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Review

The Development of a Model of Technical Expertise: Towards Innovative Teaching Methods in Technical Education

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Technical education plays a significant role in providing middle level manpower needed for work in various industries for development and economic growth of every nation. There is the need for technical education to provide students with expertise to cope with the changing industrial demands in the present knowledge and technological economy. However, research has identified a significant gap between technical education and industries. For this reason the present teaching methods and the practices of technical education have been questioned. This article discusses and analyses the cognitive processes of novice and expert technicians in line with expertise development from the perspective of cognitive psychology. The intention is to describe and propose a model of technical expertise towards the identification of innovative teaching methods for the development of technical expertise in technical schools.

Keywords: Meta-cognitive skills, cognitive strategies, technical education, design education, complex technical skills.

INTRODUCTION

The level of competence of a country's skilled workers and technicians is certainly important for the flexibility and productivity of its labour force. The skilled workers and technicians enhance the quality and efficiency of product development, production, and maintenance.

The rapid changes of technology and knowledge in the present world are expanding the cognitive and practical knowledge required for productivity in technicians. The basic and important goals of technical education in the present world of work are to help students to acquire technical expertise**.** This is to enable employees (technicians) to flexibly adjust to rapid changes in their environment (van Merrienboer and Kirschner, 2007). Despite its importance, the topic expertise development has received only limited attention in the "research on design (technical) education" community and the practice of technical education (Heylighen and Martin, 2004; Cross, 2004b). With regard to this, there is an increasing demand for a radical consideration of innovative teaching methods that could promote the development of expertise in technical education students in order to cope with complex demands of the world of work (Vogatzki, 2002; Report of the Technical Committee on the Harmonisation of Competency-Based Training in Ghana, 2009).

In order to determine innovative teaching methods to facilitate the acquisition of technical expertise in technical students, it is important to have an in-depth knowledge about the nature and the types of cognitive processes (knowledge and skills) of expert technicians. This is because the nature and types of cognitive processes (or knowledge and skills) require great differences in instruction (Leshin et al., 1992). From the perspective of cognitive psychology, there are several models of expertise (e.g., Chi et al., 1981; Chi et al.,1988; Alexander and Murphy, 1999; Alexander 2003a); but these models do not specifically handle expertise development in technical schools. van Merrienboer (1997) developed four components instructional design model (4C/ID model); but this model was originally developed for the learning of complex cognitive/technical skills in industrial training settings rather than schools. More specifically, little or no attention has been paid to a model of technical expertise for learning of technical skills in the traditional classrooms of (secondary) technical education (Cross 2004b; Vogatzki, 2002). The purpose of this article is to discuss and analyse the classical theories and research findings of expertise and the current models of expertise from the perspective of cognitive science; complex cognitive skills; the design/practical behaviours of expert technicians; and then proposes a model of technical expertise. The article is intended to contribute to knowledge and understanding of integrated set of knowledge and skills required for the development of technical expertise in technical schools. In addition, it sets out to identify innovative teaching methods that facilitate students' learning processes to promote acquisition of technical expertise in traditional classroom.

Definition of expertise

The literature on expertise portrays general consensus about what expertise is. Experts have great deal of knowledge and skills in their area (s) of specialisation. Expertise is knowledge and skills that enable one to function intelligently and smoothly in work situations or everyday tasks. As indicated by Bereiter and Scardamalia (1993), expertise is knowledge and skills that carry us beyond what nature has prepared us to do. The development of expertise has attracted a lot of attention and interest in education and training settings. The next section discusses expertise development from a cognitive science perspective.

Cognitive psychology and development of expertise

In this contribution, cognitive psychology and development of expertise are described from the perspective of classical theories of expertise and the current models of expertise.

From the perspective of classical theory of expertise, the study of expertise development has a long tradition in psychology. It is linked to the first empirical studies of de Groot's world-class chess players (1946 /1978), which started in 1930s, and most of the studies in expertise continued in the tradition of de Groot (Badke-Schaub, 2004). Expertise development as a field of interest in cognitive psychology blossomed and received greatest attention in the 1970s and 1980s. More specifically, the nature of expertise in cognitive psychology in the 1980s could be explained from the work of Chi and co-workers (1988) and Chi and co-workers (1981).These researchers propose that if experts and novices at a chosen domain are compared, the qualities exhibited by experts but not by novices become the basis for explaining expertise. Based on this proposition, various expert/novice research studies have been conducted to investigate problem solving in participants of different ages and examined cognitive mechanisms in various areas including medical diagnoses, mathematics, nursing, etc. Based on this, consistent and reliable features of expertise, across the various areas, have been documented (Alexander and Murphy, 1998; Bransford et al., 1999); suggesting that experts:

- possess extensive, rich and well-structured domain knowledge,
- are effective at recognising the underlying structure of domain knowledge,
- select and apply appropriate problem-solving procedures for the problem at hand, and
- can retrieve relevant domain knowledge and strategies with minimal cognitive effort.

