Cognitive Skills in Medical Diagnosis and Intervention

Halszka Jarodzka, Henny P.A. Boshuizen, & Paul A. Kirschner (Open University of the Netherlands / CELSTEC)

1. Definition and meaning of cognitive skills

A physician who performs catheter-based cardiovascular interventions must master many diverse skills including social skills for interacting with patients, management skills for handling and coordinating diverse case scenarios, tactile and motor skills for operating the catheter, and many more. Although these skills are crucial, they are not the focus of this chapter (e.g., for psycho-motor skills see Chapter 8). Instead, cognitive skills required to plan and actually carry out interventions which play a crucial role in the overall performance of catheter-based cardiovascular interventions, are the focus.

Psychology has a long tradition in investigating and training cognitive skills. Van Lehn (1) described cognitive skills as “the ability to solve problems in intellectual tasks, where success is determined more by subjects’ knowledge than by their physical prowess” (p. 513). To understand cognitive skills, it is important to understand the human cognitive architecture on which basis these skills depend. In this section we first discuss human cognitive architecture as a 3-storage model of sensory register, working memory, and long-term memory. Then, we discuss how cognitive skills operate in working memory in terms of perception and higher-level cognitive skills.

1.1 Human cognitive architecture in information processing

1.1.1 Atkinson’s and Shiffrin’s 3-storage model

Atkinson & Shiffrin (2, 3) describe human cognitive architecture in their information-processing model. Figure 1 refers to structures and processes assumed by this model (this
figure includes also other structures and processes assumed by models described below). Its basis is a 3-storage-assumption which states that three separate memories exist, namely an almost unlimited but extremely transient *sensory memory*, an in capacity but also temporally limited *working memory*, and an unlimited *long-term memory*. To be successfully stored, information must pass all three memory structures, but the information processing differs in each structure.

In a first step, input from the environment enters the *sensory register* which stores surface stimulus features of different nature in different sub-registers (e.g., visual, audio, haptic, olfactory, gustatory). The sensory register is able to store large amounts of information, but only for a fraction of a second. Most of the information gets lost after this very brief amount of time. Only information that is attended to in the sensory register is further processed. Hence, relevant information has to be actively selected to enter working memory. The selected information entities may be of different nature, such as words, image features, smells, or other. Next, the information selected by the attentional mechanism is transferred to *working memory* for further processing. Atkinson and Shiffrin assume that working memory is very limited in terms of capacity. That is, only a limited amount of information can be actively processed in working memory at the same time. Furthermore, information that is processed can be held in working memory for as long as it is processed and is then permanently stored in long term memory. Information that is not further processed (e.g., rehearsed, elaborated upon, etc.) deteriorates and is lost from working memory. The *long term memory* is a permanent storage for unlimited amounts of information. Atkinson and Shiffrin do not make specific assumptions on how exactly information is stored in long term memory. However, they assume that information cannot be stored in long term memory before it has passed through the other memory structures. Furthermore, they assume that information stored in long term memory can re-enter working memory. There it can be processed, changed, or integrated with new information already active in working memory. A last crucial assumption in their model concerns a possible output of these processes to the environment. In their model, higher level cognitive processes such as decision making take place in working memory. Hence, the outcome of a decision-making process depends on which information is currently active in working memory, which can be new input from the environment, old information received from long term memory, or a combination of both.

It is important to note that the description of working and long term memory as two separate entities has been criticized [in terms of coding of information in working memory: (4); recency effect in long term memory: (5, 6); fewer limitations of working memory: (7)]. Current views see the two more as constructs that help in describing certain cognitive processes (e.g., active processing of information or its storage) instead of as two distinct memory structures.

### 1.1.2 Sensory register and working memory: capacity limitations and temporal constraints

The *sensory register* stores input from the environment in an unprocessed manner for a very brief amount of time. It is assumed that this part of memory can be divided into different stores that depend on the actual sense that encountered the input, such as smell, touch, vision,
hearing and taste (8). Most research focuses on the visual (iconic) and hearing (echoic) sub-registers of sensory memory (9). Research on iconic memory has found that approximately 10 icons can be held in the sensory register (10) for about 200-400 msec (11). One important purpose of iconic memory is to provide us with a stable impression of the visual world, while our eyes are ‘jumping’ across the environment (12). Likewise, the echoic memory has also been widely studied. The echoic sub-register is capable of storing fewer items (±5), but for longer periods of time (2-3 sec) compared to the iconic memory (13). Although other sub-registers in sensory memory that may be important for medical diagnosis and intervention (e.g., tactile input) have hardly been investigated, we may assume that they function in a manner similar to iconic and echoic memory. That is, a complete afterimage of the sensation remains within the relevant memory storage for a brief time so that information can be selected from through attention.

Two theories describe the components of working memory, namely the dual coding theory by Paivio (14) and the working memory theory by Baddeley (15). Both Paivio and Baddeley assume that two separate channels exist for information processing in the human cognitive system, namely a visual-pictorial and an auditory-verbal channel. These channels are distinguished according to sensory modalities, that is, information presented to the eyes is initially processed in the visual channel, while information presented to the ears is initially processed in the auditory channel. Information that entered these two channels is passed into the according component of working memory, namely either the phonological loop or the visuospatial sketchpad. The phonological loop stores and manipulates verbal information, while the visuospatial sketchpad does the same for visual information. Baddeley describes these two components as ‘slave systems’. Besides these slave systems, there is a superior component called central executive, which controls the attentional system and integrates information from both slave systems. Moreover, within this working memory structure new information is integrated with prior knowledge activated from long-term memory, for instance in forms of schemata (see following section).

