Ivarsson, Asplund, Johnsson, & Båth, 2011; Lehtinen, 2012). The present work moves, and hopefully bridges some of the gaps, between these levels of explanation. For instance, the idea of transfer is examined on a larger scale in Studies I, II and III, whereas Studies IV and V offer a complementary view by illustrating the emerging diagnostic practices that make use of students' prior knowledge. Similarly, the possible affordances of virtual microscopy are studied both in terms of how it affects learning outcomes on cohort level (Study III) and how these affordances are realized in the actual learning situations (Studies IV and V). The fact that mere availability of high-quality materials and improving students' recognition of normal histology did not improve students' performance in histopathology is, at least partially, explained by the

more detailed analysis of students' reasoning. Studies IV and V show how materials can be enhanced with cues that evoke deliberate reasoning and how mere recognition of abnormalities is not sufficient prerequisite for successful diagnostic process. Regarding theory and methodology, the present work highlights the possible gains that can be achieved by studying the more general cognitive principles in conjunction with how these principles are applied to and realized in a real-world setting. Cognitive psychology offers insights into the fundamentals of learning, insights that can be generalized, to some extent, across domains and learning environments. Yet, optimizing learning in various domains and environments requires naturalistic studies with detailed analysis of both learning outcomes and learning processes (Ludvigsen, 2012). This is especially true to domains of rapid scientific and technological development, as this development alters the nature of cognitive capabilities that are required in such domains. Furthermore, theories that attempt to explain human cognition on a highest possible level of generalizability are not necessarily suited for explaining expertise, which, by definition, refers to exceptional performance (Ericsson, Roring, & Nandagopal, 2007). To rephrase an old adage, extraordinary performance requires an extraordinary explanation. Following this line of thought, Study V, instead of aiming at the widest possible generalizability, also describes learning practices that emerge as exceptional in the general workflow of the students.

In the past, the development of expertise in medical image interpretation has been studied by comparing novices and intermediates to experts (for reviews, see Norman et al., 1992; Patel et al., 2005). Much of this research has been based on the more or less explicit premise that in order to improve learning, students should strive and be encouraged to adopt the superior expert practices as such. However, as shown by the present work, acquiring expertise is a distinct phenomenon from applying expertise. For example, even if basic sciences were of little use to experts in their everyday work, it does not follow that basic sciences do not serve a purpose in training or in acquiring expertise. Therefore, theories, models and descriptions of expert practices should not be implemented uncritically as pedagogical models or guidelines in early training. Instead, research should focus on revealing the learning trajectories behind expertise, as each stage of development may also require qualitatively different pedagogical solutions. Indeed, the metaphor of scaffold is quite fitting. Constructing a physical or mental structure requires appropriate scaffolds in each stage, yet the scaffolds (mental or physical) are not visible in the final product. However, this does not rule out "the implications of the structure of experts' deliberate practice for early skill acquisition and general education" (Ericsson, 2005, p. 237), as deliberate practice refers to a situation in which experts are acquiring or refining, as opposed to applying, competence, making it more akin to what the novices are experiencing.

Consequently, the distinction between acquiring and applying expertise should also be reflected in the methodology. Thus far, novices have been commonly compared to experts by giving both novices and experts exactly the same tasks (e.g., Kundel & Nodine, 1983; Lesgold et al., 1988; Myles-Worsley et al., 1988; Nodine et al., 1996, 1999; Wooding et al., 1999; Crowley et al., 2003; Brazeau-Lamontagne et al., 2004; Manning, Ethell, Donovan, & Crawford, 2005). While there is no denying the value of this approach, it places the novices and experts in two completely different situations, as the subjective case difficulty can vary from impossible (for novices) to undemanding (for experts). Therefore, the conclusions about the fundamental differences between the nature of expert and novice performance might be premature, as it is uncertain whether the differences are of a quantitative or qualitative nature (cf. Rikers et al., 2000; Kaufmann et al., 2008). Instead of comparing novices and experts in tasks that are, in the worst case, non-representative for both groups, the appropriate focus, as suggested by Ericsson (2005), would be to look into how experts adapt to new situations and difficult cases, and how they improve their skills.

5.2   Practical implications for medical education

The practical implications of the present work are threefold. Firstly, the results strengthen the evidence in favor of basic sciences in the undergraduate medical curriculum. However, it should be noted that mere replicative knowledge, that is, retention of details or (visual) pattern recognition, is not necessarily sufficient (Bransford & Schwartz, 1999; Eva, 2009). Basic sciences should not be taught as a collection of facts, but as theories that explain and create coherence among a multitude of biomedical facts. Therefore, the basic sciences curriculum should be considered as "preparation for future learning" (e.g., Bransford & Schwartz, 1999), as it forms a useful basis to build biomedical and clinical knowledge upon. It is possible that the performance improvements will appear only after the students are able to integrate their basic sciences and clinical knowledge. Naturally, this requires both time and relevant experience.

Secondly, the present results, and the theoretical considerations, do not offer support for the idea of the implementation of aptitude testing. Cross (2005) suggests that tests of, for example, visual abilities and personality characteristics could be used "to determine the suitability of candidates for histopathology early in their training (entry function)" (p. 299). While the importance of innate abilities or talent cannot be ruled out, especially in the top performers of any domain, there seems to be little, if any, evidence in favor of it (Ericsson & Lehmann, 1996; Nodine & Krupinski, 1998). On the other hand,

innate abilities seem to have a detectable, positive, effect on the initial learning (Study II, Wanzel et al. 2003). Nonetheless, this phenomenon should also be considered in a larger temporal context of expertise development, as initial learning refers to tasks and abilities that necessarily differ from what experts do and, therefore, do not offer definite criteria for skills and abilities that are needed to become a top performer in the long run. This is reflected in the so-called *intermediate effect* or U-shaped developmental pattern (Schmidt & Boshuizen, 1993), which implies that the quantitative and qualitative changes in performance are not "a monotonic function of experience" (Lesgold et al., 1988, p. 319; cf. Myles-Worsley et al., 1988; Wooding et al., 1999; Rikers, Schmidt, Boshuizen, 2000; Crowley et al., 2003). Therefore, it seems plausible that the abilities and the knowledge that carry through the initial stages of learning do not necessarily play a major or decisive role in the later stages.

Finally, the present dissertation confirms the potential of virtual microscopy as an educational tool, but only in conjunction with appropriate pedagogical arrangements. Increasing the amount and improving the technical quality of the learning materials are not enough without the co-evolution of existing practices (Dillenbourg et al. 2009; Cook 2009; Säljö 2010). While virtual microscopy can be used to increase independence and enable more fluid collaboration between students, it should be integrated, not only added, into teaching practices in order to create accountability and improve feedback mechanisms.

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