Furthermore, various studies conducted in cognitive psychology suggest that the acquisition (knowledge and skills) of expertise can only be gradually acquired (Palinscar and Brown, 1984; Bereiter and Scardamalia, 1993; van Merrienboer, 1997; Mayer, 1999; Flavel, 1979). Expertise is acquired with intentional efforts or deliberate practice, and it takes considerable time and effort to reach an acceptable mastery level or expertise (van Merrienboer, 1997; Ericsson, 1993). Ericsson (1993) asserts that expertise is a result of extended practice that alters the cognitive and physiological processes of experts to a larger degree than is commonly believed possible. This indicates that knowledge and skills can be acquired up to the level of expertise only by actively using them and through progressive problem solving, in other words, deliberate practice (Dijkstra and van Merrienboer, 1997; Bereiter and Scardamalia, 1993; Anderson, 1983). To sum up, experts across various domains have similar cognitive features, and gaining expertise requires both deliberate practice and years of experience.

Current models of expertise

From the perspective of current models of expertise, it has been argued (e.g., Alexander, 2003a) that traditional cognitive theories of expertise have not translated effectively into educational or development programmes in schools. Students are still required to attain basic isolated knowledge and acquire skills that are not appropriate for their development as experts. One basic reason for this is that traditional programmes of expertise research were not undertaken with schools or students in mind (Alexander, 2003b). To remedy this situation, several models and theories of expertise (e.g., Alexander 2003b; Ackerman, 2003) have recently been developed.

The Model of Domain Learning (MDL) (Alexander, 2003b) is one of the theories of expertise that is claimed as being school centred. According to MDL, in developing expertise in schools, attention should focus on 1) domain knowledge, 2) strategic processes, and 3) interest. The three components interplay with three stages: acclimation, competence, and proficiency/ expertise. In summary, components of domain knowledge, strategic processes, and interest configure differently as an individual progresses from an acclimation stage to competence stage and proficiency or expertise stage. Thus domain knowledge, strategic processing, and interest are interrelated and expected to influence each other at every stage, but differently at each stage. Alexander (2003b) reinforces that the journey towards expertise is unceasing.

In addition, another recent model of expertise development is the one proposed by Ackerman (2003). He proposes that the personality trait, and motivational traits and skills are integral to determining the direction and intensity of cognitive investment towards the acquisition of expertise. He asserts that development of specific expertise in different domains occurs as joint consequences of ability and non-ability trait complexes. Therefore, individual differences in trait complexes may have useful properties in determining the direction and level of cognitive investment in the acquisition of expertise.

In a nutshell, both Alexander (2003b) and Ackerman (2003) explicitly describe the cognitive and non-cognitive features of expertise across various domains. However, unlike Ackerman, the MDL of Alexander is more related to academic domains (include strategic processing) in schools and it also includes 3 stages of expertise development. Unlike the traditional models of expertise, the current models of expertise emphasise non-cognitive features of expertise (e.g., Alexander, 2003b; Ackerman, 2003). However, apart from the fact that the traditional theories of expertise are out-of school oriented, the cognitive characteristics documented by traditional theories of expertise and the current theories of expertise are similar. In addition, Alexander, as with the traditional theories of expertise, considers deliberate practice as a process of expertise development in schools. It can be concluded that both the traditional theories of expertise and the current models of expertise enrich each other and as such, both are considered useful in the development of a model of expertise towards innovative teaching methods. Even though the non-cognitive features of expertise, especially trait complexes, described by current models of expertise are considered interesting and remarkable in expertise development, in this contribution the interest is not in who can be an expert and who cannot be an expert. Therefore little or no attention is paid to trait complexes**.**

The next section discusses technical expertise from a design education (or technical and vocational education) perspective.

