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The Four-Component Instructional Design Model: Multimedia Principles in Environments for Complex Learning

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Abstract

The Four-Component Instructional Design model claims that four components are necessary to realize complex learning: (1) learning tasks, (2) supportive information, (3) procedural information, and (4) part-task practice. This chapter discusses the use of the model to design multimedia learning environments and relates 14 multimedia principles to each of the four components. Students may work on learning tasks in simulated task environments, where relevant multimedia principles primarily facilitate a process of inductive learning; they may study supportive information in hypermedia systems, where principles facilitate a process of elaboration and mindful abstraction; they may consult procedural information in Electronic Performance Support Systems (EPSS), where principles facilitate a process of knowledge compilation; and, finally, they may be involved in part-task practice with drill & practice Computer Based Training (CBT) programs, where principles facilitate a process of psychological strengthening. Research implications and limitations of the presented framework are discussed.

Introduction

Theories about learning with multimedia can be positioned at different levels. At a basic level, psychological theories describe memory systems and cognitive processes that explain how people process different types of information and how they learn with different senses. Examples of such theories are Paivio's dual coding theory (1986; Clark & Paivio, 1991) and Baddeley's working memory model with a central executive and two slave systems, the visuospatial sketchpad and the phonological loop (1992; 1997). At a higher level, theories for instructional message design identify multimedia principles and provide guidelines for devising multimedia messages consisting of, for instance, written text and pictures, spoken text and animations, or explanatory video with a mix of moving images with spoken and written text. Examples of such theories are Mayer's generative theory of multimedia learning (2001) and Sweller's cognitive load theory (2004; Sweller, van Merriënboer, & Paas, 1998). At an even higher level, theories and models for course and curriculum design prescribe how to develop educational programs, which contain a mix of educational media including texts, images, speech, manipulative materials, and networked systems. Well-designed educational programs take both human cognitive architecture and multimedia principles into account to ensure that learners will work in an environment that is goal-effective, efficient and appealing.

The main goal of this chapter is to present a theory that is positioned at the third level, namely, the four-component instructional design model (for short, 4C/ID-model; van Merriënboer, Jelsma, & Paas, 1992; van Merriënboer, 1997; van Merriënboer, Clark, & de Croock, 2002; van Merriënboer, Kirschner, & Kester, 2003), and to discuss how this theory is used to design multimedia learning environments for complex learning. Such complex learning explicitly aims at the integration of knowledge, skills and attitudes; the ability to coordinate qualitatively different constituent skills; and the transfer of what is learned to daily life or work settings. The 4C/ID-model views authentic learning

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tasks that are based on real-life tasks as the driving force for learning and thus the first component in a well-designed environment for complex learning – a view that is shared with several other recent instructional theories (for an overview, see Merrill, 2002). The three remaining components are supportive information, procedural information, and part-task practice.

While the 4C/ID-model is not specifically developed for the design of multimedia environments for learning, it has important implications for the selection of—a mix of—suitable educational media as well as the presentation of information and arrangement of practice and feedback through these media. This chapter will first present a general description of how people learn complex skills in an environment that is built from the four blueprint components. Second, the relationship between the four components and the assumed cognitive architecture is explained, focusing on the role of a limited working memory and a virtually unlimited long term memory for schema construction and schema automation – processes that lay the foundation for meaningful learning. Third, educational media and 14 multimedia principles are related to each of the four components. The chapter ends with a discussion that reviews the contributions of the 4C/ID-model to cognitive theory and instructional design, indicates the limitations of the model, and sketches directions for future research.

How Do People Learn Complex Skills?

The basic message of the 4C/ID-model is that well-designed environments for complex learning can always be described in terms of four interrelated blueprint components:

1. Learning tasks. Meaningful whole-task experiences that are based on real-life tasks. Ideally, the learning tasks ask the learners to integrate and coordinate many if not all aspects of real-life task performance, including problem-solving and reasoning aspects that are different across tasks and routine aspects that are consistent across tasks.

2. Supportive information. Information that is supportive to the learning and performance of problem solving and reasoning aspects of learning tasks. It describes how the task domain is organized and how problems in this domain can best be approached. It builds a bridge between what learners already know and what may be helpful to know in order to fruitfully work on the learning tasks.

3. Procedural information. Information that is prerequisite to the learning and performance of routine aspects of learning tasks. This information provides an algorithmic specification of how to perform those routine aspects. It is best organized in small information units and presented to learners precisely when they need it during their work on the learning tasks.

4. Part-task practice. Additional exercises for routine aspects of learning tasks for which a very high level of automaticity is required after the instruction. Part-task practice is only necessary if the learning tasks do not provide enough repetition for a particular routine aspect to reach the required high level of automaticity.

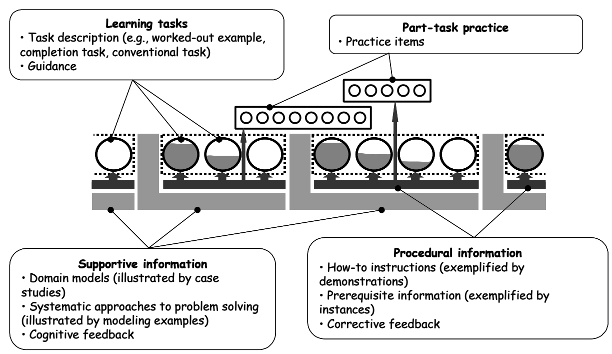

Figure 1. A schematic overview of the four components in the 4C/ID-model and their main elements.

