Andreas Gegenfurtner

Professional Vision and Visual Expertise

Habilitation

University of Regensburg
Faculty of Human Sciences
Department of Educational Science

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Habilitation Thesis

Fachmentorat / Supervisors

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Acknowledgments

"Persons in the shadow" is a powerful concept in expertise research. Developed by Hans Gruber and his team (2008), persons in the shadow are teachers, coaches, or mentors who—often in the background and unacknowledged—facilitate novices on their way toward expert performance. As my habilitation on expertise comes to a close, it is timely to acknowledge my own persons in the shadow and bring them into the bright light they deserve.

Professor Hans Gruber was one of my first teachers when I started my undergraduate studies in educational science at the University of Regensburg in 2004—leading a seminar on constructivism. In 2008, he supervised my diploma thesis and became my first co-author in submitting journal articles; when we received the first reviewer comments after many months of waiting, I remember how he calmed me down and explained what the decision "major revisions" meant. Hans Gruber encouraged me to participate in the Erasmus program at the University of Turku in 2007 and to join my first JURE and EARLI conferences in 2008. Needless to say, his prime research theme—expertise and expert performance—also became one of my research themes. So, from the very beginning of my academic career until today, Hans Gruber has served as an example for me. He teaches with humor, offers detailed comments on manuscripts, has innovative ideas (the concept of "persons in the shadow" is just one example), has created an enormous network, and, despite all his many achievements, has remained grounded. Thank you very much, Hans, for chairing the Fachmentorat.

Professor Erno Lehtinen and I first met in 2006 when he visited Hans Gruber at the University of Regensburg. He gave an invited talk and I was fascinated not only by his contents, but also—from my perspective—his obvious wisdom. Erno Lehtinen was the main reason why I decided to participate in the Erasmus program in Turku in 2007. Soon after, in 2008, he gave me an opportunity to work on one of his research projects in Finland. This project, chaired together with Roger Säljö, dealt with learning and medical imaging—the starting point for this habilitation. Learning, imaging, and professional vision was only one of his interests at the time. I remember how I asked Erno Lehtinen one day why he did research in so many different fields and used so many different methods. "Always doing the same bores me", he replied; he was interested in so much. This openness and curiosity (something you can see in his eyes during discussions) are strengths of his work and was an inspiration for me to explore different themes and methods. I can think of no better example of what it means to be an academic than Erno Lehtinen. Thank you very much, Erno, for supervising my diploma, doctorate, and now my habilitation thesis.

Professor Christian Wolff kindly accepted to be the third mentor in this habilitation's Fachmentorat. Thank you very much for your time, for your fast reaction to messages, and for your interest in this work.

I would like to highlight two other persons in the shadow: Roger Säljö and Jeroen van Merriënboer. Professor Roger Säljö and I first met in August 2008 in Herrankukkaro in Finland, at the venue of the Summer School of EARLI SIG 8 "Motivation and Emotion", where he served as a mentor for junior researchers. Erno Lehtinen introduced us, and a month

later I started to work on his research project LearnMedImage (Technologies for Seeing and Technologies for Knowing: Learning and Medical Imaging). Roger also co-supervised my doctoral thesis. From my perspective, Roger is—just like Erno and Hans—prototypical for EARLI because he integrates so many different research interests into his work. During our first meetings in Turku, I remember trying to write down word by word what he said because his line of reasoning was so clear and so elegantly phrased. And not only in talking: If I had to name authors whose style of writing and textual composition I tried to copy in the early phases of my career, then Roger Säljö would be among them (on par with Richard Mayer). Thank you very much, Roger, for your mentoring. Professor Jeroen van Merriënboer attended my first roundtable presentation—when I visited the EARLI 2009 conference in Amsterdam as a first-year PhD student—and I remember how surprised I was that such an eminent scholar would come to my table. Four years later, at the EARLI 2013 conference in Munich, he asked me if I wanted to work in his team at Maastricht University. I accepted and had the opportunity to learn from Jeroen van Merriënboer how to be a highly organized, dedicated, thorough scholar and supervisor. Thank you very much, Jeroen, for your modeling.

In addition to these persons in the shadow, I had the pleasure of working over the past 12 years with a number of people—far too many to describe here in detail. Still, considering how much joy or food for thought they offered, they deserve being mentioned: Adam Szulweski, Alex Fenzl, Alex Zitt, Andreas Michler, Andreas Oswald, Angelika Stadler, Anique de Bruin, Ann Renninger, Anna Siewiorek, Armin Eichinger, Ben Nädele, Bernadette Busler, Bernhard Schmidt-Hertha, Bettina Sorger, Brian Morris, Carla Quesada-Pallarès, Christian Ebner, Christina Hansen, Christine Bomke, Christoph Heim, Chunjie Zhu, Crina Damşa, Dagmar Festner, Detlef Urhahne, Dominik Froehlich, Doris Lewalter, Ellen Kok, Emmanuel Acquah, Erkka Laine, Erkki Svedström, Esther Kinateder, Eva Kyndt, Florian Hauser, Florian Stelzer, Gerda Hagenauer, Halszka Jarodzka, Harm Kuper, Isabella Karasek, Jake McMullen, Jan Vermunt, Jasperina Brouwer, Jean-Michel Boucheix, Julia Gorges, Julian Nothaft, Jürgen Mottok, Jutta Mägdefrau, Karen Könings, Karo Emmerdinger, Katja Kontu, Kenneth Holmqvist, Kilian van Zwoll, Koen Veermans, Kristin Seffer, Laura Helle, Laurent Testers, Maaike Endedijk, Malte Möller, Marco Seppänen, Maria Schmidt, Marja Vauras, Marjaana Veermans, Markus Gebhardt, Markus Nivala, Marlene Wagner, Martin Gartmeier, Matthias Fuchs, Max Knogler, Maximilian Sailer, Mien Segers, Minna Hannula, Nicole Schachtner, Nina Schwab, Paul Lewis, Petra Ziegler, Raphaela Fenzl, Rebecca Reuter, Regina Mulder, Renate Jakob, Ric Lowe, Richi Latzel, Robert Luzsa, Roland Zink, Sanna Järvelä, Sarah Ottinger, Sarah Reinhold, Saskia Brand-Gruwel, Simon Schober, Susanne Mayr, Susanne Schwab, Tetiana Khmelivska, Thomas Martens, Tina Seidel, Tobi Preuss, Tom Reio, Tuike Iiskala, Tuire Palonen, Ute Erbsmehl, Wolfgang Stern. Thank you.

Finally, a big thank you to my closest persons in the shadow: my partner, parents, brother, sister-in-law, nephews, family-in-law, and friends beyond my academic life. As Hans Gruber and colleagues (2008, p. 238) wrote in their seminal paper on persons in the shadow, the "important role of particular social contacts for the long term development of individuals" needs to be acknowledged. I thank you for who you are and what you do.

Plattling, in March 2020
Andreas Gegenfurtner

List of Publications

This cumulative habilitation thesis includes a total of 16 manuscripts published in or submitted to peer-reviewed journals. These manuscripts are listed below and ordered chronologically by publication and submission date.

1. Gegenfurtner, A., Lehtinen, E., & Säljö, R. (2011). Expertise differences in the comprehension of visualizations: A meta-analysis of eye-tracking research in professional domains. *Educational Psychology Review*, *23*(4), 523–552. https://doi.org/10.1007/s10648-011-9174-7

2. Helle, L., Nivala, M., Kronqvist, P., Gegenfurtner, A., Björk, P., & Säljö, R. (2011). Traditional microscopy instruction versus process-oriented virtual microscopy instruction: A naturalistic experiment with control group. *Diagnostic Pathology*, *6*(S1), S81–S89. https://doi.org/10.1186/1746-1596-6-S1-S8

3. Seppänen, M., & Gegenfurtner, A. (2012). Seeing through a teacher's eyes improves students' imaging interpretation. *Medical Education*, *46*(11), 1113–1114. https://doi.org/10.1111/medu.12041

4. Gegenfurtner, A., & Seppänen M. (2013). Transfer of expertise: An eye-tracking and think-aloud study using dynamic medical visualizations. *Computers & Education*, *63*, 393–403. https://doi.org/10.1016/j.compedu.2012.12.021

5. Gegenfurtner, A., Kok, E., Van Geel, K., De Bruin, A., Jarodzka, H., Szulewski, A., & Van Merriënboer, J. J. G. (2017). The challenges of studying visual expertise in medical image diagnosis. *Medical Education*, *51*(1)*,* 97–104. https://doi.org/10.1111/medu.1320

6. Gegenfurtner, A., Lehtinen, E., Jarodzka, H., & Säljö, R. (2017). Effects of eye movement modeling examples on adaptive expertise in medical image diagnosis. *Computers & Education*, *113,* 212–225. https://doi.org/10.1016/j.compedu.2017.06.001