In addition to these assumptions about components of and processes occurring in working memory, research in cognitive psychology has also studied its storage size and duration. Initially, it was assumed that the working memory storage is limited to 7±2 entities and that this can be increased by chunking several information entities into one large entity (16). More recent findings suggest that this ‘magic number’ may not be as strict as initially assumed (7, 17). Furthermore, working memory is also temporally restricted to around 18 sec (18) though some research has put it as low as 2 sec. and as high as 30 sec. As with the working memory size, we may assume that this exact number should be seen more as an approximation than a fixed setting.

1.1.3 Long-term memory structures: schemata, scripts, and network models

Many theories deal with the storage of knowledge in long-term memory, such as the network model (19), ACT* theory (20) and many more. This chapter will not go into these theories in depth, but will limit itself to schemata or scripts as forms of knowledge storage in long-term memory, because these are deemed to be especially relevant by researchers on medical
expertise (see Section 2). The concept of schemata was introduced by Bartlett (21). Van Lehn (22) describes schemata and their use in the following way: In an optimal situation, where the task performer has a high-level of expertise in a domain, she or he has already acquired many schemata. A schema consists of two components, namely information on the task or problem and information on its solution. Schemata are constructed in that all schema-relevant information is activated simultaneously in working memory. Schemata have two central functions. First, they are an efficient way to store and organize knowledge in long-term memory. Second, they reduce the load in working memory, in that they subsume several information entities into one (i.e., chunking) and thus, only occupy one entity of the 7±2 available. Frequent schema activation results in schema automation, which means that a schema can be used very quickly while causing minimal load on working memory. Experts in domains like medical diagnosis store elaborate schemata in an efficient manner in long-term memory, so that they can be direct accessed in working memory by means of retrieval cues (23).

1.2 Cognitive skills operating in working memory

When prior knowledge is activated from long-term memory or when new information enters the human cognitive system, all interpretation and manipulation of this information takes place in working memory. Cognitive skills operating within the working memory system are either perceptual (i.e., when information enters from the environment) or higher order (i.e., when perceived information is further manipulated and prior knowledge is activated) as described in the following.

Perception of information from an environmental input has two components, namely a bottom-up and a top-down component. The bottom-up component refers to influences from the environment itself. For instance, if a part of a grey stimulus is yellow, it is more visually salient and hence more likely to be perceived (24). The top-down component refers to influences from our previous knowledge or expectations. For instance, one person looks at the same painting differently with different tasks in mind (25), or people with different expertise levels look differently at the same painting (26). One important aspect of perception is attention, which refers to processes involved in the selection of elements within a stimulus for further processing while ignoring others (27). Allocation of visual attention is guided by both exogenous and endogenous cues; again top-down and bottom-up (28). Another important aspect of perception is pattern recognition; the ability to give meaning to a complex stimulus such as a street scene. Several theories on pattern recognition exist, all of which basically state that we compare what we perceive to a model or prototype that we have stored in our memory [e.g., (8, 29, 30)]. If this stored model sufficiently matches the perceived object, it is recognized as a certain pattern (e.g., a character, a face). This process occurs within a very short time and does not require higher levels of processing.

Higher order cognitive skills include language production and understanding (not the focus of the current chapter), decision making (see Chapter XY this book), and problem solving. Van Lehn (22) describes schema-driven problem solving in the following manner: When executing a task or solving a problem based on schemata, three processes occur: (a) selecting
Selecting a schema is supposed to happen very early in the task performance process. Once a schema is activated, it affects or guides the further processing of the task. Usually, a general schema is activated first, guiding the activation of more specific schemata. In a next step, the schema is instantiated, that is, it is adapted to the task at hand. It is important to note here that Van Lehn describes a schema as a structure that consists of givens and demands, so-called slots. When adapting a schema to a specific task, these slots are filled with task-specific information. This process often goes hand in hand with choosing a more specific schema. Finally, the solution procedure that is part of the schema is executed step by step (for routine tasks at least). This part, however, is not always trivial. Often, the solution procedure consists of sub-problems that also have to be solved.

1.4 Nomenclature and summary of cognitive skills

Figure 1 presents a summarized model of human cognitive architecture as it is assumed by the described theories. Central terms and processes re-occurred in those theories. The most important are:

**Sensory memory**: A pre-cognitive system that is unlimited in capacity, but very limited in time. Information is only processed further in the human cognitive system if attended to (i.e., selected).

**Working memory**: A central system where all active mental processes occur which is limited in both time and capacity. Here, new information is organized and integrated in schemata activated from long-term memory. The schemata are then further adapted and instantiated resulting in the execution of the solution procedure attached to the schema. Note that these cognitive skills can only operate if working memory capacity is not exceeded.

**Long-term memory**: Where knowledge is stored and optimally organized in schemata.

**Perception**: The first step of conscious information processing. It requires attention to certain elements within a stimulus and allows for pattern recognition within this stimulus.

**Higher order cognitive skills**: An elaborate and further processing of perceived information, its integration with prior knowledge, and its further manipulation. These skills compose language understanding and production, decision making, and problem solving.