Figure 1 provides a schematic overview of the four components. The learning tasks are represented as circles; a sequence of tasks serves as the backbone of the course or curriculum. Equivalent learning tasks belong to the same *task class* (in Figure 1, the dotted rectangles around a set of learning tasks). Learning tasks within the same task class are equivalent to each other in the sense that they can be performed on the basis of the same body of knowledge – but they are different on the dimensions that also vary in the real world such as the context in which the task is performed, the way the task is presented, the saliency of defining characteristics, and so forth. Each new task class is more difficult than the previous task classes. Students receive much support and guidance for their work on the first learning task in a class (in Figure 1, this is indicated by the filling of the circles), but support smoothly decreases in a process of scaffolding as learners acquire more expertise. One type of—product-oriented—support is embraced in the *task descrip-*

tion: For instance, worked examples provide maximum support because they present both a problem and an acceptable solution that must only be studied or evaluated by the learners; completion tasks provide medium support because they present a problem and a partial solution that must be completed by the learners, and conventional tasks provide no support at all because they present a problem that must be solved independently by the learners. Another type of—process-oriented—support has the form of *guidance*: This is information in the form of process worksheets or guidelines that lead the learner through the problem-solving process. In general, students work without any support on the final learning tasks in a task class; these conventional tasks without guidance may also be used as test tasks for the assessment of students' performance.

The supportive information is linked to task classes, because this information is relevant to all learning tasks within the same class (see the L-shaped, light gray shapes in Figure 1). For each subsequent task class, the supportive information is an addition to or an embellishment of the previously presented information, allowing learners to do things that they could not do before. It is the information that teachers typically call 'the theory' and consists out of three parts. First, it describes *domain models*, answering questions like "what is this?" (conceptual models), "how is this organized?" (structural models), and "how does this work" (causal models). These models are typically illustrated with case studies. Second, supportive information describes *Systematic Approaches to Problem solving* (SAPs) that specify the successive phases in a problem solving process and the rules-of-thumb that may be helpful to successfully complete each phase. SAPs may be exemplified by modeling examples, which show an expert who is performing a task and simultaneously explaining why s/he is doing what s/he is doing. Third, supportive information pertains to the *cognitive feedback* that is given on the quality of the learner's task performance. Because there is no simple correct or incorrect behavior for the problem solving and reasoning aspects of performance, cognitive feedback will often invite students to critically compare their own solutions with expert solutions or solutions of their peers.

The procedural information is represented in Figure 1 by dark gray rectangles with upward pointing arrows, indicating that information units are explicitly coupled to separate learning tasks. This information is preferably presented exactly when learners need it to perform particular routine aspects of learning tasks. This removes the need for memorization beforehand. Procedural information primarily consists of *how-to instructions*, rules that algorithmically prescribe the correct performance of the routine aspects of learning tasks. They are formulated at the level of the lowest-ability learner, so that all students can correctly perform them. How-to instructions may be exemplified by demonstrations that are preferably given in the context of the whole, meaningful task. Second, procedural information may pertain to *prerequisite information*, that is, information that learners must know to correctly perform the how-to instructions. This information may be exemplified by so-called instances. For example, a how-to instruction may state that "You now connect the digital device to one of the USB ports". Related prerequisite information for carrying out this instruction may give a definition of what a USB port is, and an instance may show a photograph of the USB ports of a personal computer. Finally, *corrective feedback* may be given on the quality of performance of routine aspects. Such feedback indicates that there is an error, explains why there is an error, and gives hints that may help the learner to get back on the right track. If learners start to master the routine aspects, the presentation of the procedural information quickly fades away in a process of fading.

Part-task practice is indicated in Figure 1 by the small series of circles, representing *practice items*. Often, the learning tasks provide sufficient practice for routine aspects of performance to obtain the desired level of automaticity. But for routine aspects that are very basic or that are critical in terms of safety additional part-task practice may be necessary, such as musicians practicing musical scales, children drilling multiplication tables, or air traffic controllers practicing the recognition of dangerous air traffic situations from a radar screen. Part-task practice for a selected routine aspect never starts before this aspect has been introduced in a whole, meaningful learning task, so that there is an appropriate cognitive context. It is preferably intermixed with learning tasks, so that there is distributed or spaced practice of routines. Drill & practice on a vast set of practice items is an effective instructional method to obtain a very high level of automaticity.

Complex learning requires that students work on whole, meaningful learning tasks. The tasks may have different descriptions (e.g., worked examples, completion tasks, conventional tasks) and different levels of guidance. To be able to perform the problem solving and reasoning aspects of those tasks and to learn from them, students consult and study domain models and SAPs and receive cognitive feedback on the quality of their performance. During task performance, how-to instructions specify how to perform the routine aspects of the task. Prerequisite information ensures that learners can carry out those instructions and corrective feedback is given if errors are made. Finally, part-task practice may offer a large set of practice items for the additional training of routine aspects.

From this description, it should be clear that people learn from words, pictures and other representations (realia, smell, touch etc.) in many different ways. On the one hand, each of the four components itself may require that learners combine representations: Learning tasks may ask learners to simultaneously read displays, process spoken text, and operate controls; supportive information may include a video recording of an expert modeling a problem-solving process and explaining why he is doing what he is doing; procedural information may include a quick reference guide with written instructions for operating a complex device as well as pictures of this device, and part-task practice may include operating a software program with texts and icons. Furthermore, procedural information is typically presented to learners while they are working on learning tasks or performing part-task practice, yielding two sources of information ("how-to" information and a task for which this information is relevant) that must be mentally integrated by the learner in order to successfully complete the task. For each situation, another set of multimedia principles applies because there are different learning processes involved. This will be further explained in the next section.

Cognitive Architecture and Meaningful Learning

The 4C/ID-model assumes that all human knowledge is stored in cognitive schemata. It further supposes a cognitive architecture that is broadly accepted in the psychological literature and for which ample empirical support is available. This architecture distinguishes a working memory with a very limited capacity when dealing with novel information as well as an effectively unlimited long term memory, holding cognitive schemata that vary in their degree of richness (i.e., number of elements and interconnections between those elements) and their level of automation. Learning processes are either related to the construction of schemata, including the formation of new schemata and the embellishment of existing schemata, or to the automation of schemata.