7. Szulewski, A., Gegenfurtner, A., Howes, D., Sivilotti, M., & Van Merriënboer, J. J. G. (2017). Measuring physician cognitive load: Validity evidence for a physiologic and a psychometric tool. *Advances in Health Sciences Education, 22*(4), 951–968. https://doi.org/10.1007/s10459-016-9725-2

8. White, M. R., Braund, H., Howes, D., Egan, R., Gegenfurtner, A., Van Merriënboer, J. J. G., & Szulewski, A. (2018). Getting inside the expert's head: An analysis of

physician cognitive processes during trauma resuscitations. *Annals of Emergency Medicine*, *72*(3), 289–298. https://doi.org/10.1016/j.annemergmed.2018.03.005

9. Szulewski, A., Egan, R., Gegenfurtner, A., Howes, D., Dashi, G., McGraw, N. C. J., Hall, A. K., Dagnone, D., & Van Merriënboer, J. J. G. (2019). A new way to look at simulation-based assessment: The relationship between gaze-tracking and exam performance. *Canadian Journal of Emergency Medicine*, *21*(1), 129–137. https://doi.org/10.1017/cem.2018.391

10. Szulewski, A., Braund, H., Egan, R., Gegenfurtner, A., Hall, A. K., Howes, D., Dagnone, J. D., & Van Merriënboer, J. J. G. (2019). Starting to think like an expert: An analysis of resident cognitive processes during simulation-based resuscitation examinations. *Annals of Emergency Medicine*, *74*(5), 647–659. https://doi.org/10.1016/ j.annemergmed. 2019.04.002

11. Gegenfurtner, A., Boucheix, J.-M., Gruber, H., Hauser, F., Lehtinen, E., & Lowe, R. K. (2020). The gaze relational index as a measure of visual expertise. *Journal of Expertise*, *3*(1), 32–40.

12. Gegenfurtner, A., Gruber, H., Lehtinen, E., & Säljö, R. (2019). *Horizontal transition of expertise*. Manuscript submitted for publication.

13. Gegenfurtner, A., Lehtinen, E., Helle, L., Nivala, M., Svedström, E., & Säljö, R. (2019). Learning to see like an expert: On the practices of professional vision and visual expertise. *International Journal of Educational Research*, *98*(1)*,* 280–291. https://doi.org/10.1016/j.ijer.2019.09.003

14. Gegenfurtner, A., Gruber, H., Lewalter, D., Lehtinen, E., Holmqvist, K., Khmelivska, T., Hauser, F., & Vermunt, J. (2019). *Expertise in noticing: An eye tracking study of pre-service teachers, in-service teachers, and school principals*. Manuscript submitted for publication.

15. Gegenfurtner, A., Lewalter, D., Lehtinen, E., Schmidt, M., & Gruber, H. (2020). Teacher expertise and professional vision: Examining knowledge-based reasoning of pre-service teachers, in-service teachers, and school principals. *Frontiers in Education*, *5*, 59. https://doi.org/10.3389/feduc.2020.00059

16. Ottinger, S., Lewalter, D., Gruber, H., & Gegenfurtner, A. (2020). *Interaktionskomplexität moderiert die professionelle Unterrichtswahrnehmung von Mathematiklehrkräften*. Manuscript submitted for publication.

1. General Introduction

1.1. All Vision is Perspectival

Consider these two examples from education and medicine. Example 1: A mathematics teacher at school observes two student teams in her classroom who are engaged in a small-group activity; based on her observations, she decides to let one team work independently and to scaffold the other team "because I saw they did well but spotted immediately that the others needed help". Example 2: A radiologist at a hospital struggles to interpret a new kind of digital tomogram that was introduced to his department, so he asks a colleague to re-check the screening "because I wasn't sure if I saw everything diagnostically relevant". These two cases exemplify the importance of seeing professionally. As Goodwin (1994, p. 606) notes:

> All vision is perspectival and lodged within endogenous communities of practice. An archaeologist and a farmer see quite different phenomena in the same patch of dirt (e.g. soil that will support particular kinds of crops versus stains, features, and artifacts that provide evidence for earlier human activity at this spot). An event being seen, a relevant object of knowledge, emerges through the interplay between a domain of scrutiny (a patch of dirt, the images made available by the King videotape, etc.) and a set of discursive practices (dividing the domain of scrutiny by highlighting a figure against a ground, applying specific coding schemes for the constitution and interpretation of relevant events, etc.) being deployed within a specific activity (arguing a legal case, mapping a site, planting crops, etc.).

Vision can be learned as one develops expertise in a domain. Using the two examples from the beginning of this page, this cumulative habilitation focuses on professional vision and visual expertise in the domains of medicine (particularly radiology and emergency medicine) and education (particularly mathematics education). Why were these domains chosen? As Chernikova and colleagues (2020) argue, the diagnostic processes and underlying visual skills for collecting and integrating case-specific information are similar. Figure 1 presents a classroom situation (Hugener et al., 2007) and a computer tomography image (Gegenfurtner & Seppänen, 2013) as examples of this case-specific information. Both medicine and teaching are vision-intensive domains—and expertise in these domains relies on the skilled diagnosis of visual information (presented in classrooms or on medical visualizations). This similarity has resulted in a call to explore connections between both fields (Chernikova et al., 2020; Gartmeier et al., 2015; Stürmer et al., 2016). The present habilitation answers this call. In this first part of the habilitation's summary paper, the general introduction, we first address theories and findings from previous research associated with professional vision and visual expertise—for physicians (section 1.1.1) and for teachers (section 1.1.2). We then present an own theoretical framework that can be used to study expert performance in both domains: the cognitive theory of visual expertise (section 1.2) which guided the aims and research questions of the habilitation. The general introduction closes with a discussion of the methodology used (section 1.3).

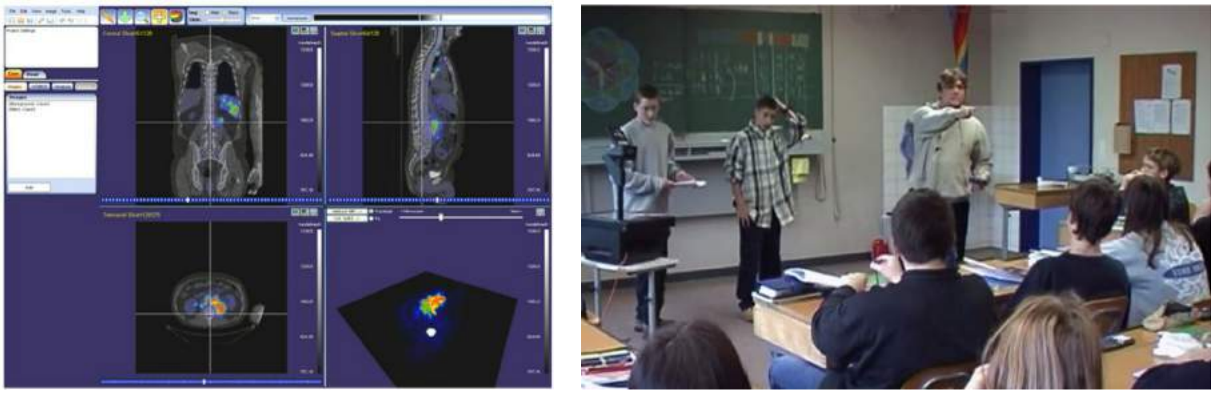

Figure 1. Examples of visual material in the domains of medicine and teaching: a positron emission / computer tomography (PET/CT) visualization and a classroom situation in secondary school mathematics education.

1.1.1. Professional Vision and the Visual Expertise of Physicians

Despite their similarities, the domains of interest in this habilitation—medicine and teaching—conceptualize the skills of seeing professionally with different terms and theories. It is thus necessary to describe the two disciplinary lines of reasoning separately before aiming toward synthesis. First, in medicine, work on visual expertise is highly influenced by Ericsson's expert-performance approach (Ericsson, 2017; Williams et al., 2017). Expert performance is defined as maximal adaptation to task constraints (Ericsson, 2017; Feltovich et al., 2018; Gruber et al., 2010) and visual expertise in medicine as reproducibly superior visual skills when making a diagnosis from a visualization (Gegenfurtner & Van Merriënboer, 2017; Kok, 2016). Clearly, visual expertise in medicine is not restricted to medical images, and a number of studies use mobile eye tracking to study visual expertise in the wild—for, example, in emergency rooms (Gegenfurtner et al., 2018; Szulewski, Egan, et al., 2019). There is, however, no general agreement on the terms that describe the information processing of visual experts (Boucheix, 2017; Gegenfurtner, Kok, Van Geel, De Bruin, Jarodzka, et al., 2017). What one sees in individual papers are italicized verbs and nouns—such as *detection*, *interpretation*, *perceiving*, *seeing*, *reasoning*, and the like—and different authors use different terms to describe the same processes when studying visual expertise in medicine.