Technical expertise

Expertise manifests itself in several domains including engineering sciences (e.g., architectural engineering, civil engineering, mechanical engineering, etc). People who specialise in these areas are normally referred to as technicians or engineers. The main functions of technicians are to produce artefacts (e.g., spinners, buildings, cars, bicycles, sewing machines) that satisfy human needs. In that respect, technical expertise can be described as knowledge and skills that enable technicians to function intelligently and smoothly in their work settings. The main activities of expert technicians, which depend on the life cycle of an artefact (e.g., Dijkstra, 2000), are categorised as such: the design of the artefact; the realisation of the artefact; the use and maintenance of the artefacts; and the restoration or disposal of the artefact. In this paper, technical expertise can therefore be defined as the integrated set of knowledge and skills to be acquired by (secondary) technical students to function smoothly in the world of work.

More specifically, in order to identify innovative teaching methods to support students' acquisition of technical expertise, it is important to understand and identify the cognitive processes of novice and expert technicians (Cross 2004b; Dorst, 2004).

Cognitive processes of expert technicians

Lindekens et al. (2003) conducted an empirical study in which four architects - two novice and two experts designers - were asked to develop a concept for the reorganisation of and extension to an architectural school. The subjects were asked to 'think aloud' while designing. During the session, all actions of the designers were recorded. The intention was to reveal the cognitive processes of building designers. The results of the analysis reveal that:

- experts reason on the concepts and principles of building drawing continuously until the very end of the session;
- (expert) designers refer to the basic principles of architectural design (e.g., materials, symbols, economic, volume) when designing;
- expert building designers display four categories of strategies: 1) analysis, 2) synthesis, 3) evaluation (the designer switches between these three categories of strategies), and 4) explicit strategies (organisation of tasks before design starts, examining how he should cope with deferent tasks, and thinks about how he should continue the design),
- while sketching/drawing, the designers' decisions and choices are based on the problem brief, some of them are based on the basic principles, or their own preconceptions; and
- decisions are sometimes very clear and architects do not seem to doubt their choice. At times they suggest a solution for part of the design and continue this line of thought and find out whether it also offers a solution for other parts. If so, they continue their proposal. If not, it is rejected and another proposal is chosen for evaluation.

Table 1: Experts cognitive features that are absent in novices

Experts from other field	Experts from design engineering (technical education)
From the perspective of other fields (as described in cognitive psychology) experts:	*From design engineering (technical education) perspective experts:*
• possess extensive and rich structured domain knowledge	• use basic structured concepts, rules, and principles of domain knowledge
• are effective at recognizing the underlying structure of domain knowledge	• use conceptual and functional reasoning on the domain knowledge
• select and apply appropriate problem solving procedures for the problem at hand	• use rules of thumb, reflective strategies, and problem solving strategies when solving problems
• can retrieve relevant domain knowledge and (cognitive) strategies concurrently with minimal cognitive efforts	• use basic domain principles/rule-based behaviours (e.g., application of standards and symbols) and reflective strategies simultaneously - expert building designers reflect on client needs or problem brief while drawing/designing a building plan)
• are creative, analytical, and practical	• use analysis, evaluation, synthesis, and explicit strategies

Still at other times, different possibilities are considered simultaneously.

In a similar direction, Casakin (2004) conducted an empirical study to investigate the use of visual analogical reasoning by novice and expert architectural designers during the design process. Twenty-six architectural designers participated in the experiment: eleven expert architects and fifteen novice architects. On one hand, the analysis of the cognitive processes revealed that 1) during drawing/designing, novice designers reproduced almost exact copies of the source provided and focused on surface properties which did not lead to a successful solution; 2) novice designers failed to retrieve a structured principle and establish an analogy with problem. On the other hand analysis of the cognitive processes also revealed that 1) while sketching and drawing/designing, expert designers did not copy exactly what was provided, instead only managing to activate their memory and retrieve knowledge related to the row house organisation, and 2) while designing, expert designers decided to add further constraints than those that were required in the original goals. They refined their sketches or drawings where necessary.

In addition, to describe practice behaviours or cognitive processes of expert technicians, Cross (2004a) reports three empirical studies that reveal the cognitive processes of three successful/expert designers from three different domains of design: bicycle luggage carrier, sewing machine, and racing car. Comparative review of the three studies indicates that the cognitive processes of design expertise are similar in different domains.