Memory Systems

To begin with, all novel information must be processed in working memory to construct cognitive schemata in long-term memory. This processing is heavily limited by the fact that only a few elements can be simultaneously active in working memory: About seven distinct elements that need to be stored or about two to four elements and their interactions if the elements need to be interrelated to each other. Furthermore, it is assumed that working memory can be subdivided into partially independent channels or processes (Baddeley, 1992). One channel consists of a phonological loop to deal with verbal material based on an auditory working memory; another channel consists of a visual-spatial scratch pad to deal with diagrammatic or pictorial information based on a visual working memory. Using both the visual and auditory channels rather than either one channel alone increases the effective working memory capacity (Penney, 1989). Long-term memory alters the characteristics of working memory by reducing or even eliminating its limitations. Human expertise is the result of the availability of rich and automated cognitive schemata, *not* from an ability to engage in reasoning with many elements that yet need to be organized in long-term memory. Human working memory simply does not support this type of many-elements processing.

Expertise develops through two complementary processes, namely, schema construction and schema automation. Schema construction refers to the—often conscious and mindful—formation of increasing numbers of ever more complex schemata, by combining elements consisting of lower-level schemata into higher-level schemata. These schemata organize and store knowledge, but also heavily reduce working memory load because even highly complex schemata can be dealt with as *one* element in working memory. Thus, a large number of elements for one person may be a single element for another, more experienced person, who already has a cognitive schema available that incorporates the elements. As a result, novel information may be easy to understand by someone with relevant experience, and very hard to understand by someone without this experience.

Schema automation occurs if a task performer repeatedly and successfully applies a particular cognitive schema. As is the case for schema construction, automation can free working memory capacity for other activities because an automated schema directly steers the routine aspects of behavior, without the need to be processed in working memory. As a direct consequence, instructional designs for complex learning should not only encourage the construction of problem-solving and reasoning schemata, but also the automation of schemata for those aspects of a complex skill that are consistent across problems or tasks. In a learning environment that is developed according to the 4C/ID-model, learners' work on learning tasks and study of supportive information helps them to *construct* cognitive schemata; their consultation of procedural information, repeated performance of routine aspects of learning tasks, and drill on part-task practice helps them to *automate* schemata. Thus, meaningful learning is the result of both schema construction and schema automation.

Cognitive Processes that Lead to Meaningful Learning

The 4C/ID-model makes a further division in learning processes that are directly coupled to the four components of the model. With regard to schema construction, a distinction is made between induction through experiential learning, which refers to the construction of schemata by—often mindfully—abstracting away from concrete learning tasks (component 1), and elaboration, which refers to the construction of schemata by relating already existing knowledge in long term memory to new supportive information (component 2). *Induction* is at the heart of complex learning and refers both to the generalization and discrimination of cognitive schemata (see Holland, Holyoak, Nisbett, & Thagard, 1989). When learners generalize or abstract away from well-designed learning tasks, they construct schemata that leave out the details so that they apply to a wider range of events or to events that are less tangible. Discrimination is just the opposite of generalization. A more specific schema may be constructed if a set of failed solutions is available for a class of related tasks. Then, particular conditions may be added to the schema and restrict its range of use. Induction is typically a strategic and controlled cognitive process, which requires conscious processing from the learners (also called 'mindful abstraction'; Perkins & Salomon, 1989).

The *elaboration* of new supportive information refers to those cognitive activities that integrate new information with cognitive schemata already available in memory (see Willoughby, Wood, Desmarais, Sims, & Kalra, 1997). When learners elaborate new supportive information, they first search their memory for general cognitive schemata that may provide a cognitive structure for understanding the information in general terms, and for concrete schemata or cases that may provide a useful analogy. These schemata are connected to the new information, and elements from the retrieved schemata that are not part of the new information are now related to it. Thus, learners use what they already know about a topic to help them structure and understand the new information.

With regard to schema automation, a distinction is made between knowledge compilation, which refers to the preliminary automation of schemata on the basis of procedural information (component 3), and strengthening, which refers to the development of very high levels of automaticity through part-task practice (component 4). *Knowledge compilation* refers to the process by which procedural information is embedded in automated schemata that directly steer behavior, that is, evoke particular actions under particular conditions. Newly acquired schemata or worked examples may be used to yield an initial solution, and compilation is the process that creates highly specific schemata from this solution (Anderson, 1993; Anderson & Lebiere, 1998). After the knowledge is compiled, the solution is generated by directly coupling the actions to the conditions in the specific schema. This greatly speeds up performance.

Finally, *strengthening* makes it possible for learners to perform a routine aspect of a complex skill, after it has been separately trained in a process of part-task practice, at a very high level of automaticity. It is usually assumed that an automated schema has a strength associated with it, determining the chance that it applies under the specified conditions as well as how rapidly it then applies. While knowledge compilation leads to highly specific schemata, which are assumed to underlie accurate performance of the skill, they still have a weak strength. Strengthening is a straightforward learning mechanism. It is simply assumed that automated schemata accumulate strength each time they are successfully applied. The improvement that results from strengthening requires long periods of 'overtraining' (Palmeri, 1999).