Several theories explain the processes that underlie expertise in the comprehension of visualizations. First, the information-reduction hypothesis (Haider & Frensch, 1999) focuses on the learned selectivity of information processing. This theory suggests that expertise optimizes the amount of processed information by neglecting task-redundant information and actively focusing on task-relevant information. Second, the theory of long-term working memory (Ericsson & Kintsch, 1995) focuses on changes in memory structures. This theory assumes that expertise extends the capacities for information processing owing to the acquisition of retrieval structures. If it is true that medical expertise increases the selective allocation of attentional resources and speeds the retrieval of knowledge stored in long-term memory, then these changes should be reflected in trackings of eye movements and recordings of think-aloud protocols. Other prominent theories beyond the information-reduction hypothesis and the model of long-term working memory include, but are not limited to, Boshuizen's encapsulation theory (e.g., Boshuizen & Van de Wiel, 2014), Boshuizen et al.'s (2020) theory of knowledge restructuring through case processing, Sheridan and Reingold's (2017) holistic processing account, and Kundel et al.'s (2007) holistic model of image perception. Several publications review these theories, so they are not repeated here (see, e.g., Billett et al., 2018; Feltovich et al., 2018; Gegenfurtner et al., 2011; Gruber & Harteis, 2018; Norman et al., 2018; Patel et al., 2019).

Many sociotechnical domains—and among them: medicine— face rapid and constant change owing to frequent technological innovations that challenge the way experts work in these domains. These challenges also concern what constitutes expert performance in novel environments, and how experts adapt their practices to technological shifts. As specialized areas of modern medicine increasingly rely on digital technologies, the constant development and implementation of novel digital tools invite an analysis of how established expert practices and routines change. In addressing this topic, a pioneering study by Rystedt and colleagues (2011) examined how experts interpreted an image produced by what was then a new technology, tomosynthesis, and how experts revised their routine practices of seeing. The re-working of their practices aimed at improving diagnostic accuracy and making their diagnoses accountable. Of course, adaptation is not always accomplished easily, and difficulties or problems are frequently encountered. Still, to date, little research exists on how experts adapt their knowledge and skills to novel kinds of visualizations.

Another gap in the literature refers to the use of technology enhanced learning in medical education and training to facilitate the development of visual expertise in medical students and physicians. While medical education has embraced digital learning environments in the past, only a few have been directly dedicated to the development of visual expertise. This is unfortunate if we consider that medicine is a vision-intensive domain, with many diagnostic processes relying on visual information processing. Thus, it would be useful to examine the extent to which technology enhanced learning can be used to support visual expertise development instructionally. One promising approach is called virtual microscopy, which allows viewing specimens via the Internet from one's computer screen instead of using a light microscope (Helle et al., 2011). Another approach is called eye movement modeling, in which the eye movements of an expert are recorded and then shown to learners as an example where, how often, and in which order experts look at different areas of interest when producing a diagnosis from a medical visualization (Seppänen & Gegenfurtner, 2012). This gap in the instructional literature needs to be addressed when studying the (early) development of visual expertise in medicine.

1.1.2. Professional Vision and the Visual Expertise of Teachers

When studying the visual expertise of teachers, the terms used are typically professional vision and teacher noticing. The concept of professional vision was developed by Charles Goodwin and refers to a set of "discursive practices used by members of a profession to shape events in the domain of professional scrutiny they focus their attention upon" (Goodwin, 1994, p. 606). Early work on professional vision adopted a situated, practice-based perspective on seeing and learning. More recent work also uses the term professional vision in cognitively oriented research to examine individual differences in selective attention allocation, reasoning, and visual expertise. Within the broader framework of professional vision, the construct of teacher noticing was developed to focus on the professional vision of teachers in educational contexts. Teacher noticing describes what teachers see in the classroom, where they look, how they make sense of what they see, and which actions they take in response. In the conceptualization of Sherin and Van Es (2009), teacher noticing is associated with two components: selective attention and knowledge-based reasoning. The former process describes the allocation of attentional resources to specific visual cues in the classroom. The latter process describes the interpretation of selected classroom information. Jacobs and colleagues (2010) added a third component to teacher noticing: decision-making and teacher responses to noticed events. In the conceptualization of Seidel and Stürmer (2014), teacher noticing is included as a component of professional vision alongside knowledge-based reasoning (with its sub-processes of *describing*, *explaining*, and *predicting*).

To understand which information in classrooms novice and expert teachers rapidly select, eye movements are useful process measures. Indeed, teacher expertise research has used eye tracking (e.g., Haataja et al., 2019; McIntyre & Foulsham, 2018; Stürmer et al., 2016) to analyze expert-novice differences in fixations and saccades. A fixation occurs when the eye remains still over a period of time; a saccade is the rapid motion of the eye from one fixation to another (Holmqvist & Andersson, 2017). In a pioneering study, Yamamoto and Imai-Matsumura (2013) showed teachers a video of first graders. After watching the video, participants were asked if they noticed students who misbehaved (i.e., did not follow the teacher instruction to close their textbook). Participants who were aware of the misbehaving students fixated on these students more often and longer than did non-aware participants. Van den Bogert and colleagues (2014), using videos of secondary education teachers, reported longer fixation durations for pre-service compared with in-service teachers. Using a mobile eye tracker in the classroom, Cortina et al. (2015) found that expert teachers showed better classroom monitoring than pre-service teachers. These are just a few examples that explored the visual expertise of teachers. Typically, eye tracking studies contrast pre-service and in-service teachers. Yet, in schools, teachers are not the only group who develop professional vision. Principals and school leaders are frequently tasked with classroom observation to evaluate the teaching of their teachers. To date, and to the best of our knowledge, the eye movements of principals were not yet reported in research on teacher noticing and visual expertise. It would thus be a timely issue to explore how principals process classroom information.

When processing classroom information, pre-service teachers, in-service teachers, and school principals can focus their attention on a number of different areas of interest, including female students, male students, other teachers, or instructional material such as boards, worksheets, and textbooks. Not all of these areas are used in all studies on teacher noticing, and the selection of areas depends on the research interest. For example, if one is interested in how a teacher monitors and manages one's own classroom, (misbehaving) students will be the dominating area of interest and a (second) teacher is likely absent from the visual scene. Conversely, if one is interested in learning from other teachers—for example, in video clubs (Sherin & Van Es, 2009; Van Es & Sherin, 2008)—then the dominant area of interest is the teacher. And if one studies the professional vision of school leaders and principals, who frequently observe and evaluate other teachers, then these other teachers are the dominating area of interest. These differences in research design and research material might partly explain the mixed evidence reported in the literature as to which areas of interest receive the greatest attention allocation in visual tasks.

In summary, a range of different theories were developed in the domains of medicine and education to explain and reconstruct the visual expertise of physicians and teachers. Some theories can be used in both domains (e.g., Haider and Frensch's information-reduction hypothesis)—but then the theory captures only a small portion of the information processing system of experts (e.g., selective visual attention). Conversely, some theories capture the breadth of information-processing (e.g. Sherin and Van Es' noticing framework)—but then the theory is very domain-specific (focusing on teachers' pedagogical content knowledge). Reflecting on this heterogeneity and domain-specificity of frameworks, it becomes clear that different terms and models emerged as a product of the disciplinary traditions of theorizing and empirically studying visual expertise. Differences in terms and frameworks must be seen as a product of different epistemological perspectives with their own methodologies. What is needed is what many expertise researchers call for: theory development. If we synthesize the theoretical approaches across both domains—medicine and education—then it is necessary to focus on the processes and practices experts use when they comprehend visual information, regardless if this information is contextualized in classrooms or on medical visualizations. A newly developed model of professional vision and visual expertise should be applicable across contexts and synthesize existing evidence. The next section presents such a theoretical synthesis: the cognitive theory of visual expertise.

1.2. Cognitive Theory of Visual Expertise

The cognitive theory of visual expertise uses as a starting point Mayer's (2014) cognitive theory of multimedia learning (CTML, shown in Figure 2). Mayer's theory assumes that learners see a picture (for example: an animation) in the environment with their eyes. Visual information from the picture is briefly held in the visual register (sensory memory) and, if *selected*, transformed into an internal representation in working memory. Mayer calls this internal representation of the external picture an "image". Multiple images are *organized* into a mental model and *integrated* with prior knowledge stored in long-term memory. In the most recent edition of CTML, Mayer speculated, "How will the cognitive theory of multimedia learning evolve? A useful next step would be to better incorporate the role of motivation and metacognition in multimedia learning" (Mayer, 2014, p. 65); he assumes that motivation and metacognition influence the three processes of selecting, organizing, and integrating. CTML is useful as it models the active information processing of a novice learner with limited capacity in working memory and limited prior knowledge in long-term memory.