**Schema**: How knowledge is organized and stored in long-term memory. When activated in working memory, schemata reduce working memory load. Schemata consist of givens and slots that need to be filled with context information and solution procedures.
2. Cognitive skills as they apply to medicine

The previous section reviewed the concept of cognitive skills. This section discusses how these concepts apply to the medical domain. The role of cognitive skills in medicine has been an important research topic for the past 30 years (for an overview on research history on cognitive skills in medicine see (31), Chapter 1). This topic was investigated from two perspectives which were not incorporated up until now. First, research on the development of knowledge structures in long-term memory across expertise levels and its influence on higher-level cognitive processes such as clinical reasoning is almost exclusively based on the analysis of written medical records without taking into account that clinical practice often requires using and thus perceiving medical images [e.g., (32-36)]. Second, findings on the perception of medical images were not related to higher-level working memory processes or long-term memory [e.g., (37-39)]. This section begins by describing research on the development of long-term memory structures and then higher-level working memory processes. Next, it describes what is known about the perception of medical images. In a last step, it makes a first attempt to bring the findings from both research perspectives together in one model.

2.1 Storage and organization of medical knowledge in long-term memory throughout expertise development

The storage and recall of knowledge in long-term memory is critically important for the development of cognitive skills. Research in cognitive psychology has suggested that knowledge is optimally stored in forms of schemata (1, 22). The nature and development of schemata across expertise levels can be described in greater detail for the medical domain, where a 3-stage model describing changes in knowledge organization with increasing expertise has been proposed [e.g., (32-36)].

The first stage describes the knowledge organization of novices such as interventional fellows. These novices acquire large amounts of knowledge from basic sciences, including vascular anatomy, pathophysiology of the human cardiovascular system and pharmacology. This knowledge is often referred to as biomedical knowledge. The amount of knowledge
novices need to acquire is considerable and proper reasoning with such large amounts of knowledge can be difficult, particularly when it is organized in a way that does not fit the task at hand which is customary in the daily medical practice. Knowledge networks that link concepts studied provide an important starting point at this stage. These networks are composed of nodes that represent concepts which may be of different order levels [cf. the idea of general and specific schemata presented by Van Lehn (22)]. Higher order concepts describe diseases more generally (e.g., heart failure). These higher order concepts contain lower-order concepts, such as specifications of the higher concept (here: diastolic failure, systolic failure, type and functional stage of the primary cardiac disease) and symptoms and signs related to this disease or phenomenon (here: fatigue, dyspnea, thoracic X-ray congestion of lungs, echocardiography findings and other). These concepts are interconnected via links that symbolize hierarchical order or double relations of certain concepts. For instance, tachycardia may be related to the progression of heart failure, side-effects of medication, anxiety or other factors. The network system of high complexity level has to be built over a long time and may take years to develop by improving and adding new concepts to the existing network and establishing new connecting links. The aim of teaching and learning at this stage is to augment and validate these knowledge networks. At the end of this stage, the trainee should be able to make direct lines of reasoning between different concepts within the networks that are based on sound pathophysiological and clinical principles.

When the trainee has acquired a sufficient number of knowledge networks, he/she may begin to apply his knowledge in clinical encounters with real patients. The main task of this second stage consists of fine-tuning the existing networks. By using the acquired knowledge in practice, the novice activates concepts and links between those concepts confirming or disproving their validity. Frequent activation of specific connections serves the development of basic routines based on recall of automated links. This successive automation entails clustering concepts within one line of reasoning together, such that intermediate concepts can be skipped and only the starting and ending concepts remain. For instance, in the condition of liver cirrhosis you may encounter in the anatomy of a patient the following: hepatitis, cell destruction, nodular regeneration, increased pressure on supplying veins, portal hypertension, ascites, extended abdomen, esophagus varices, hemorrhage, etc. The line of reasoning can be abbreviated to hepatitis can lead eventually to portal hypertension and esophagus varices. These clusters are summoned under semi clinical terms, like portal hypertension. These summary terms, in turn, serve as tools for reasoning. This process is called knowledge encapsulation (32, 34, 35), a phenomenon that has been extensively investigated and verified in the medical domain [e.g., (40-43)]. In sum, at this stage of expertise, the theoretical knowledge of cardiovascular diseases becomes integrated by means of encapsulation into practical clinical knowledge of manifestations of real diseases in actual patients. In catheter-based cardiovascular interventions, additional knowledge translating disease concepts into interventional strategies and the conduct of actual interventions must be acquired along with general knowledge of cardiovascular diseases. This type of knowledge is formed primarily by learning about the biomechanical properties of the cardiovascular system and the interventional instrumentation and their mutual interactions during the interventional process (i.e., during clinical practice).
When a physician or operator has extensive clinical experience and has become an expert in her/his domain, one speaks of the third stage of knowledge organization in expertise development. At this stage, expert knowledge is organized in an entirely different qualitative way, namely in so-called illness scripts (44). Based on illness scripts, the knowledge about diseases becomes stored in three components. The first component specifies general conditions that enable or constrain a disease including contextual (i.e., social, hereditary, and environmental) information. The second component contains the assessed pathophysiological process of the actual specific disease, such as the stage and degree of organ dysfunction in an individual patient. This knowledge is again encapsulated (i.e., as in Stage 2, lines of reasoning are often reduced to a few semi-clinical terms). The third component spans the subjective and objective symptoms and signs of the disease as present in an individual patient. In catheter-based cardiovascular interventions, the expert knowledge also comprises knowledge on interventions within the illness-scripts. It is important to note that this kind of organization is structured in a less causal, but more temporal manner in contrast to the network-structure common in Stage 2. Here knowledge is organized based on operational clusters and temporal patterns allowing speedy and highly efficient processing. Moreover, the amount of clustering and complexity of the knowledge structures is substantially higher, more focused and better targeted than in the second stage.