Table 1

Examples of Prominent Multimedia Principles for Each of the Four Components of the 4C/ID-Model

Multimedia Principle	Example
Learning Tasks and Learning in Simulated Task Environments	
1. Sequencing principle	For physics students who learn to troubleshoot electrical circuits, start with circuits with only very few elements (e.g., a lamp, battery and switch) and continue with circuits with increasingly more elements.
2. Fidelity principle	For medical students who learn to diagnose patients, start with textual case descriptions, continue with computer-simulated patients or patients played by peers, go on with simulated patients played by actors, and end with real patients in an internship in hospital.
3. Variability principle	For law students who learn to prepare pleas to be held in court, make sure that learning tasks ask them to prepare pleas for different fields of law (civil law, criminal law), different clients (guilty, not guilty), different courts (police court, law court, supreme court), and so on.
4. Individualization principle	For computer science students who learn to write computer programs, continuously assess with which programming constructs they have difficulties and select new learning tasks that offer optimal opportunities to remedy their misconceptions.
5. Training-wheels principle	For accountancy students who learn to make budgets with a spreadsheet program, first block all toolbars and menu options that are not strictly necessary to perform the task, but only add these when they become necessary because students progress to making more complex budgeting tasks.
6. Completion-strategy principle	For students in architecture who learn to design constructional blueprints, first let them evaluate the qualities of blueprints of existing buildings, then let them redesign blueprints for the renovation of buildings, and finally let them design blueprints for new buildings.
Supportive Information and Learning from Hypermedia	
7. Redundancy principle	For students in econometrics who learn to explain periods of economic growth, first present a qualitative model (allows them to predict if there will be any growth) and only then present a more encompassing quantitative model (laws that may help them to compute the amount of growth) – but *without* repeating the qualitative information as such.
8. Self-explanation principle	For medical students who learn to diagnose malfunctions in the human cardiovascular system, present an animation of how the hart works and provide prompts that provoke them to explain the underyling mechamisms to themselves or their peers.
9. Self-pacing principle	For students in psychotherapy who learn to conduct intake conversations with depressed clients, show video-examples of real-life intake conversations and give them the opportunity to stop/replay the recording after each segment in order to reflect on this particular segment.
Procedural Information and Electronic Performance Support Systems	
10. Temporal split-attention principle	For students in web design who learn to develop web pages in a new software environment, tell them how to use the different functions of the software environment precisely when they need them to implement particular aspect of their design – instead of discussing all available functions beforehand.
11. Spatial split-attention principle	For social science students who learn to conduct statistical analyses on their data files with SPSS, present procedural information describing how to conduct a particular analysis also on the computer screen and not in a separate manual.
12. Signaling principle	For students in car engineering who learn to disassemble an engine block, animate the disassembling process in a step-by-step fashion and always put a spotlight on those parts that are loosened and removed.
13. Modality principle	For students in instructional design who learn to develop training blueprints by studying a sequence of more and more detailed blueprints, explain the blueprints with narration or spoken text instead of visual (on-screen) text.
Part-task Practice and Drill & Practice CBT Programs	
14. Component-fluency principle	For students in air traffic control who learn to direct incoming aircraft, provide additional and extensive part-task practice on immediately recognizing potentially dangerous air traffic situations from the radar screen.

Meaningful Multimedia Learning According to the 4C/ID-Model

As discussed in the previous section, the four components (learning tasks, supportive information, procedural information, part-task practice) aim at the facilitation of different learning processes, with clear implications for the selection of suitable educational media and relevant multimedia principles. These media and principles are discussed in the next sections.

Learning Tasks and Learning in Simulated Task Environments

Learning tasks primarily aim at schema construction through inductive learning. The educational medium must allow learners to work on those tasks and typically takes the form of a real or simulated task environment. One may think of a project room, a simulated office, a physical simulator, or an internship in a real company. In multimedia learning, the heart of the learning environment will typically consist of a computer-simulated task environment. For many complex skills, such as holding a plea in court, conducting psychological experiments, or troubleshooting a chemical factory, current multimedia technology does not yet offer the possibilities that are needed for high-fidelity simulation (i.e., missing input-output facilities, lack of simulation models that can run in the background, etc.). The opportunities will be better in the near future thanks to Virtual Reality (VR), broadband technology, and new input and output devices such as VR-helmets and data gloves. Although the necessary multimedia technology to implement optimal instructional methods is not always available, many multimedia applications already offer the opportunity to perform learning tasks that are somehow based on real-life tasks. Table 1 summarizes the main multimedia principles (1-6) that should be taken into account in simulated task environments and provides for each principle an example of how it could be applied.

Sequencing principle. The sequencing principle indicates that it is often better to sequence learning tasks or complex pieces of information from simple to complex, than to present them in their full complexity at once. Mayer and Moreno (2003) refer to this as a 'pretraining' effect, when they review studies showing better transfer test performance when students must first study which components make up a system (i.e., a conceptual model) and only then how the system works (i.e., a causal or functional model, Mayer, Matthias, & Wetzell, 2002). These results are consistent with the findings of Pollock, Chandler and Sweller (2002), who found that for high-element interactivity materials first presenting isolated elements and only then the interrelated elements is better than presenting all elements simultaneously, and of Clarke, Ayres and Sweller (in press), who found that for learning mathematics with spreadsheet applications, especially for low-expertise learners it is important to present and practice enabling, technological skills (i.e., using spreadsheets) before practicing the ultimate skills the training is aiming at (i.e., mathematical skills). Kester, Kirschner and van Merriënboer (2003; in press a; in press b) studied the sequencing principle in the context of the 4C/ID-model. In the domain of electronics troubleshooting, they found that presenting high-element interactivity supportive information either before or after low-element interactivity procedural information, led to better transfer test performance. The 4C/ID model primarily uses task classes to accommodate the sequencing principle. Task classes and their related supportive information range from simple to complex, while the learning tasks within the same task class are equally difficult. The basic guideline of the 4C/ID-model is to start with a task class where the learning tasks can be solved on the basis of a simple domain model or SAP, and to continue with task classes where the supportive information pertains to increasingly more complex and elaborated domain models or SAPs (i.e., mental model progression, van Merriënboer, Kirschner, & Kester, 2003).