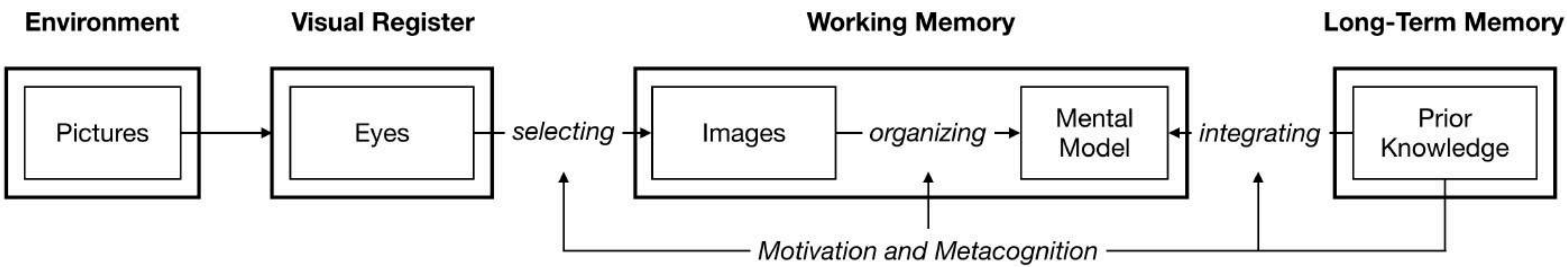

Figure 2. Cognitive theory of multimedia learning (CTML; adapted from Mayer, 2014).

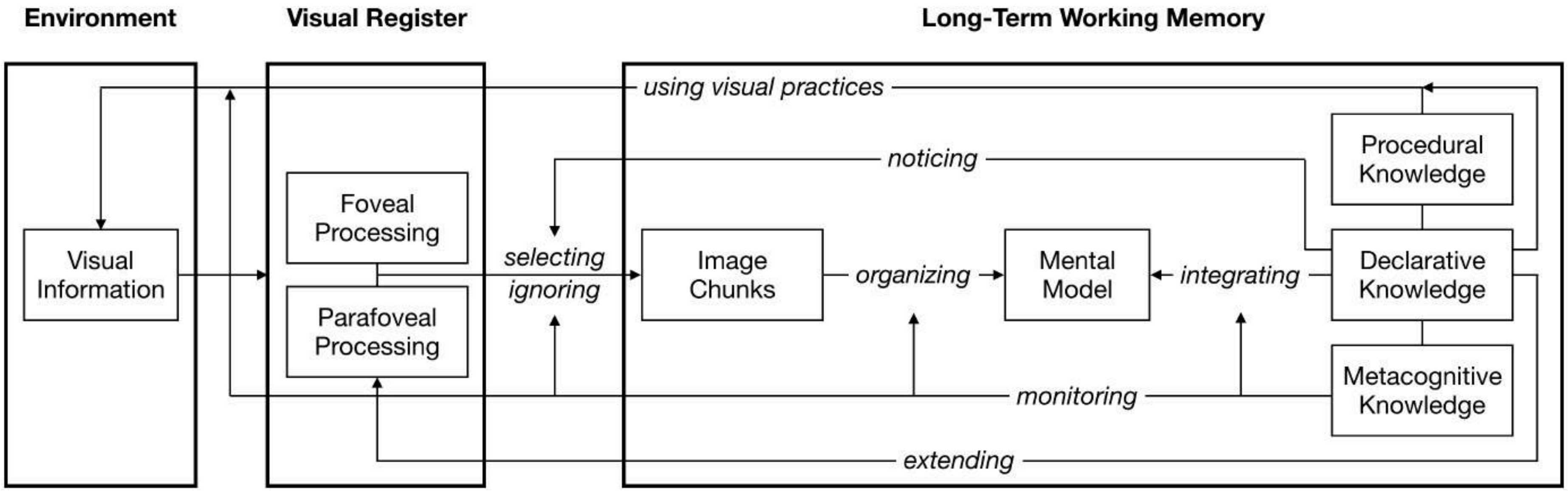

Figure 3. Cognitive theory of visual expertise (CTVE).

If we consider an expert professional instead of a novice learner, then information processing changes as expertise develops. These changes—shown in the cognitive theory of visual expertise (CTVE, Figure 3)—are associated with the number of memory stores, memory components, and cognitive processes. First, instead of the three memory stores visual register, working memory, and long-term memory from CTML, we assume only two memory stores in experts: the visual register and long-term working memory that expands the capacity limits in novices' working memory (Ericsson, 2017). Second, we assume that foveal processing (seeing with the eyes in CTML) is extended in experts who have developed the capacity for parafoveal processing which allows them to process information holistically (Kundel et al., 2007; Sheridan & Reingold, 2017). Third, we assume that experts engage not only in the process of selecting information, but also in ignoring information (Haider & Frensch, 1999). And we assume that experts not only select images, but larger image chunks (Delaney, 2018). Fourth, we assume that prior knowledge plays a much bigger role in experts' compared with novices' information processing (Boshuizen & Van de Wiel, 2014). CTVE models prior knowledge in terms of declarative knowledge, procedural knowledge, and metacognitive knowledge. Declarative knowledge is needed for experts to notice information, which is then selected or ignored (Sherin & Van Es, 2009; Seidel & Stürmer, 2014). Declarative knowledge is also assumed to be the reason why experts are able to engage in parafoveal processing. Finally, CTVE assumes that experts actively change visual information in the environment using visual practices (Goodwin, 1994) to render visible relevant information or to create artifacts that produce new visual information relevant for a task. Necessary for using visual practices is procedural knowledge, which is "lodged within endogenous communities of practice" (Goodwin, 1994, p. 606). In summary, CTVE modifies Mayer's (2014) CTML for experts by synthesizing the theories addressed in the previous sections 1.1.1 and 1.1.2, integrating them into a unified framework. Still, though theoretically reasonable, the CTVE needs empirical data to test its validity.

To test the assumptions of the CTVE, a number of aims and research questions can be developed. A first aim of the habilitation that spans the domains of education and medicine was to examine information processing as expertise develops; more specifically, we were interested in advancing our understanding how expertise changes memory structures, particularly in long-term working memory and the visual register; how expert declarative knowledge extends the visual register through parafoveal processing and influences the noticing, selecting, and ignoring of information; how experts use visual practices to interact with visual information in the environment; and how they use metacognition to monitor their information processing. These research questions are grounded on the assumptions inherent in the cognitive theory of visual expertise shown on the previous page.

In addition to this first aim, a second aim was to instructionally support the development of visual expertise, particularly in medical domains; more specifically, we were interested in exploring virtual microscopy to facilitate the performance of medical students in visual tasks; to analyze the teaching of expert visual practices as an instructional support for the early development of visual expertise; and to test eye movement modeling examples to support not only students, but also experienced physicians in their horizontal transition when the introduction of technological innovations changes the representativeness of their domain. Table 1 presents an overview of aims and research questions.

Table 1
Aims and Research Questions based on the Cognitive Theory of Visual Expertise

Aim	Research Question
Examine information processing as expertise develops	How does expertise change the structures in memory?
	How does expert declarative knowledge extend the visual register through parafoveal processing?
	How does expert declarative knowledge influence the noticing, selecting, and ignoring of information?
	Which visual practices do experts use to interact with information in the environment?
	How do experts use metacognition to monitor their information processing?
Support the development of visual expertise instructionally	How does technology enhanced learning support the early development of visual expertise?
	How can the teaching of expert visual practices support the early development of visual expertise?
	How do eye movement modeling examples support the horizontal transition of experts?

1.3. Methodology

This section describes the habilitation's methodology based on the aims of Table 1. Across the 16 individual studies, the habilitation used multiple, mixed methods. Expertise research is an interdisciplinary field known for its methodological pluralism—which can be considered a strength of the field, for it allows dialogue and triangulation of the findings of mono-method approaches. Which participants were sampled and which research designs were chosen?

1.3.1. Participants

The empirical studies sampled people across the continuum of expertise development: novices, intermediates, and experts. Prime target groups were prospective or experienced physicians and teachers in the domains of medicine and education. Participants in medicine were recruited in Finland (Turku), Canada (Kingston), and Germany (Regensburg). Participants in education were recruited in Germany (Munich). Generally, the novice participants included first-, second-, and third-year medical students, pre-service teachers in mathematics education, or inexperienced laypeople without prior domain knowledge. The group of intermediate participants was comprised of medical residents. And the expert participants were peer-nominated professionals that showed superior task performance in the domains of medicine (radiology, pathology, emergency medicine, nuclear medicine) and education (in-service mathematics teachers and school principals). Table 2 offers an overview. Study 5 was literature-based and did not sample participants; the paper is, therefore, excluded from Table 2.