These results provide empirical evidence that while cognitive processes of expert technicians are similar in different domains, cognitive processes of expert technicians are qualitatively different from cognitive processes of novice technicians. More importantly, the cognitive activities of expert technicians revealed by these analyses confirm the evidence of Akin and Lin (1996) that design in engineering sciences (domains) is an iterative process of activities and several of these activities occur simultaneously. As described above, Lindekens and co-workers (2003), Casakin (2004), and Cross (2004a) provide empirical evidence that cognitive processes used by experts/novices in engineering sciences (e.g., architectural engineering, civil engineering, mechanical engineering) and cognitive processes used by experts and novices in other fields as described in expert/novice research in cognitive psychology are very similar. Table 1 highlights experts cognitive features that are absent in novices. The underlying logic is that knowledge about cognitive functions of expertise development in cognitive psychology research can be applied to expertise development in design engineering or technical education. Based on the above discussion and complex technical skills by van Merrienboer (1997), the next section proposes and describes a model of technical expertise.

The model of technical expertise: Integrated set of knowledge and skills for development of technical expertise

Specifically, as depicted in the previous section, the practice of expert technicians involved several cognitive activities or behaviours. And most of these activities take place simultaneously during the design. This makes engineering design a highly complex activity that requires execution of a varied and integrated set of knowledge and skills. Research on expertise in cognitive psychology indicates that in developing expertise, students should be helped to acquire a rich and a well-structured knowledge of academic domain as well as deep-level processing strategies concurrently. According to van Merrienboer (1997) and Dijkstra and van Merrienboer (1997) the body of knowledge that constitutes integrated set of knowledge and skills (complex technical skills) consists of non-recurrent skills and recurrent skills. For instance, in building design, the nonrecurrent aspects pertain to reasoning on the conceptual and functional principles of building drawing, reflective practice, and the use of rules of thumb by expert building designers; and the recurrent aspects pertain to the use of rule-based behaviour as well as application of symbols, dimensions, procedures, and other routines by expert building designers.

The non-recurrent skills can be described in terms of cognitive schemata and the recurrent skills can be described in terms of cognitive rules or automated schemata (van Merrienboer, et al., 2002). Cognitive schemata refer to knowledge structures that may range in their level of complexity, generality, and abstractness. Cognitive schemata direct problem solving behaviour and allow for reasoning of the domain. Cognitive schemata consist of mental models and cognitive strategies. It is important to note that in the cognitive literature, mental models and (cognitive) schemata are often used interchangeably. According to van Merrienboer et al., (2002), and therefore in this article a mental model is described as a set of highly structured *declarative knowledge* in which the nodes may be facts, concepts, plans, or principles that are related to each other non-arbitrarily. For instance, a mental model about cause effect relationships of different kinds of soil and types of foundation enables an expert building designer to choose the right foundation.

Cognitive strategies can be described as general strategies of solving problems (Derry, 1990). They are strategies employed by learners in a particular learning situation to facilitate the acquisition of knowledge and skills or to carry out a complex task. They are strategies that individuals employ on their own. van Merrienboer et al. (2002) distinguish between systematic approaches of problem solving (SAPs) and rules of thumb or heuristics. Systematic approaches to problem solving describe the successive phases in a problem solving process. Experts apply cognitive strategies on the domain knowledge when solving a problem. For instance, in designing a building plan, the expert designer has to think about and identify the goal of the design, think of the appropriate solutions, select the right solutions, then execute the solution. Or sometimes if a learner is solving a question, he has to think and choose the correct mental tactics that he thinks will enable him to solve the problem. Heuristic strategies are general plans or approaches for accomplishing tasks in a given domain. Heuristic methods are intelligent and systematic search strategies (De Corte, 1990). They are very helpful to reach a problem solver's goal but cannot guarantee that the goal will be reached. van Merrienboer (1997) calls them weak methods. For instance, in designing a building plan for a given geographical area, an expert building designer may roughly sketch the plan on ordinary paper, see to it that it is in line with his goal, and refine it until it suits his goal.