Fidelity principle. Learning tasks are performed in some kind of task environment. While the learning tasks are based on real-life tasks, they can yet be performed in an environment that is very close to the real task environment (i.e., high fidelity) or in an environment that merely offers to opportunity to perform the tasks, with no attempts to mimic the real task environment (i.e., low fidelity). The fidelity principle indicates that for novice learners, a high fidelity task environment often contains irrelevant details that may deteriorate learning. This principle is in agreement with the finding that there is better transfer when interesting but irrelevant materials, such as background music and non-essential video clips, are excluded from a training program. Students perform better on transfer tests after receiving a concise narrated animation instead of an embellished narrated animation (Mayer, Heiser, & Lonn, 2001; Moreno & Mayer, 2000). For a web-based course, Gulikers, Bastiaens and Martens (in press) found that novices perform better in a low-fidelity, text-based environment than in a high-fidelity environment where multimedia features are used to mimic the real task environment. Harp and Mayer (1998) also report that 'seductive details' that are not directly relevant for learning deteriorate performance. According to the 4C/ID-model, training should best start with task classes in which the learning tasks are performed in a low-fidelity environment, which only represents those aspects of the real environment that are necessary to perform the task. There is a high *psychological* fidelity because the learning task is representative for a real-life task, but there is no or little physical correspondence with the real environment. Only in later task classes and with more advanced learners, it becomes necessary to perform the learning tasks in a high fidelity or real environment (see also Maran & Glavin, 2003).

Variability principle. The variability principle indicates that learning tasks must be sufficiently different from each other to allow for the construction of general, abstract schemata that make transfer of learning possible. Ideally, learning tasks should differ on all dimensions that also vary in the real world, such as the conditions under which the task is performed, the way of presenting the task, or the saliency of defining characteristics. Several studies showed that a high variability across learning tasks yields superior transfer test performance (e.g., Quilici & Mayer, 1996; Paas & van Merriënboer, 1994). Van Merriënboer, Schuurman, de Croock and Paas (2002) and de Croock, van Merriënboer and Paas (1998) studied contextual interference, which is a special type of variability referring to the way in which differences between tasks are divided across acquisition tasks. Suppose that students learn to diagnose three types of errors: A, B and C. Low contextual interference may then be produced by a blocked practice schedule, in which the skills necessary for diagnosing one type of error are practised before continuing to another type of error (e.g., AAA, BBB, CCC). High contextual interference may be produced by a random practice schedule, in which different errors are sequenced in a random order (e.g., CABBCABAC). High contextual interference prohibits a quick and smooth mastery of the skills being trained, but yields higher transfer test performance because learners are promoted to construct general cognitive schemata. The 4C/ID-model takes the variability principle into account and suggests including in *each* task class, learning tasks that exhibit high variability and high contextual interference. Recent research of Gerjets, Scheiter and Catrambone (2004), however, seems to imply that optimal transfer does not always require a high variability of learning tasks within each task class, as long as the variability is sufficiently high for the learning tasks in the *whole set* of task classes (i.e., in the whole training program).

Individualization principle. Recent studies show that adaptive training systems, which dynamically select learning tasks based on the characteristics of the individual learner, yield higher transfer than non-adaptive training systems, which present a fixed sequence of tasks that is identical for all learners (Salden, Paas, & van Merriënboer, in press). In these adaptive systems the dynamic selection of the next learning task is typically based on performance (i.e., accuracy and/or speed), but it can also be based on the amount of mental effort invested in performing the previous task(s), on a combination of performance and mental effort (for examples, see Camp, Paas, Rikers, & van Merriënboer, 2001; Kalyuga & Sweller, in press; Salden, Paas, Broers, & van Merriënboer, 2004), or on a qualitative student model (e.g., van Merriënboer & Luursema, 1996). The individualization principle typically takes differences between learners into account by selecting learning tasks in such a way that the task difficulty and/or the available level of support is adjusted to the learner. This fits in very well with the 4C/ID-model. For each learning task, performance needs to be assessed in order to give cognitive feedback to the learners (Straetmans, Sluijsmans, Bolhuis, & van Merriënboer, 2003). This assessment information can also be used to select a new task: If performance is low, an equivalent task with a higher level of support will be selected from the same task class or, in the worst case, an easier task will be selected from a previous task class; if performance is high, an equivalent task with a lower level of support will be selected from the same task class, or, if all performance criteria have been reached, the learner is allowed to move on to the next task class from which a more difficult task with a high level of support is selected.

Training-wheels principle. Even performing relatively easy learning tasks in a low-fidelity environment is difficult for novice learners, because it are still 'whole' tasks that require the coordination of many different constituent skills. One way to help learners is to provide either process-oriented worked examples that show an expert who is performing the task (van Gog, Paas, & van Merriënboer, 2004) or to give process worksheets that ask leading questions that guide the learners step-by-step through the problem solving or reasoning process (e.g., Nadolski, Kirschner, & van Merriënboer, 2001). However, a potential drawback of these methods is that learners must divide their attention between the task and the support, which may negatively affect learning (van Merriënboer, Kirschner, & Kester, 2003). An additional way to support learners is to *constrain* their performance, that is, to make sure that they cannot perform actions that are not necessary to reach the performance goals. A metaphor for these performance constraints is provided by the training wheels on children's' bikes, which prevent them from falling over (Carroll, 2000). Dufresne, Gerace, Thibodeau-Hardiman and Mestre (1992) studied the training wheels principle for a problem-solving task in physics. Students' performance was constrained in such a way that they had to mimic an expert's approach to problem solving, which had positive effects on their transfer test performance. In another study, Leutner (2000) also found positive effects of training wheels on test performance, but his study also indicated that both too many constraints and too little constraints might produce suboptimal effects on learning. In the 4C/ID-model, the training wheels principle is included as one way to decrease guidance for learning tasks within one task class. While the learning tasks in the same task class are equally difficult, they start with high guidance and guidance decreases until none as expertise increases.