Table 2
An overview of the sampled participants by study

Study	Novice	Intermediate	Expert	Domain
1	893 novices	187 inter-mediates	819 experts	Sports, medicine, transportation, other
2	120 medical students	.	.	Pathology
3	26 medical students	.	.	Radiology
4	.	.	9 physicians (5 nuclear medicine, 4 radiology)	Radiology, nuclear medicine
6	14 medical students	.	9 physicians (5 nuclear medicine, 4 radiology)	Radiology, nuclear medicine
7	13 medical students	9 residents	10 attending physicians	Emergency medicine
8	.	.	4 attending physicians	Emergency medicine
9	.	41 residents	.	Emergency medicine
10	.	10 residents	.	Emergency medicine
11	14 medical students	.	9 physicians (5 nuclear medicine, 4 radiology)	Radiology, nuclear medicine
12	.	.	1 radiologist, 1 pathologist, 2 nuclear medicine physicians	Radiology, pathology, nuclear medicine
13	4 laypeople	.	1 radiologist	Radiology
14	25 pre-service teachers	.	25 principals, 25 in-service teachers	Math education
15	25 pre-service teachers	.	25 principals, 24 in-service teachers	Math education
16	.	.	24 in-service teachers	Math education

1.3.2. Research Designs

The research designs were contingent on the different research questions. If we categorize designs as qualitative, quantitative, or mixed methods approaches, then a qualitative approach was used in three studies (Studies 8, 12, 13), a quantitative approach in eight studies (1, 2, 3, 7, 9, 11, 14, 15), and a mixed methods approach in four studies (4, 6, 10, 16). In the introduction to our special issue on visual expertise (Gegenfurtner & Van Merriënboer, 2017), we presented a comparative metaphorical mapping that is built around four metaphors. As Sfard (1998, p. 4) notes, “metaphors are the most primitive, most elusive, and yet amazingly informative objects of analysis”. We believe that their value and power stems from the fact that metaphors converge and portray, in a snapshot format, what took years of scientific discourse to develop. Of course, metaphors are simple and simplistic; there is no claim that they attempt to depict all of the breadth and depth of what often is a complex epistemology. Table 3 describes the methods used in the habilitation. Study 5 does not include empirical analyses and is thus excluded from the table. Our neuroscience studies using the activation metaphor were not part of this habilitation; if interested, however, the full-texts are available upon request (Gegenfurtner, Kok, Van Geel, De Bruin, & Sorger, 2017; Kok et al., 2018; Kok et al., 2021).

Why were these different methodologies chosen? An answer to this question would include recognizing that seeing and learning are, as Lehtinen (2012) writes, not "monolithic" phenomena. Theorizing about learning and seeing thus necessitates an awareness of the complexity of the practical dimensions—what it means to see professionally—and as a consequence being aware of the multifold units of analysis that can (perhaps: must) be chosen (Säljö, 2009). Per se, methods tend to reduce the complex reality—upwards or downwards (Lehtinen, 2012). Using multiple designs aimed to narrow reductionist biases of mono-method approaches and, at the same time, intended to afford a more complete picture of visual expertise and professional vision (Gegenfurtner et al., 2013). Clearly, this integration is hard to achieve in a single study. But in a programmatic research agenda—and a habilitation thesis is a great opportunity for being programmatic—it is possible to adopt diverse theoretical and methodological discourses across studies using multiple kinds of measures and analyses. First, in terms of measures, we included performance and process measures: performance measures were diagnostic accuracy, sensitivity, and specificity (receiver operating characteristics analysis, ROC) as well as time-on-task and exam score. Process measures included eye movements (fixations, saccades, time to first fixate) and pupillometry (pupillary change index, peak pupil size); verbal reports from think-aloud protocols, video recordings, and biographic and phenomenological interviewing; as well as visual practices embodied in movements and gestures. Second, in terms of analyses, we used quantitative analyses (meta-analytic synthesis, analyses of variance, correlational and regression analyses), qualitative analyses (conversation analysis, ethnomethodology, phenomenology, cognitive task analysis, documentary method), and sequential mixed method approaches. In summary, these measures and analyses helped us produce a number of findings on professional vision and visual expertise, too many to repeat in this summary paper. A synthesis of the principal findings, however, is presented in the next chapter.

Table 3

A comparative metaphorical mapping of the methods used in the habilitation

	Activation	Detection	Inference	Practice
Indicators of visual expertise	Neurophysiologic activity	Eye movements	Verbal reports	Visual practices
Unit of analysis	Individual	Individual	Individual and social	Sociotechnical
Place of visual cognition	Neural network system	Optic system	(Distributed) memory system	Activity system
Analytic time span	Milliseconds	Seconds	Minutes to few hours	Minutes to decades
Associated methodology	Cognitive neuroscience	ROC analysis; eye tracking	Protocol analysis; interviews	Interviews, video recordings, ethnomethodology
Studies	(e.g. Kok et al., 2018, 2021)	1, 2, 3, 4, 6, 9, 11, 14, 16	4, 6, 7, 8, 10, 15, 16	12, 13

2. General Discussion

This second part of the habilitation's summary paper, the general discussion, reflects on the results of the work presented in this habilitation. In section 2.1, we synthesize the principal findings of the 16 individual studies using the cognitive theory of visual expertise as an organizing framework. In section 2.2, we discuss the implications of these findings for expertise theory and methods (section 2.2.1), for educational practice (section 2.2.2), and for directions for future expertise research (section 2.2.3). Finally, we close this summary paper with a conclusion (section 2.3) for a broader readership.

2.1. Principal Findings

Considering the different theoretical and methodological approaches included in the habilitation thesis, what are the main results? Synthesizing the results of all 16 individual journal articles, we present the principal findings with reference to the aims and research questions presented in Table 2, using the CTVE as an organizing framework.

Associated with the first aim—to examine information processing as expertise develops—a first principal finding relates to changes in memory structures, particularly in long-term working memory (Figure 4). The evidence presented in our meta-analysis (Study 1) suggests that experts are faster than novices in visual tasks, which can be explained with superior memory structures of experts, specifically with rapid retrieval of information from declarative knowledge through retrieval structures and its integration into a mental model (Ericsson, 2017; Gegenfurtner et al., 2011). This finding is not only present in Study 1, but also in Studies 4, 6, 15, and 16, in which experts verbalized more comments than novices relating to the organization of image chunks and the integration with clinical (Studies 4, 6), biomedical (4, 6), episodic (Studies 15, 16), and content (Studies 15, 16) knowledge—but not with pedagogical content knowledge (Study 15). The development of long-term working memory helps experts also reduce cognitive load when processing complex visual information, which was found in Study 7 when measuring the pupillary change index (but not peak pupil size) and in Study 10 with verbalizations of experts managing cognitive overload.

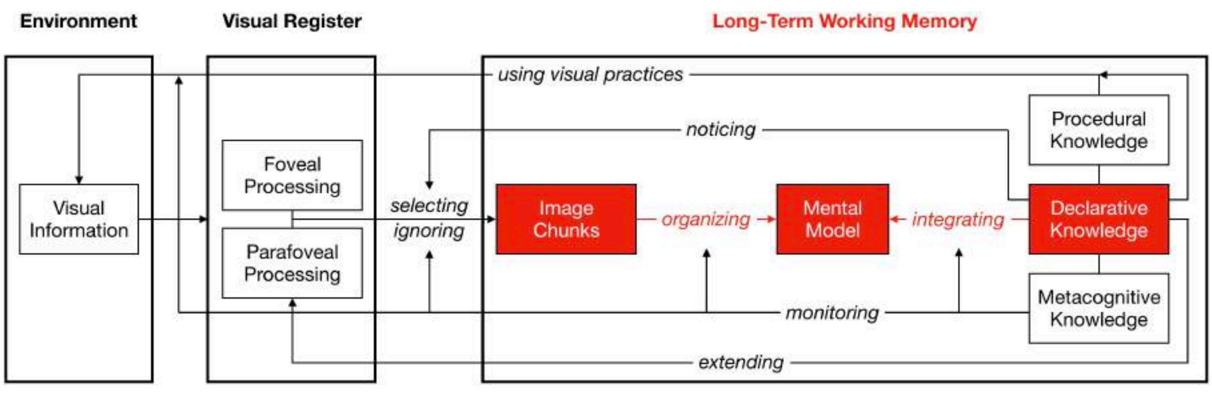

Figure 4. Visual expertise and memory structures.

A second finding relates to the development of parafoveal and holistic processing capacities in the visual register which extends the visual span of experts in domain-specific visual tasks (Figure 5). Indicators of this capacity are longer saccadic amplitudes. We found evidence for longer saccades in experts compared with non-experts in our meta-analysis (Study 1), covering diverse domains including medicine, but not in our study on teachers (Study 14). In the domain of medicine, the extension of the visual span is also indicated in the practice of zooming (Study 13), which essentially aims to broaden the visual field. Although not included in this habilitation, our neuroscience studies also suggest that parafoveal and holistic processing—indicated through neural activation in the fusiform face area—was associated with visual expertise (Gegenfurtner et al., 2017; Kok et al., 2021).