The exploration of cognitive processes of expert technical (e.g, architectural) designers indicated the presence of self-reflection, self-monitoring, and self-evaluation - metacognitive skills - in problem solving behaviour of expert building designers. Metacognitive knowledge and skills were originally described by Flavell (1979). Metacognitive knowledge is described as learners' awareness and knowledge of their own learning processes (cognitive strategies); and metacognitive skills are described as learners' abilities to control these learning processes during learning/problem solving. When learners acquire more cognitive strategies (e.g., heuristics, SAPs), they encounter a new management or control problem with respect to how to select among the possible cognitive strategies, how to decide when to change strategies, etc. Metacognitive skills help learners to solve such control problem. Collins et al. (1989) described metacognitive skills as control strategies. For instance, in the course of designing a cost-effective building plan for a given geographical area, by employing metacognitive knowledge and skills, the learner or an expert may reflect on his cognitive schemata and the goal of the problem and realise that he is not using the right method to achieve the goal and therefore adjust his selection of method. Metacognitive skills or control strategies play a very important role in expert knowledge (Shuell, 1986; Bereiter, 2002; Bereiter and Scardamalia 1993; Driscoll, 2005). In brief, van Merrienboer (1997) acknowledged that the cognitive schemata acquired in former problem solving situations (e.g., in classroom context) may help to solve the non-familiar aspects of current problem situation

The body of knowledge that pertains to the recurrent aspects of the constituent skills is termed as automated schemata or cognitive rules or *procedural knowledge* structure (van Merrienboer, 1997; Dijkstra and van Merrienboer, 1997) that link particular characteristics of the problem situation (condition) to particular actions. Automated schemata connecting (a) particular condition(s) to (b) particular action(s) are termed as rules or productions (Anderson, 1983). Experts may reach a level of practice where they execute recurrent skills or routines automatically without investing any mental power or cognitive effort. For instance, an expert building designer may display open symbols and use room dimensions automatically (without conscious control). Automated schemata acquired in former problem solving situations (e.g., in a classroom context), help to solve the

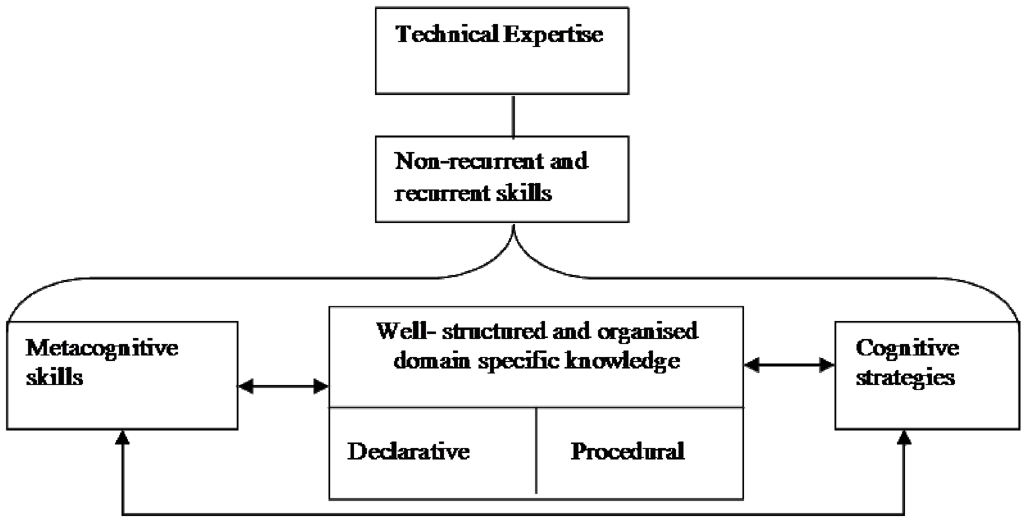

Figure 1: Model of technical expertise

familiar aspects of current problem situation (van Merrienboer, 1997).

To summarise, in this contribution, the answer to the question "what are the knowledge and skills that must be mastered by students in technical education in order to become an expert technician" are:

- well-structured and organised domain specific knowledge (declarative and procedural)
- cognitive strategies, and
- metacognitive skills.