2.2 Higher-level working memory processes – Clinical reasoning

Section 1 discussed how higher-level working memory processes include the activation of schemata from long-term memory, instantiation of these schemata with context information from the task at hand, and ending with an execution of the schemata-related procedural solutions. Boshuizen and Schmidt (33) formulated these processes (here: clinical reasoning) in greater detail for the medical domain. When a cardiovascular specialist is confronted with a patient case, she/he immediately activates one or more illness scripts. Which scripts are activated depends on the given enabling conditions and the observed consequences. For example, if an acutely ill drug-user exhibits shaking chills, high heart rate, murmurs, and petechiae then the illness script “Acute Bacterial Endocarditis” would probably be activated. Once the script is activated, it is not necessary to spend additional mental resources to actively search through all of the available diagnostic options associated with each of the signs/symptoms including their relevant decision-trees. After the script has been activated, it is instantiated with case-specific information to match the script with the case-specific data of the individual patient. Moreover, expectations concerning the likely course of the disease are generated. In the course of this script instantiation, the expectations given by the script are updated or replaced by data from the actual patient. Some scripts automatically activate look-alikes or imitators of a certain disease that always have to be considered in a differential diagnosis. If the selected script fails, it is disabled and an alternative script is initiated. A successfully instantiated script triggers the disease management process including diagnostic work-up and treatment schedule. It is important to note that this process is more or less automated and thus, remains largely subconscious. In the case that no activated script matches the given patient scenario, the expert must fall back on active clinical reasoning.
based on biomedical and clinical knowledge. This process is much more time consuming, laborious and substantially more prone to errors.

Clinical workplaces differ in the rhythm at which information gathering, reasoning and action take place. It is an issue brought up by Eraut (45). Catheter-based cardiovascular interventions, for example, require that clinical reasoning takes place to a large extent during a data gathering process. Little research has been done on this form of clinical scenario. An exception here is the research carried out by Wagenaar (46) who used video-stimulated recall (47) to compare cognitive processes of mental health care professionals with different level of expertise while conducting an in-hospital admission interview. The study showed that less experienced mental health care professionals focused mostly on one thing at a time and tried to collect as much data as possible to think about later. With increasing expertise, the mental health care professionals “thought on their feet”; that is, they specifically asked for the information needed to verify or falsify the hypotheses at hand to support or discard the currently activated illness-scripts. At the same time they monitored other aspects of the interview such as time management, relation with the patient, etc. In catheter-based cardiovascular interventions, the patient’s data comes mostly from directly acting on the patient under time constrains and risks. Therefore, the ability of the expert to gather the data needed to verify or falsify hypotheses and generate new ones and to form and execute interventional strategies on the fly is substantially more crucial than in the Wagenaar study. The operator must first activate any pertinent illness-scripts before carrying out the intervention. While carrying out the intervention, she/he must quickly fill in the slots of the most likely script, generate expectations about intended outcomes and match all with the actual outcomes. If the patient data do not match an activated script, this script has to be either quickly adapted or discarded. Successful execution of this highly complex cognitive process requires a combination of a critical amount of knowledge, accurate and efficient information processing, sustained attention, rapid decision making based on correct judgments, and skilled execution of intended interventional actions.

2.3 Perceptual processes in working memory

Many diagnostic tasks require the processing and interpretation of complex, visual input thereby posing strong demands on perception [i.e., perceptual tasks, cf. (48, 49)]. This is also the case for catheter-based cardiovascular interventions. When the operator cognitively instantiates the disease schema and strategy of treatment, she/he must know where to look for key abnormalities and interpret findings. Therefore, reading and interpreting X-ray images or CT scans in real-time are critical parts of the interventional process. Hence, an important aspect of cognitive interventional skills is of a perceptual nature comprising the ability to (a) perceive relevant information from a stream of irrelevant data and (b) interpret it correctly.

These perceptual processes as they apply to medical imaging are usually investigated by means of eye movement tracking, a method to measure direction, length and order of person’s gazes (50). Extensive research data has shown that experts possess far more sophisticated perceptual skills than novices. Experts identify relevant parts within the image faster and study these parts longer [e.g., (37-39, 51)]. This research has focused at the visual
selection and interpretation of abnormalities in medical images. Higher-level cognitive processes such as image interpretation within the context of other patient symptoms, signs or medical findings have scarcely been investigated with the exception of the classical research carried out by Lesgold and colleagues (52) who investigated the cognitive interpretation of static X-ray images of the chest performed experts and novices. The main findings were:

1. Experts diagnose X-ray images in three steps: (a) a mental representation of the visualized anatomy is formed, (b) findings are quickly matched with an appropriate schema\(^1\) to formulate the diagnosis, and (c) means to confirm the diagnosis are defined or in case of incongruence the schema is discarded.
2. Less experienced individuals experience difficulties in that they (a) cannot find appropriate schema, (b) either do not test schema for applicability or do not draw appropriate consequences if a schema fails to stand the test, or (c) miss important details of the diagnosis.
3. Expertise development in reading X-rays is not a monotonic process. In several cases residents performed worse than beginners.