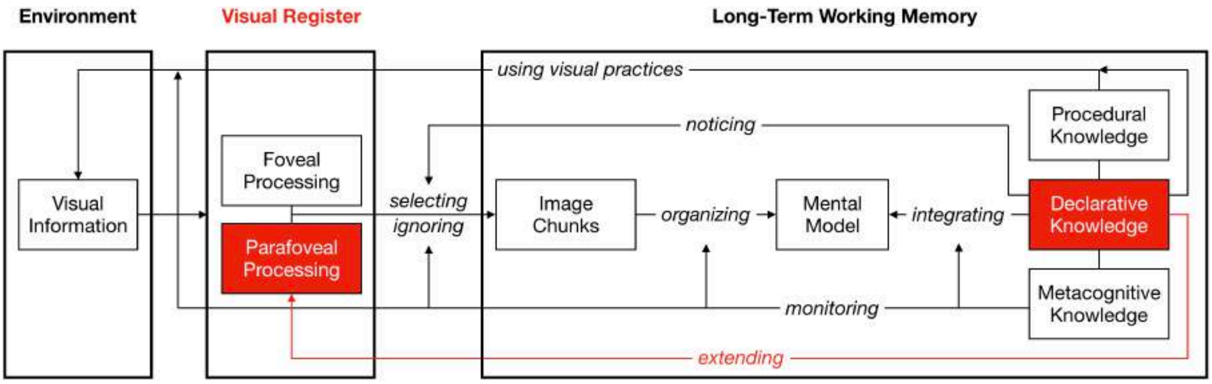

Figure 5. Visual expertise and parafoveal processing.

A third main finding relates to the selective allocation of attentional resources as expertise develops (Figure 6). We see this capacity reflected in a number of studies in which we contrasted the number and duration of fixations on task-relevant and task-irrelevant information, for example in our meta-analysis (Study 1), our studies in medicine (Studies 4, 6, 11), and our studies in education (Study 14, 16). And not only in eye movements: the selective attention of task-relevant information and the active ignoring of task-irrelevant information is also reflected in concurrent think-aloud protocols and retrospective verbal reports in the domains of medicine (Studies 4, 6, 8, 9, 10) and teaching (Studies 15, 16). Furthermore, selective attention allocation can be supported instructionally through eye movement modeling examples (Studies 2 and 6). Interestingly, the visual practice of highlighting used by experts to teach laypeople also mirrors the principle of selective allocation of attentional resources, in terms of directing the foveal processing to what is (diagnostically) relevant in a task. On a conceptual level, the processes of selecting or ignoring are associated with logistical and situational awareness (Studies 8 and 10) and closely linked with the rapid noticing of what is relevant in a complex visual scene (Study 14), which is, in turn, associated with declarative knowledge. This very quick noticing of task-relevant information is reported in our neuroscience publications as an enhanced N170 component (Gegenfurtner et al., 2017) and activation in the mirror-neuron system (Kok et al., 2018). Ultimately, the selective allocation of attentional resources results in shorter time-on-task of experts compared with non-experts, for which we found meta-analytic evidence reported in Study 1.

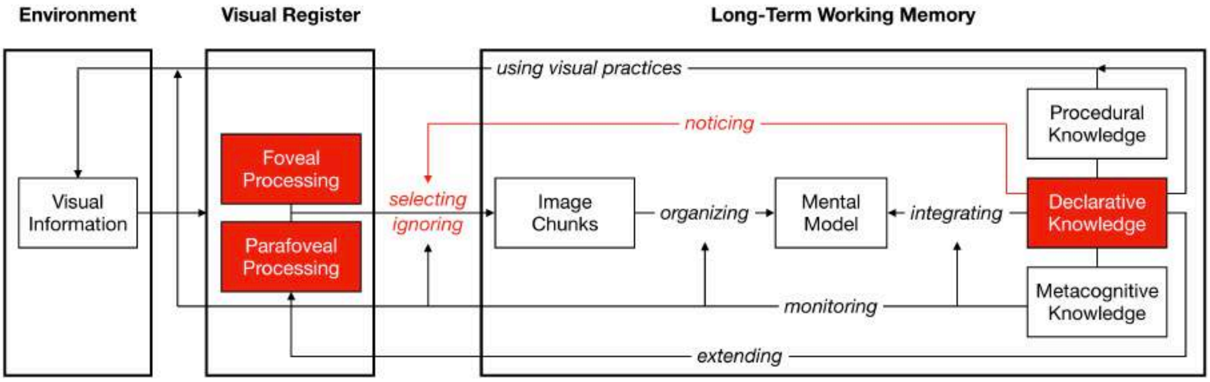

Figure 6. Visual expertise and selective attention allocation.

A fourth main finding relates to the use of visual practices (Figure 7). Most prominently, visual practices were explored in our qualitative analyses in Studies 12 and 13, in which experts used the practices of highlighting, zooming, and rotating the visualization, and in which they reported how they used semiotic resources in their environment for the solution of visual tasks (even when these tasks changed through technological innovations). Visual practices are also articulated in Study 8, suggesting that emergency medicine residents positioned their bodies in such a way that they could appropriately observe key clinical areas in the emergency room, using the monitor as an anchor and strategically prioritizing tasks. Also in Studies 4 and 6, we see evidence from verbal reports on the use of visual practices, in these studies through active manipulations of the three-dimensional dynamic PET/CT visualization. Central for the use of visual practices is procedural knowledge (that is: knowing how to execute the practice) and declarative knowledge (that is: knowing when and why to use certain visual practices). The development of a repertoire of visual practices, as outlined in Goodwin's work, constitutes professional vision that differs from classical information-processing approaches (e.g., Mayer, 2014) because—as is evidenced in the studies reported here—experts actively interact with the environment to extract visual information. They are not just consuming visual information presented in, for example, an animation, but they actively change visualizations, navigate in them, zoom in, highlight, or even create new forms of visual representations. Thus, the use of visual practices modeled in the CTVE and in Goodwin's work represents a transformational view on visual expertise.

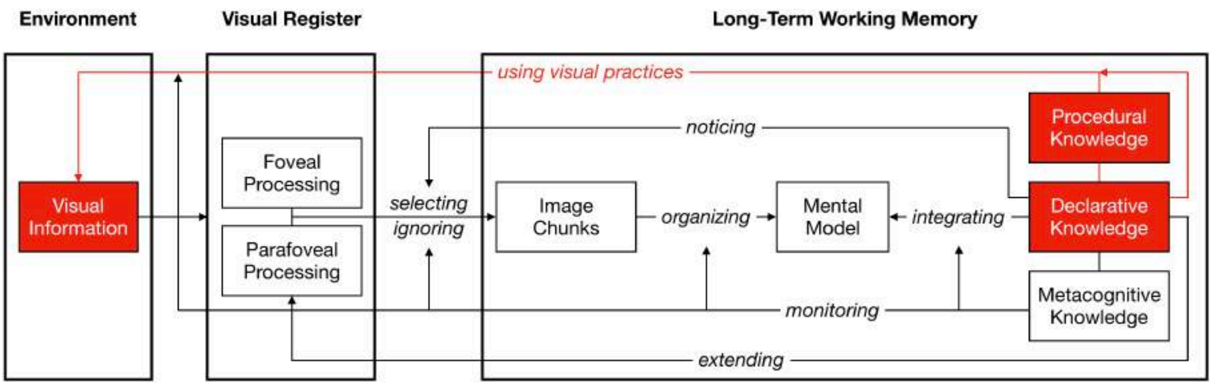

Figure 7. Visual expertise and visual practices.

Finally, a fifth main finding relates to metacognitive monitoring of the visual information processing system (Figure 8). In a number of studies in both the education and medical domains, we found that experts compared to non-experts verbalized more control strategies (Studies 4, 6, 15), re-checked possible task solutions and handled uncertainty (Studies 8, 10, 16). Although not included in the habilitation, we found metacognitive activity also in eye-tracking augmented debriefing sessions after performing objective structured clinical examinations (OSCEs): seeing where residents looked during the OSCE encouraged them "to reflect on their performance, leading them to critique responses to specific situational cues and to identify new insights into their performance" (Szulewski et al, 2018, p. 361). This higher metacognitive engagement of experts, indicated in verbalizations of more frequent monitoring, is an exciting finding because, to date, metacognition and self-monitoring tend to be underrepresented in visual expertise research.