Completion-strategy principle. In contrast to the training-wheels principle, which primarily concerns guidance or *process support*, the completion-strategy principle concerns support that is implied by the task description. The completion strategy (van Merriënboer, 1990; van Merriënboer & de Croock, 1992) starts with worked examples that must be studied by the learners, continues with completion tasks that present partial solutions that must be completed by the learners, and ends with conventional tasks for which the learners must independently generate whole solutions. Many studies indicate that novice learners learn more from studying worked examples (for an overview, see Atkinson, Derry, Renkl, & Wortham, 2000) or from performing completion tasks that require them to complete partial solutions (for an overview, see Sweller, van Merriënboer, & Paas, 1998) than from solving the equivalent conventional problems. In addition, Kalyuga, Chandler, Tuovinen and Sweller (2001) and Tuovinen and Sweller (1999) found that this effect reverses for more experienced learners, which is an example of the 'expertise reversal effect' (Kalyuga, Ayres, & Chandler, 2003). Thus, novices benefit more from studying worked examples but experienced learners profit more from solving the equivalent conventional problems. The completion strategy accommodates the findings on the expertise reversal effect and proved to be very effective in facilitating transfer of learning (Renkl & Atkinson, 2003; Renkl, Atkinson, & Grosse, 2004). In the 4C/ID-model, the completion-strategy principle is included as one way to decrease support for learning tasks within one task class. In the beginning of a task class, high support may provided by the use of worked examples; then, increasingly lesser support may be provided by completion tasks for which the learners have to generate larger and larger parts of the solution; and finally, conventional tasks provide no support at all.

Supportive Information and Learning from Hypermedia

Supportive information mainly aims at schema construction through elaboration, that is, connecting new information to knowledge that is already available in long-term memory. Traditional media for supportive information are textbooks, teachers and realia. Textbooks contain a description of the 'theory', that is, the domain models that characterize a field of study and, alas, often in a lesser degree the SAPs that may help to solve problems and perform non-trivial tasks in the domain. Teachers typically discuss the highlights in the theory (lectures), demonstrate or provide expert models of SAPs, and provide cognitive feedback on learners' performance. Realia or descriptions of real entities ('case studies') are used to illustrate the theory. Hypermedia and hypertext systems may take over—part of—those functions. They may present theoretical models and concrete cases that illustrate those models in a highly interactive way, and they may explain problem-solving approaches and illustrate those approaches by showing, for example, expert models on video. As indicated before, it is critical that students elaborate and deeply process this information. On the one hand, hypermedia may well help to reach this goal, because their structure reflects the way that human knowledge is organized in elements (called "nodes") and non-arbitrary relationships between those elements (called "links"). But on the other hand, it is of utmost importance to provoke deep processing through asking questions, stimulating reflection, and promoting discussion. Principles 7-9 in Table 1 summarize the main multimedia principles that should be taken into account in hypermedia systems and provide illustrations of their application.

Redundancy principle. This principle indicates that the presentation of redundant information typically has a negative impact on learning (for an overview of studies, see Sweller, van Merriënboer, & Paas, 1998). It is a counter-intuitive principle, because most people think that the presentation of the same information, in a somewhat different way, will have a neutral or even positive effect on learning. However, learners have to find out that the information from different sources is actually redundant, which is a cognitively demanding process that does not contribute to meaningful learning. In recent studies, Mayer, Heiser, and Lonn (2001), Moreno and Mayer (2002), and Leahy, Chandler and Sweller (2003) presented visual information to learners (e.g., an animation) and a concurrent narration that explained this visual information. Negative effects on learning were found when the concurrent narration was duplicated by a—redundant—on-screen text. Kalyuga, Chandler and Sweller (2000) related the redundancy principle to the expertise reversal effect. They found that information that is helpful for novice learners is detrimental to more experienced learners, because it is redundant with what they already know. The 4C/ID-model relates the finding that the presentation of redundant information may seriously hamper learning primarily to the distribution of supportive information over task classes. The supportive information for each new task class is always an addition to, or embellishment of, the information that has been presented for previous task classes. While the conceptual link between the new information and the previous information should be pointed out to the learners, it is important *not* to repeat the information from previous task classes in order to prevent negative effects of redundancy.

Self-explanation principle. Salomon (1998) discusses the so-called ‘butterfly defect’ in hypermedia and web-based learning: “... touch, but don’t touch, and just move on to make something out of it”. Multimedia may act as an affordance to relax (cf., watching television) – while for meaningful learning to occur they should be associated with deep processing and invite learners to ‘self-explain’ information. Renkl (1999) introduced the self-explanation principle in the context of learning from worked examples. The degree to which learners explain the solution steps in worked examples to their selves is a good predictor for learning outcomes, and direct elicitation of self-explanation by prompting the learners had some beneficial effects on transfer. Stronger evidence for the facilitation of transfer by self-explanation was found in a study with the completion strategy (Atkinson, Renkl, & Merrill, 2003). In this study, prompts were designed to encourage learners to identify the underlying principles illustrated in worked-out solution steps, and these prompts had beneficial effects on transfer test performance. Similar results were found in a study by Mayer, Dow, and Mayer (2003), who found positive effects on learning by using prequestions to guide self-explanation; Aleven and Koedinger (2002), who found better transfer by using a cognitive tutor to guide self-explanation in a classroom setting, and Moreno and Valdez (in press), who found positive effects on transfer of postponing feedback so that learners had to evaluate their own actions. For the presentation of supportive information, the 4C/ID-model stresses the importance of instructional methods that promote elaboration and schema construction. Prompting for self-explanation of domain models and SAPs, as well as illustrations of them by case studies and modelling examples, is one particularly important instructional method to reach this.