In other words, the answer to the above question is: recurrent and non-recurrent skills. More importantly, as discussed above (e.g., Heylighen and Nueckermans 2003; Lindekens, et al., 2003) when expert technicians/engineers are solving design problems they execute most of these knowledge and skills *simultaneously*. Therefore they should be developed concurrently (van Merrienboer, 1997). Figure 1 sheds light on model of technical expertise. The proposed model of technical expertise is practical and effective in developing expertise in building drawing in traditional classroom of secondary technical schools (Sarfo and Elen, 2007)

Towards innovative teaching methods for acquisition of technical expertise

A well-designed innovative teaching methods for acquisition of technical expertise (integrated set of knowledge and skills – the proposed model) should not aim at students' gain of each of these knowledge and skills separately, in the traditional classroom, with the assumption that a set of integrated knowledge and skills is achievable (by learners) as the sum of the parts. Instead, well designed innovative teaching methods for acquisition of technical expertise should foster students' learning processes that facilitate the acquisition of the knowledge and skills in a coordinated and integrated fashion. And this can be achieved by providing learners, in the traditional classroom, with authentic learning tasks based on real life tasks. This is because we cannot teach learners "hate" in the traditional classroom and ask them to go and practice "love" in the world of work. The integrated set of knowledge and skills can be acquired in an authentic realistic context (Brown et al., 1989) and more particularly in learning environments which: 1) are task centred; 2) activate students prior knowledge; 3) demonstrate what is to be learned; 4) encourage learners to integrate the new knowledge to their everyday life; 5) are application oriented; and 6) consider the fact that students learn in different ways (Merrill, 2002, 2006; van Merrienboer, 1997; van Merrienboer and Kirschner, 2007). More specifically, instructional techniques that can promote technical students' learning processes to facilitate the acquisition of an integrated set of knowledge and skills as depicted in the proposed model of technical expertise in the traditional classroom (Sarfo and Elen, 2007; van Merrienboer and Kirschner, 2007) are:

- learning tasks,
- practise of a series of equivalent but dissimilar learning tasks,
- inductive inquisitory approach and inductive expository approach,
- the case studies and modelling examples,
- scaffolding, and
- activation.

Learning tasks are authentic and meaningful real-life experiences that are provided to the learners in the classroom. The learning tasks are to perform in real or simulated learning environment. The learning tasks engage the learners and direct them to activities that require them to work with the integrated set of knowledge and skills. This invites the learners to construct adequate and integrated schemata on the whole technical skill (e.g., designing a building plan) in the traditional classroom under the guidance of the teacher. The practice of a series of equivalent but dissimilar learning tasks challenges the learners to fine-tune their existing schemata. This is useful for solving new problems. The inductive inquisitory approach is an instructional strategy that stimulates learners to construct meaningful relationships among concepts and principles based on the examples presented. The inductive expository approach helps learners to work from specific examples to general information. This also helps learners to understand a concept. A case study is an instructional strategy that describes a given state, a desired goal state, and a chosen solution. It enables the learners to participate in an actual problem situation in real world. It may take different forms such as a description of particular situation or an artificially designed object (e.g., mock-ups). A modelling example is worked-out example together with a demonstration of problem-solving process leading to the presented solution. Example, when an expert is working on the problem and explaining why he/she is doing what he/she is doing in order to reach a solution. The case studies and model examples (e.g., teacher thinks aloud while sketching a building plan) also help learners acquire appropriate problem solving strategies (e.g., heuristics, and metacognitive skills). The scaffolding is instructional support giving to learners when working on the learning tasks in the classroom. This support fades away as learners gain experience. The activation is instructional approach that stimulates learners' prior knowledge and makes it active for use in the working memory to serve as a foundation for new information.

The proposed model of technical expertise and its associated innovative teaching methods has been tested empirically (e.g., Sarfo and Elen 2007) and found to be practical and effective in developing expertise in building drawing in traditional classroom of secondary technical schools (Sarfo and Elen, 2007).

CONCLUSION AND RESEARCH IMPLICATIONS

This article extensively discusses and analyses the research findings from cognitive psychology and design education in a systematic manner and proposes a model of technical expertise and associated innovative teaching methods for technical schools. The model is generated based on empirical findings. Technical subjects in technical schools include building drawing, woodwork, auto mechanics, applied electricity, technical drawing and others. As described in this article, expertise in all these areas requires the acquisition of integrated set of knowledge and skills as shown in the proposed model of technical expertise. Based on the notion of the proposed model it is concluded that teaching in technical schools should not focus on domain specific knowledge (procedural and declarative) alone. An equal attention should also be paid to cognitive strategies and metacognitive skills which are also teachable. The model therefore suggests to (technical) education practitioners about the types and nature of knowledge and skills that technical students should acquire in order to perform as competent or expert technicians in the world of work. The proposed model can facilitate research studies to extend the innovative teaching strategies for the development of technical expertise in technical schools. This is important contribution to technical education which is relatively less studied area.

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