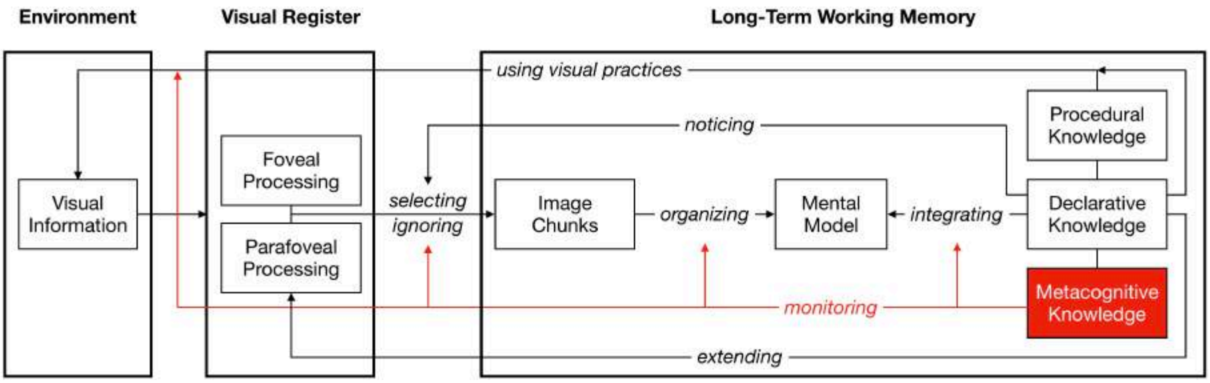

Figure 8. Visual expertise and metacognitive monitoring.

These five principal findings shown in Figures 4 to 8 are associated with the first aim. The second aim was to support the development of visual expertise instructionally. In this habilitation, we tested in a number of studies how to instructionally support non-experts on their way toward excellence. First, evidence in Study 2 suggests that the introduction of virtual microscopy in undergraduate pathology education facilitated the performance of medical students, particularly of conscientious high achievers, who used the ubiquitous availability of digital microscopic specimen for deliberately practicing the visual diagnosis of tissues. Second, evidence in Study 3 and 6 signals that eye movement modeling examples supports the selective allocation of attentional resources—both for novice medical students and for experts who are tasked with producing a diagnosis from semi-familiar visualizations. As noted above, seeing one's own eye movements (Szulewski et al., 2018) prompted retrospective metacognitive activity. And finally, third, the teaching and modeling of visual practices typically used for producing radiologic diagnoses of X-ray scans supported laypeople with no prior knowledge to notice task-relevant information (Study 13). We shall note here that the second aim of the habilitation, instructional support of visual expertise development, was addressed in the domain of medicine only. Still, although these instructional interventions were not tested in the domain of education, there is reason to assume that eye movement modeling examples, the modeling of visual practices, and the implementation of an ubiquitously available database of visual classroom scenes could also facilitate the visual expertise of teachers. To date, this is speculation; but future research could offer more insights and evidence to replicate the studies performed in the medical domain. Below, we will reflect more deeply on this direction for future research.

Overall, these principal findings form the synthesis of evidence from the 16 journal articles. Of course, each study offers a unique set of results, and these results are too numerous to review here. Still, one theme that is among the more important findings is the novel concept of "horizontal transition of expertise". We will discuss findings related to this concept (reported in Studies 4, 5, 6, and 12) in the next section. Before we turn to the implications, however, we shall reflect once more on the principal findings and compare the reported evidence by domains. Table 4 shows an overview.

Table 4

Cross-Domain Comparisons of the Evidence Associated with Expert Information Processing and Instructional Support

	Medicine	Education
Expert information processing		
Memory structures	Evidence in Studies 1, 4, 6, and 7 associated with more knowledge retrieval, fewer fixations, and lower cognitive load	Evidence in Studies 15 and 16 associated with the retrieval of more episodic and content (but not pedagogical content) knowledge
Parafoveal processing	Longer saccades (Study 1) and use of the zooming practice (Study 13)	No statistically significant expertise effect in Study 14 on saccadic amplitudes
Selective attention allocation	Indicated with eye movements and verbal reports in Studies 1, 4, 6, 8, 9, 10, and 11	Indicated with eye movements and verbal reports in Studies 14, 15, and 16
Use of visual practices	Interaction with visual information reported in Studies 4, 6, 8, 12, and 13	Not studied
Metacognitive monitoring	Verbalization of control strategies (Studies 4, 6)	Verbalization of control strategies (Studies 15, 16)
Instructional support		
Virtual microscopy	Effective only for conscientious high achievers (Study 2)	Not studied
Modeling of expert visual practices	Effective for laypeople (Study 13)	Not studied
Eye movement modeling examples	Effective for medical students (Study 3) and for professionals in semi-familiar task conditions (Study 6)	Not studied

2.2. Implications

Before offering some final concluding remarks, we discuss the principal findings in light of (a) their implications for expertise theory and methods, (b) their significance for educational practice, and (c) potential directions for future expertise research.

2.2.1. Implications for Expertise Theory and Methods

Why was Anders Ericsson so influential for the study of expertise and expert performance? A possible answer to this question is because he pioneered novel theories and methods—including the ideas of long-term working memory, deliberate practice, thinking aloud, and the expert performance approach—that offered new ways of conceptualizing and studying expertise. Any good expertise research should be assessed by the extent to which novel theories and methods are developed. In this habilitation thesis on professional vision and visual expertise, three ideas prevail: the novel notion of a horizontal transition of expertise, a new metric called the gaze relational index, and the cognitive theory of visual expertise (which section 1.2 described in detail).

First, the idea of a novel concept to study the horizontal transition of expertise (Study 12) emerged when we realized how the introduction of new technologies changes the way experts work in a domain over many years (Gegenfurtner, 2013; Gegenfurtner et al., 2009). This change necessitates a novel framework for studying how experts adapt to these changes, which could not be addressed with the more traditional theories of expertise associated with a vertical transition. Expert performance in the sense of a vertical transition addresses the development from novice to expert as a result of maximal adaptations to stable task constraints (Ericsson, 2017). In contrast, expert performance in the sense of a horizontal transition addresses the development and maintenance of expertise as a result of recurring adaptations to dynamic task constraints. If we conceptualize expertise as being interdependent between human agency, minds, bodies, and digital tools (Säljö, 2010), and if we further assume that digital tools frequently change in sociotechnical professions (Lehtinen et al., 2014), then we can adopt a relational perspective on expertise—one that is interested in the recurring adaptations of expert work to dynamic task constraints. Such a lens invites an analysis of experts and their professional agency and how experts orient "toward the future, with people not merely repeating past routines but challenging, reconsidering and reformulating their ideas, projects and plans" (Damşa et al., 2017, p. 447). Although it is intuitive to assume that experts need to adapt their practices regularly, there is still a paucity of studies addressing expertise in changing contexts. This line of research can complement work on expert performance in controlled contexts with representative tasks that remain relatively unchanged. Horizontal transition of expertise is thus the first implication this habilitation thesis offers to expertise research. This implication is closely aligned with the work done in the domain of medicine. To date, horizontal transition as a concept has not yet been applied to other domains. The domain of education seems to be an intuitive choice because it is a vision-intensive domain and shares some underlying diagnostic characteristics

(Chernikova et al., 2020; Gartmeier et al., 2015), but we shall note that the domain of teaching is not as technological as medicine. If technological change is understood as impetus for a horizontal transition, then other, technology-intensive fields are probably better candidates, for example meteorology, aviation, or transportation.

Second, the idea of a novel metric called the gaze relational index emerged when we read the work of Lowe and Boucheix (2016) on the comprehension of dynamic animations. To study the processing of visual information, particularly under conditions of information transience, the gaze relational index (GRI, Study 11) as the ratio of fixation duration to fixation number can be a useful measure of visual expertise. If we assume that relational processing—with a tendency of fewer, but longer fixations—reflects the degree to which selected visual information is integrated with prior knowledge to build mental models and if we further assume that exploratory processing—with a tendency of more, but shorter fixations—reflects the degree to which visual information is explored and selectively attended to, then the gaze relational index affords novel insights for expertise research because it *integrates* fixation duration and count in one metric. This integrated metric affords a quicker interpretation of information processing differences, and it offers an opportunity for a combined analysis that is unavailable if fixation number and duration are analyzed separately. The gaze relational index is thus the second implication this habilitation thesis offers to expertise research. Again, this metric is based on the work performed in the medical domain. Yet, unlike the notion of horizontal transition, we see good chances to replicate the GRI in the domain of education as well because teachers are tasked to work in visually complex scenes in classroom settings in which the GRI is likely to capture levels of visual expertise.