Self-pacing principle. The self-pacing principle indicates that giving learners control over the pace of the instruction may facilitate elaboration and deep processing of information. Elaboration is an effortful, time-consuming process and especially ‘streaming’ or transient information (video, dynamic animation etc.) may leave learners insufficient time for this type of processing. Mayer and Moreno (2003) report higher transfer test performance if information is presented in learner-controlled segments rather than as one continuous unit, an example of the self-pacing principle they called the ‘segmentation effect.’ In an experiment of Mayer and Chandler (2001), learners who were allowed to exercise control over the pace of a narrated animation performed better on transfer tasks compared with learners who received the same narrated animation at normal speed without any learner control. Tabbers (2002) found the same result for visual text accompanying diagrams: Self-paced presentation of the instructional texts led to higher transfer test performance than system-paced instructional texts. In the 4C/ID-model, ‘streaming’ information will often refer to case studies (e.g., an animation illustrating a particular dynamic domain model) and modeling examples (e.g., a video of an expert modeling a particular problem solving process or SAP). For this type of multimedia information presentation, it is important to give learners control over the pace in which the information is presented to them. The self-pacing principle allows them to pause and better reflect on the new information in order to couple it to already existing cognitive structures.

Procedural Information and Electronic Performance Support Systems

Procedural information primarily aims at schema automation through knowledge compilation. The traditional media for procedural information are the teacher and all kinds of job and learning aids. The teacher's role is to walk through the classroom, laboratory or workplace and to watch over his learners' shoulder (the teacher's name is Aloys – the Assistant Looking Over Your Shoulder), and to give directions for performing the routine aspects of learning tasks (e.g., "No – you should hold that instrument like this...", "Watch, you should now select this option…"). Job aids may be the posters with frequently used software commands that are stuck on the wall of a computer class, quick reference guides next to a piece of machinery, or booklets with safety instructions for interns in industry. In multimedia learning environments, these functions are mainly taken over by Electronic Performance Support Systems (EPSSs) such as on-line job aids and help systems, wizards, and (intelligent) pedagogical agents (Bastiaens, Nijhof, Streumer, & Abma, 1997). Such systems provide procedural information on request of the learner (e.g., on-demand help) or on their own initiative (e.g., pedagogical agent), preferably precisely when students need it for their work on the learning tasks. Table 1 summarizes the main multimedia principles (10-13) that should be taken into account in EPSSs and provides some examples of how they can be applied.

Temporal split-attention principle. The temporal split-attention principle originally indicates that learning from mutually referring information sources is facilitated if these sources are not separated from each other in time, that is, if they are presented simultaneously. Mayer and Moreno (2003) refer to the principle as the 'temporal contiguity effect' and review several studies that report higher transfer test performance for the simultaneous presentation of mutually referring pictures and text than for their consecutive presentation. The same is true for the concurrent presentation of animation and corresponding narration, which yields better transfer than their successive presentation (Mayer & Anderson, 1991; Mayer & Anderson, 1992; Mayer & Sims, 1994; Mayer, Moreno, Boire, & Vagge, 1999). In the context of the 4C/ID model, the temporal split-attention principle is particularly important for the presentation of procedural information, which refers to how-to instructions for performing the routine aspects of the learning task the learner is working on. If this information is presented *just in time*, precisely when the learner needs its, all elements necessary for knowledge compilation to occur are available in working memory at the time the skill is practiced. Kester, Kirschner and van Merriënboer (2003; see also Kester, Kirschner, & van Merriënboer, in press a) compared the just in time presentation of procedural information with a split-attention format (i.e., first present the information and then practice the task) and found beneficial effects on transfer test performance of the simultaneous presentation.

Spatial split-attention principle. The spatial split-attention principle, which is also called the 'spatial contiguity effect' (Mayer & Moreno, 2003), refers to the finding that higher transfer test performance is reached when mutually referring information sources are physically integrated with each other in space. Extensive research has been carried out showing the beneficial effects of integrating pictures with explanatory text: the text that refers to the picture is typically split up in smaller segments so that the text segment that refers to a particular part of the figure can be linked to this particular part or be included in the picture (e.g., Chandler & Sweller, 1991; Chandler & Sweller, 1992; Kalyuga, Chandler, & Sweller, 1999). In the context of the 4C/ID-model, Kester, Kirschner and van Merriënboer (in press b) studied the integration of procedural information in the task environment, in such a way that it was physically integrated with the learning tasks students were working on. Specifically, they integrated the procedural information in electronic circuits students had to troubleshoot. This also resulted in higher transfer test performance, a finding that is in agreement with Cerpa, Chandler, and Sweller (1996), who demonstrated that students learning a computer application learned better if all of the material was placed on the computer screen, as opposed to having a manual and computer on which to work. Combining both information sources prevents spatial split-attention between the task environment (i.e., the computer screen) and the procedural information in the manual (see also Sweller & Chandler, 1994; Chandler & Sweller, 1996). In general, procedural information should thus be presented in such a way that it is optimally integrated with the learning tasks and the task environment.

Signaling principle. The signaling or attention-focusing principle indicates that learning may be improved if the learner's attention is focused on the critical aspects of the learning task or the presented information. It reduces the need for visual search and so frees up cognitive resources that may then be devoted to schema construction and automation, with positive effects on transfer test performance. Jeung, Chandler and Sweller (1997) and Tabbers, Martens and van Merriënboer (in press) found beneficial effects on learning from the synchronous use of explanatory spoken text and cues in complex pictures, that is, the moment a particular part of the complex picture was explained it was highlighted or color-coded. Kalyuga, Chandler, and Sweller (1999) found similar positive effects of signaling with visual-only instructions. Furthermore, Mautone and Mayer (2001) found positive effects of signaling on transfer test performance when it was used in printed text, spoken text, as well as spoken text with corresponding animation. In the 4C/ID-model, signaling is particularly important if procedural information is related to routine aspects of task performance. For instance, if a teacher instructs a learner how to operate a piece of machinery it is useful to point a finger at those parts that must be controlled, and if a video-based example is used to demonstrate particular routine aspects of performance it is helpful to focus the learners' attention through signaling (e.g., by spotlighting hand movements) on precisely those aspects.