Similar processes are likely operative in catheter-based cardiovascular interventions. An important difference between the cognitive task studied thus far and the settings of catheter-interventions, however, is the dynamic character of data flow contained in X-ray images or CT scans (e.g., cine sequences) in coronary angiography with 30 images/second. Rapid sequences of images and their continuous changes with different projections and/or following interventional actions imposes significantly greater perceptual challenges on the operator compared to reading static X-ray images in the quiet of the reading suite. At present, little is known about the perceptual skills required to read complex and dynamic medical images. In a recent study (53) experts, residents, and novices were compared in their ability to formulate medical diagnoses based on a specific type of dynamic images, namely the observation of video cases of infant patients that were suspected of suffering from epileptic seizures. Results showed that with growing expertise, individuals identified relevant target areas more reliably, scrutinized these areas in greater detail and were not so easily distracted by the remainder of the video. In terms of cognitive interpretation of the medical image, individuals with greater expertise explored less data, but generated and evaluated more hypotheses. As perceptual skills were not the primary focus of this study, no more detailed analyses on the nature and development of perceptual processes were conducted. In another domain – classification of biological motion patterns – only one study, investigated perceptual skills while interpreting dynamic images (54). This study showed that experts attend longer to relevant areas, whereas novices are more often distracted by irrelevant areas. Moreover, experts use knowledge- and experience-based heuristics in performing the task (as show in cognitive and visual processes).

Based on the structure of the interventional process, it can be assumed that expert interveners will also employ sophisticated perceptual skills enabling them to quickly identify important characteristics of individual cases, focus on key abnormalities of the target sites and interpret

\(^{1}\) In terminology of Boshuizen and Schmidt, the schema would be called “illness-script”.
observed abnormalities by matching them to stored illness-scripts. The matching process between the actual case and stored illness-script will also probably use procedural based heuristics – reflected at both the cognitive and the perceptual level. It is likely that experts employ individually different perceptual strategies throughout their professionalization.

2.4 Summary model of cognitive skills in medicine

For the medical domain, comparable assumptions about cognitive processes as described in Section 1 exist, but the assumptions are more specific (Figure 2). First, we start off with a stimulus that may be olfactory (e.g., breath and/or body odor), auditory (e.g., what the patient says during examination), tactile (e.g., resistance felt during an examination of the vessels), proprioceptive (e.g., muscle tension in the right arm) or visual (e.g., a chest X-ray). All these constantly streaming stimuli contain information relevant for diagnosis and intervention, though much of this information is irrelevant. Second, all this information from the outer-world remains active in sensory memory for a very short time depending on to which information attention is paid. The challenge for a physician is to attend quickly and constantly to relevant incoming information and ignore irrelevant information. Third, through this process of actively attending to information, this information is perceived and enters working memory. From this step onwards, one can speak of cognitive processes. In this step, relevant information is searched for and selected (which is an interactive process with the sensory system) and then interpreted. Fourth, the interpreted information is further processed in working-memory on a higher level. These higher-level processes are composed of three sub-processes. First, the information is organized into a mental model of the patient’s anatomy. In the second sub-process, clinical reasoning begins in which an illness-schema is activated, instantiated, tested, and if necessary adapted or rejected. The final sub-process involves decision making based on all the so-far mentioned processes. Fifth, the decision about a diagnosis and an interventional procedure are the output of the above described cognitive processes. Sixth, and finally, all biomedical and clinical knowledge is stored in long-term memory. Here the knowledge on diseases is organized and stored in illness-scripts and can be activated if needed for clinical reasoning in the working memory.
3. **How exploring cognitive skills can improve professional performance in medicine**

The previous section outlined the processes taking place and the cognitive skills that lie at the basis of expertise in catheter-based cardiovascular interventions. This section looks at the conclusions that may be drawn from these insights with respect to teaching and improving the acquisition of cognitive skills for carrying out medical tasks. It also reviews the first attempts being made to teach perceptual skills in medicine.

3.1 **Acquisition of cognitive skills in medicine**

As stated, catheter-based cardiovascular interventions require complex, high-level cognitive skills. These skills are based on two pillars, namely extensive biomedical knowledge and substantial clinical practice. Novice medical students must acquire a large body of biomedical knowledge and organize it in an efficient manner such that they will be able to retrieve it when the need arises. Intermediates who have already obtained the prerequisite biomedical knowledge need to apply and test this knowledge in clinical settings so as to obtain a certain degree of expertise in medicine. Furthermore, due to the rapid developments in medicine, medical knowledge and medical technology, medical expertise rapidly becomes dated and thus requires constant updating. Hence, to maintain a high level of expertise, physicians have to engage in lifelong learning; in interventional medicine, deliberate practice appears to be the most efficient means to both develop and maintain expertise. This section reflects upon the organization of learning in the domain of catheter-based cardiovascular interventions with increasing expertise.
3.1.1 Learning in the beginning: Novice students must acquire large amounts of biomedical knowledge