2.2.2. Implications for Educational Practice

The habilitation thesis has a number of implications for educational practice that are worth noting. These implications are associated with a process-oriented instruction, eye movement modeling, and expert visual practices. First, our findings from Study 2 on the use of virtual microscopy in an undergraduate pathology course suggest that students benefitted from a process-oriented instructional approach, particularly when students were high in conscientiousness. The process orientation was based on two design principles: (a) a gradual shift from teacher-regulated instruction to self-study and (b) the assignment of tasks, feedback, and the use of process worksheets. Traditional instruction in pathology is typically teacher-led and consists of the presentation of cases at the university's lecture hall; virtual microscopy now offers students immediate access to cases from home. As Helle et al. (2011, p. 1) note: "The basic idea is that the specimens can be viewed via the Internet from one's computer screen instead of using a light microscope. Thus, inspection of the slides is no longer restricted to tutorials: students can view images of the slides at any time from almost any computer with an Internet connection." This ubiquity affords the possibility to practice seeing, which was further enriched by the process-oriented design elements.

A second implication for educational practice concerns the use of eye movement modeling examples (EMME). EMMEs are inherently process-oriented because they visualize fixations while diagnosing. The usefulness of EMME was explored with medical students (Study 3) and experts (Study 6). In Seppänen and Gegenfurtner (2012, p. 1114), we argue that "it seems likely that the improvement in imaging interpretation was caused by more efficient perceptual processes facilitated by the teacher's eye movements, which guided the students' visual attention away from task-redundant areas to task-relevant information in the CT image". In Gegenfurtner, Lehtinen et al. (2017, p. 222), we state that "when confronted with unfamiliar visualizations, medical experts had higher levels of diagnostic performance, more efficient eye movements, and more task-relevant verbalizations after watching the modeling example." Interestingly, EMME was more efficient for experts than for students in Study 6, probably because previous knowledge and experience had prepared them to adapt their visual fixation processes. In a related study—not included in this habilitation—we explored how a replay of one's own gaze can be used as a resource for debriefing sessions in simulation-based training (Szulewski et al., 2018). EMMEs are, to conclude, a useful process-oriented instructional tool.

A third implication relates to expert visual practices. In Study 13, we explored how an expert uses particular visual practices to model diagnostic processes to a group of laypeople. In analyses of the moment-by-moment unfolding of discourse around chest X-ray films, Study 13 indicates how an expert communicates to a group of laypeople the way radiologists accomplish parts of their diagnostic work. Three practices emerged from the analyses: highlighting, zooming, and rotating. The educational implication of this empirical material relates to the role of social support needed to make transitions and develop understanding, which can play a role in medical undergraduate education and professional training (Froehlich & Gegenfurtner, 2019). Overall, these empirical analyses of professional vision form a sociocultural alternative (Goodwin, 1994) to studies that adopt a cognitive or physiologic stance on visual perception and expertise. How these practices can be implemented in medical education curricula can be explored in future research.

As indicated in Table 4, work on instructional support was grounded on the domain of medicine only; the domain of education and the work of teachers were deemphasized. This focus on medicine can be framed as a limitation of this habilitation. On the other hand, considering the similarities of both domains in terms of their diagnostic characteristics and vision-intensive tasks (Chernikova et al., 2020; Gartmeier et al., 2015; Stürmer et al., 2016), it seems logical to examine the effectiveness of instructional support strategies—proven in the medical domain—also in the educational domain. In that sense, the focus on medicine offers now a chance for future research sampling pre-service teachers in teacher education.

2.2.3. Implications for Future Expertise Research

Speaking of future research, this section of the habilitation delineates directions for further inquiry that follow from the work presented here. First, future research may wish to generate empirical material for some of the ideas in the habilitation. For example, a meta-analysis of visual expertise research could aim to verify or falsify the tentative assumptions and processes described in the cognitive theory of visual expertise (see section 1.2). Another example where more empirical data are needed is the methodological idea of the gaze relational index as a measure of visual expertise (Study 11). First tests were promising; more work needs to be done, however, until the measure is fully established. And yet another example where more empirical work is needed is the idea of a horizontal transition of expertise (Study 12). We have good reason to assume that experts develop and adapt their skills horizontally when technologies in a domain change. Still, although promising and plausible, more work needs to consolidate this novel concept as a useful addition to the existing repertoire of expertise theories. One could also study a horizontal transition as conceptual change (Lehtinen et al., 2020). To summarize this first direction for future research, the habilitation thesis offers new theoretical and methodological ideas for expertise research to inspire future work.

Second, future research may wish to replicate the findings from the studies included here in domains beyond medicine (and teaching). For example, the use of eye movement modeling examples prevailed in the medical disciplines. It would be interesting to explore how EMME can be used in the teaching profession as well—would pre-service teachers develop noticing skills more efficiently through EMME as part of a training intervention (Huang, 2018; Seidel & Stürmer, 2014; Stürmer et al., 2016; Van Es & Sherin, 2008)? Other domains where the use of EMME could be examined include, but are not limited to, sports (Gegenfurtner & Szulewski, 2016) or software programming (Hauser et al., 2019), largely because these domains are vision-intensive and require professionals to allocate their attentional resources away from task-irrelevant areas toward task-relevant information—EMME could facilitate selective attention allocation in those domains. In addition to EMME, more research is needed to replicate expertise differences in noticing and knowledge-based reasoning in domains beyond medicine and teaching. Replication studies can include original research—for example with police officers, a yet understudied population in expertise research—or meta-analytic syntheses of already published work; a new meta-analysis could update the findings reported in Study 1 and test the predictive validity of the cognitive theory of visual expertise. It would also be interesting to combine these three directions for future research: with studies that examine how expertise differences in domains such as sports, software programming, or police work can be remedied through eye movement modeling examples.

2.3. Conclusion

For a broader readership, what was this habilitation about? This habilitation focused on the gaze of professionals. When a radiologist, for example, looks at an x-ray scan of a patient's lung, she sees very quickly if the patient has lung cancer—while somebody without expertise in radiology does not see the same symptoms in an x-ray scan, or might look at irrelevant parts of the visualization. Consider a second example: When a teacher looks at his students in the classroom or lecture hall, he "reads" his students and sees very quickly who pays attention, who is daydreaming, who needs support, and who does not follow the instructions. These two examples from the fields of medicine and education show how important the gaze is in some professions. To become expert in such a domain requires training one's gaze and developing a "professional vision". How the professional vision of experts differs from non-experts in a domain is, however, far from evident. What are the underlying mechanisms? How does an expert look at a visual scene compared to, say, a novice or a student in training? And how can novices be supported instructionally to develop visual expertise? These were the overarching questions that guided the work reported here.

To answer these questions, the research performed in the habilitation was interdisciplinary and international. First, it was interdisciplinary because theories and methods from educational science, psychology, and medicine were needed to answer our questions on professional vision and visual expertise. For example, we used receiver operating characteristics (ROC) analysis from medicine to measure how accurate the diagnoses of radiologists and medical students were; we used eye tracking from psychology to measure where experts and novices looked at and for how long; and we designed learning environments to contribute to the education of novices. We used a range of methods, from quantitative statistical calculations to qualitative conversation analysis, largely because the research questions we had required a set of different methodologies used in the medical, psychological, and educational sciences. Still, the notion of "professional vision", interestingly, had its origins neither in education, psychology, nor medicine—but was coined by Chuck Goodwin (†), who was a linguist and anthropologist. In addition to being interdisciplinary, the research performed in the habilitation was international because colleagues from (in alphabetic order) Australia, Canada, Finland, France, Germany, the Netherlands, and Sweden collaborated to answer our joint research questions in the 16 individual journal articles that together form this cumulative, publication-based habilitation.

What we learned was that experts compared to non-experts are faster in solving visual tasks; they are more accurate and precise in their solutions; their reasoning processes are more knowledge-based; they use a repertoire of visual practices; they look more and longer on task-relevant information and tend to ignore task-irrelevant information; they look at visual scenes holistically; and they metacognitively monitor their information processing. Seeing the eye movements of an expert during task solution is a useful educational intervention for students and for professionals in training. This is the essence of the 16 manuscripts that we published in peer-reviewed educational, psychological, and medical journals.

The habilitation includes some pioneering work. We were the first to perform a systematic meta-analysis of eye-tracking research on expertise differences. We were the first to use eye movement modeling examples with dynamic, three-dimensional visualizations. We were the first to use eye tracking in the domain of emergency medicine. We were the first to examine the professional vision of school principals. We were the first to apply the gaze relational index as a measure of visual expertise. And we were the first to develop the frameworks of horizontal transition of expertise and the cognitive theory of visual expertise. Ultimately, we hope these new kinds of evidence, measures, and theories are useful for other researchers in the field of expertise and professional vision, and we hope the findings inspire educational practitioners who wish to support their learners in the early development of visual expertise. We close this habilitation's summary paper with a quote from Goodwin that we also used to open the summary paper—indicating how important it is to be aware and to consider different disciplinary perspectives when we seek to understand (a) why an expert teacher and a teacher student spot different cues in the same classroom or (b) why a radiologist and a medical student see different things when they look at the same chest x-ray scan, simply because, as Goodwin (1994, p. 606) said: "All vision is perspectival".

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Appendix