At the beginning of a study in medicine, trainees must acquire knowledge of all relevant aspects of the human body and learn this by heart. This biomedical knowledge contains information about the anatomy, the function and the malfunction of human body. Trainees must achieve to mastery level two main goals in this stage, namely the acquisition of a vast amount of knowledge and the efficient organization of this knowledge. For instance, trainees need to know the anatomy and function of the heart and the entire cardiovascular system. They also need to know about pathophysiology and the management of specific cardiovascular diseases and disorders. Norman, Eva, Brooks, and Hamstra (55) warned that some research results may have misrepresented the importance of biomedical knowledge in high-level medical expertise. For instance, Patel and Groen (56) reported that - based on thinking-aloud protocols - experts made less use of biomedical knowledge than residents. Does this mean that experts do not make use of biomedical knowledge? Schmidt and Boshuizen (34) revealed what happens to this ‘missing’ biomedical knowledge. They found that the reason for this apparently limited use of biomedical knowledge by experts is that the knowledge of these experts is encapsulated; it is present, but numerous information entities are clustered into one large entity. The fact that this knowledge is still present becomes evident when it becomes necessary to unfolded this encapsulated knowledge (57), for instance, when encountering a difficult patient case (58). Hence, acquisition of biomedical knowledge forms the basis for all medical expertise; lack of that knowledge leads to errors and misconceptions (59).

A possible instructional approach for acquiring and encapsulating biomedical knowledge is through the use of example-based learning [for a current review on this topic see (60)]. Research on example-based learning has found that it is more efficient and effective to learn from skilled experts than by discovering how to carry out a task on one’s own. The greater efficiency of example-based learning is based on the fact that novices do not need to spend their cognitive resources searching for a solution or partial solution, continually comparing what they have found with the goal and readjusting their intermediate goals (weak problem solving method), but instead can devote all of their available cognitive capacities to learning the correct solutions and the path to such a solution. This assumption is often translated into learning from worked-out examples or from teaching cases. Worked-out examples are composed of a problem formulation, a solution, and the procedure to solve the problem in a step-wise manner (61-64). In this way, worked-out examples help the learner to build schemata. It is important to note that worked-out examples are particularly suited for the initial phase of skill acquisition and expertise development. However, this is only true, if worked-out examples are presented for those tasks that are very familiar to the experienced learner. If a new topic is introduced, worked examples can also support skill acquisition at higher levels of expertise (65). Van Merriënboer and Kirschner (66) noted that similar very effective technique is the use of modeling examples. Modeling examples provide maximum guidance to the learner – necessary when first acquiring a complex skill – “because they confront learners with professionals performing the complex task, simultaneously explaining
why the task is being performed the way it is. A modeling example is, thus, similar to a case study that needs to be studied and evaluated by the learner, but which also pays explicit attention to the processes needed to reach an acceptable solution” (p. 50). In cases of extreme complexity, they propose their 4-Component Instructional Design model proposes beginning with simplified whole tasks with maximal guidance. In medicine, the high degree of complexity of working with real patients can require the adjustment of teaching cases to the knowledge level of the trainees (33). These authors have shown that it is better to present a reduced amount of complexity when providing novices with clinical examples (e.g., paper cases, simulated patients) than real, complex cases. As students have to execute the entire line of reasoning, the information that is presented, though simplified, should be both complete and relevant. If this is not the case, students may be overwhelmed and can easily overlook information when they do not know it is relevant. As described previously in this chapter, this is particularly true for perceptual medical tasks (53).

Norman et al. (55) state, however, that the implementation of clinical examples and teaching cases into medical curriculums has, thus far, been limited. Though research on example-based learning in medicine may be in its beginnings, as pedagogical approach it has a long tradition in instructional design research and, thus, the question as to what to consider when designing example-based curriculums has been widely investigated. Atkinson et al. (61), for example, provide an overview on how to implement examples in a curriculum (so-called inter-example features). In their summary of the literature on this topic, they conclude with four instructional guidelines for such curriculums. First, it is beneficial to provide several examples instead of only one (cf. the claim by Norman et al. (55) on the importance of examples). Second, providing different problem types in worked-out examples aids learning. Third, one problem type should be represented by several examples with varying surface features (i.e., task irrelevant) to demonstrate the variability of its appearances. Fourth, and finally, after presenting an example, students should receive a comparable case to solve on their own.

3.1.2 Learning to apply knowledge: Residents become experts through clinical practice

As described in the previous section, the foundation of medical expertise is solid and sound biomedical knowledge. However, it has been clearly demonstrated that it is not the simply the amount of knowledge that makes up expertise [e.g., intermediates consistently recall more information than novices and experts; (35)]. In addition to the amount, the organization of knowledge is the other key to expert performance in all fields, and especially in medicine. In line with this reasoning, Eva, Norman, Neville, Wood, and Brooks (67) describe medical expertise as synthesizing all the details into a brief but coherent problem formulation and ignoring extraneous details. Thus, along with the acquisition of knowledge, the organization and synthesis of the acquired knowledge should also be in focus of medical curriculums. This can be achieved through exposing learners to clinical practice [i.e., for gaining clinical knowledge; (36, 55)]. Many researchers nowadays emphasize the importance of clinical practice and its interrelation with biomedical knowledge [e.g., (33, 55)].
As is the case for novice learning, example-based learning and exposure to clinical practice plays a crucial role in the learning of intermediates (55). It is important that medical residents be exposed to as many as possible examples in practice to allow them to structure and organize their knowledge and finally achieve automated retrieval of relevant information [e.g., (68, 69)]. Exposure to examples, however, may also trigger diagnostic errors. It has, for example, been demonstrated that in teaching residents to interpret ECGs, they may become biased in their interpretations by a case that they have read prior to the current case causing erroneous diagnosis (70). It is crucial that residents at this stage of expertise development consciously review every single patient case they encounter to avoid diagnostic errors. In fact, research has shown that this ‘availability bias’ can be counteracted by having residents review and reflect upon their diagnostic decisions (71). Nevertheless, Norman et al. (55) conclude that in medicine “it takes many examples, and not just formal knowledge, to become an expert” (p. 345) – a view that is in line with many other researchers that typically do not investigate expertise development in the medical domain [e.g., (61, 72)]. A problem particular to residents is that they learn within a specific workplace. Hence, they often only encounter specific types of cases in their clinical practice. Providing residents with patient case examples, for instance by means of patient video cases, may counteract this unbalanced experience.

For efficient transfer of medical knowledge, the design of the teaching cases and clinical examples is critical. Boshuizen and Schmidt (33) suggest – in accordance with the 4C/ID model (66) adapting the degree of complexity of examples to the expertise level of the learners. In other words, residents should be exposed to and should learn from more elaborate patient cases than novices. More complex cases should entail a greater number of interacting elements (i.e., should be more complex) and should have a higher degree of uncertainty concerning the completeness and relevance of provided information (e.g., should be more ill-structured / open ended). Actual interactions with real patients provide the ultimate test for the usefulness of theoretical concepts and procedures acquired from lectures and textbooks. Each confirmation of theory in clinical practice leads to encapsulations of biomedical knowledge into higher level cognitive concepts (34).

3.1.3 Keeping expertise up-to-date: Lifelong learning in medicine through deliberate practice

Once the students have reached professional levels of expertise in their fields, one should not assume that their learning processes have been completed. There are at least two reasons for this. First, research has shown that with increasing years of experience that diagnostic accuracy declines (73-75). Second, expertise is ‘dynamic’ in the field of medicine (55); medicine is a field in which knowledge, techniques, medicines and tools are constantly either being updated or are changing. To counter this decline and to keep up with progress in medical knowledge, techniques and technologies, medical practitioners must learn to maintain and even broaden their expertise.

As experts, practitioners possess high-level skills and considerable amounts of knowledge. Consequently, it is difficult to find instances where an expert can learn to further improve her/his professional skills. An instructional approach to increase expertise can be found in
deliberate practice (72) which is a form of training of highly specific cognitive or psycho-motor skills required to master complex tasks. This approach was initially introduced to train exceptional performance in musicians and athletes, but can easily be transferred to medicine. Implementing this approach to catheter-based cardiovascular interventions requires expert professionals to generate mental models of how interventions should be optimally performed (i.e., master strategies), actually perform them, fully document the interventions as designed, and review and critically analyze the outcome of cases. During this process, the intervener should look out for mistakes / errors and seek / think of options for improvement. If possible, sub-tasks identified as problematic by case review and analysis should be practiced afterwards. In this way even highly skilled interveners can further improve their diagnostic and interventional skills.

3.2 Training of perceptual skills via eye movement modeling examples

Clinical knowledge based on the actual experience with real patients also involves perceptual skills. In both, research and clinical education, the development of perceptual skills has been largely neglected. Rather than conveying perceptual skills directly, they are often paraphrased in written text and accompanied by static pictures. Research data show that this approach is associated with suboptimal results [e.g., (76)]. An effective approach would provide perceptual experience in real-life settings. Accordingly, the use of patient video cases is becoming increasingly common [PVCs; cf. (77)]. Compared to traditional written of patient case descriptions, using PVCs for educational purposes has been shown to significantly improve diagnostic processes in medical students (76, 78, 79).

These studies, however, did not focus on individual learning benefits, but rather on improvement of collaboration. Improving individual learning outcomes is crucial, as suggested by studies demonstrating critical perceptual problems of novices based on PVCs (53). These results have corroborated the learning outcome based on static, abstract medical images (e.g., (37-39, 51, 52]) and realistic photographs of patients (80). Hence, when dealing with complex perceptual medical tasks such as catheter-based cardiovascular interventions, novices must be helped to acquire perceptual skills by employing realistic instructional materials such as fully documented authentic clinical teaching cases.

The efficiency of learning from these materials can be enhanced by a number of techniques. One very promising technique is that of eye movement modeling examples [EMME; cf. (81-83)]. EMME are video examples that are accompanied by verbal, pedagogically modeled explanations – often given by the expert - for carrying out a task (i.e., it contains both what is done and why it was done). This explanation is augmented such that during the explanations, the gaze focus of this expert model is superimposed onto the video. EMME are based on the assumption that it is more efficient, effective, and motivating to learn from skilled professionals as opposed to learning on one’s own [cf. example-based learning: (63); or cognitive modeling alone: (84)]. Teaching cases are ‘worked-out’ (i.e., each step required to execute the task is presented to the learner).
To learn from examples, it is crucial to attend to the relevant features of the examples at the right time (85). An important possibility to guide students’ attention is by means of cueing [(86); also called signaling: (87)]. For instance, De Koning and colleagues - in a series of experiments – investigated the effectiveness of cueing when learning the functioning of the cardiovascular system from animations. In a first study (88) he and his colleagues compared a group of students learning from an animation where one subsystem of the cardiovascular system – the heart valves – was cued to a group learning from an non-cued animation. Results showed that learning from a cued animation helped understanding not only the cued, but also the non-cued parts of the cardiovascular system in contrast to learning from a non-cued animation. In two further studies, however, the authors were unable to replicate this effect [(89, 90); for a review: (91)]. One problem may lie in the fact that often it is not clear where researchers – all of whom were not medical practitioners - place cues; that is, it is likely that researchers have either highlighted features based on what they thought would be important to focus on for novices. This, however, may not be the appropriate way to do it. Rather, it may be better to set cues based on empirical evidence. One successful way to set cues was presented by Grant and Spivey (92) who confronted participants with Duncker’s radiation problem in which a tumor needs to be destroyed without harming the surrounding healthy tissue. This problem was accompanied by an abstract drawing of the problem (see Figure 2). Participants, who solved the problem correctly – the laser needs to be split into two rays that cross on the tumor – looked significantly more at the skin area (as indicated by means of eye tracking) than participants who could not solve the problem. Based on this, the authors conducted a follow-up experiment where either (a) this skin area was highlighted, (b) an irrelevant area was highlighted, or (c) nothing was highlighted. This experiment showed that participants seeing the drawing with the skin area highlighted solved the problem significantly more often than participants from the other two conditions. Hence, designing cues based on eye movements of successful task performers appears to facilitate problem solving.

![Figure 2. Duncker’s radiation problem as used to investigate cueing. From Eye movements and problem solving: Guiding attention guides thought, by E. R. Grant & M. J. Spivey, 2003, Psychological Science, 14, 462-466 (Published with kind permission of © SAGE publications, 2003).](image)
Note that the image used by Grant and Spivey (92) was very abstract and by no means resembles medical images used in clinical practice in terms of perceptual complexity. Litchfield, Ball, Donovan, Manning, and Crawford (93) used a similar method for a perceptually more complex task, to improving nodule detection in X-rays. They presented chest X-rays with superimposed eye movement patterns of radiologists searching for nodules (Figure 3). Results show that novice radiologists profit from this type of cueing based on eye movements in that they find nodules in these images more often.

Figure 3. Cueing based on eye movements directly on chest X-rays. From Viewing another person’s eye movements improves identification of pulmonary nodules in chest X-ray inspection, by D. Litchfield, L. J. Ball, T. Donovan, D. J. Manning, & T. Crawford, 2011, Journal of Experimental Psychology: Applied, 16(3), 251–262.

The medical image studied by Litchfield and colleagues (93) still does not fully resemble the perceptual situation encountered by physicians who perform catheter-based cardiovascular interventions, because the images used in the study were static and the clinical context of interventional suites was missing; efficient navigation through dynamic images under pressure and time constrains are far more difficult compared to image reviews in radiological reading rooms. Moreover, both studies just presented only investigated improvement of the task at hand. They did not investigate whether this ability could be carried over (i.e., transferred) to other examples.

In sum, we have learned that the task of performing catheter-based cardiovascular interventions includes a large perceptual part. Moreover, we have learned – given on existing literature – that novices are very likely to lack these skills. As we have seen in this section, to study these skills it is crucial to guide students’ attention. This attention guidance, however, should not be based on what the instructional designer thinks is important, but rather on where successful task performers actually look at. A recent instructional method that successfully makes use of this type of instruction are EMME. In that, students learn by means of videos of actual patient cases that are verbally explained by an expert model. In addition, the attention focus of the expert guides the students’ attention to the right spot at the right time. This approach could also be used to teach perceptual skills required to execute catheter-
based cardiovascular interventions. Video recordings of different interventions could be verbally explained by an expert cardiologist, who explains why s/he took which steps. Moreover, a visual cue based on this expert’s eye movements should be superimposed on these videos to guide the students’ attention.

4. Summary and conclusions

This chapter highlights the importance of cognitive training and skill development in carrying out complex tasking including medical reasoning and decision making applicable to catheter-based cardiovascular interventions. The first part discussed cognitive skills from a cognitive psychology perspective. To understand the nature of cognitive skills, their foundation in human cognitive architecture was introduced as a 3-storage model. This model includes the sensory register, working memory, and long-term memory. Moreover, the operation of cognitive skills in working memory in terms of perception and higher-level cognitive processes was discussed. Based on this, in the second part of the chapter, theories of cognitive skills in medical expertise were introduced. These theories make more precise predictions as they all refer to the specific task of medical diagnosis. It is important to note, however, that although the cognitive structure and cognitive skills required for medical diagnosis are already well described, assumptions on their perceptual counterparts remain vague. Hence, future research should integrate existing theories on purely cognitive aspects of medical expertise with research on medical image perception. This is in particular true for dynamic medical images, like CT scans. Moreover, future research should be directed towards the analysis of cognitive skills required for mastery of cardiovascular interventional treatments. In sum, insight into cognitive skills is very important to address problems at a perceptual and higher cognitive level. For teaching, however, you need insight in all levels of skills required for medical diagnosis and interventions, like perceptual, cognitive, social, motors, etc.

References


79. De Leng BA, Dolmans DHJM, Van de Wiel M, Muijtjens AMM, Van der Vleuten CPM. How video cases should be used as authentic stimuli in problem-based medical education. Medical Education. 2007;41:181-8.