Modality principle. The modality principle indicates that dual-mode presentation techniques that use auditory text or narration to explain visual diagrams, animations or demonstrations, result in better learning than equivalent, single-mode presentations that only use visual information. Moreno and Mayer (1999) and Tindall-Ford, Chandler and Sweller (1997) present results that provide empirical support for the modality principle. The positive effect of dual-mode presentation is typically attributed to an expansion of effective working memory capacity, because for dual-mode presentations both the auditory and visual subsystems of working memory can be used rather than either one subsystem alone. This hypothesis was confirmed by Tabbers, Martens and van Merriënboer (2001), who found that students who studied complex diagrams explained by spoken text reported lower perceived mental effort than students who studied the same diagrams with visual text. With regard to the 4C/ID-model, procedural information that just-in-time specifies how to perform routine aspects of learning tasks can thus better be spoken by a teacher or other pedagogical agent than be visually presented.

Part-task Practice and Drill & Practice Computer Based Training

With regard to the fourth component, part-task practice aims at schema automation through strengthening. Especially for this component, the computer has proved its worth in the last decades. Drill & practice Computer Based Training (CBT) is without doubt the most successful type of educational software. The computer is sometimes abused for its use of drill, but most critiques seem to miss the point. They contrast drill & practice CBT with educational software that focuses on rich, authentic learning tasks. But according to the 4C/ID-model drill & practice will never replace meaningful whole-task practice; it merely complements the learners' work on rich learning tasks and is applied *only* when the learning tasks themselves cannot provide enough practice to reach the desired level of automaticity for selected routine aspects. If such part-task practice is necessary, the computer is probably the most suitable medium because it can make drill effective and appealing through giving procedural support; compressing simulated time so that more exercises can be done than in real time; giving knowledge of results (KR) and immediate feedback on errors, and using multiple representations, gaming elements, sound effects and so further. Table 1 gives an example of the application of the component fluency principle (14), that is, the most important multimedia principle in drill & practice CBT programs.

Component-fluency principle. The component-fluency principle indicates that drill & practice on one or more routine aspects of a task may have positive effects on learning and performing the whole task. Strengthening may produce a very high level of automaticity for routine aspects, which frees up cognitive capacity because these automated aspects no longer require resources for conscious processing. As a result, all available cognitive capacity can be allocated to the non-routine, problem-solving and reasoning aspects of whole-task performance. Carlson, Sullivan and Schneider (1989) and Carlson, Khoo and Elliot (1990) found evidence for the component fluency principle, but *only* when part-task practice took place after the learners were introduced to the whole task, that is, when it was provided in an appropriate 'cognitive context'. For this reason, the 4C/ID-model is reserved with the application of part-task practice and, if it is used at all, suggests starting part-task practice for particular routine aspects only *after* the learners have been introduced to these aspects in the context of whole learning tasks. Only then, the learners are able to identify the activities that are required to integrate the routines in the whole task.

Discussion

The 4C/ID-model provides guidelines for the design of environments in which complex learning takes place, that is, learning directed towards the integration of knowledge, skills, and attitudes, the ability to coordinate qualitatively different constituent skills, and the transfer of what is learned to real-life situations. This model was elaborated for the design of multimedia learning environments. Such applications are typically build around a simulated task environment that offers the opportunity to perform learning tasks (component 1). They may further contain hypermedia that allow learners to actively study supportive information (component 2), EPSSs with procedural information specifying how to perform routine aspects of complex tasks (component 3) and, finally, drill & practice CBT programs that provide opportunities for overlearning selected routine aspects that need to be performed at a very high level of automaticity after the training (component 4). Each of these four components relates to another set of prominent multimedia principles.

In the Introduction to this chapter, theories about learning with multimedia were positioned at three different levels: The psychological level, the message design level, and the course design level. As a theory at the level of course and curriculum design, the 4C/ID-model yields no direct contributions to cognitive theory in the sense that it provides a new perspective on human cognitive architecture or uncovers new cognitive processes. We believe, however, that it indirectly contributes to cognitive theory by synthesizing many different findings and showing the importance of the psychological study of real-life complex task performance. Learning processes such as inductive learning, elaboration, knowledge compilation and strengthening have each been thoroughly studied in many experimental studies, often using relatively straightforward laboratory tasks. No doubt, this is vital research but in addition it is becoming more and more important to study different types of learning processes in connection with each other. The 4C/ID-model tries to do so, and our results clearly indicate that complex learning on the basis of real-life tasks can only be described in terms of qualitatively different learning processes that often simultaneously occur.

With regard to instructional design and, in particular, theories at the level of message design, the contributions of the 4C/ID-model are more straightforward. Traditional design models analyze a learning domain in terms of distinct learning objectives. A common premise is that different objectives can best be reached by the application of particular instructional principles (the 'conditions of learning', Gagné, 1985). The optimal principles are chosen to design the 'message' for each objective; the objectives are taught one-by-one; and the general educational goal is believed to be met after all messages have been conveyed. In the early 1990's, authors in the field of instructional design started to question the value of this approach because it yields instruction that is fragmented and piecemeal (e.g., Gagné & Merrill, 1990). For real-life tasks, there are many interactions between the different aspects of task performance and their related objectives. Integrated objectives should not only aim at the ability to effectively perform each aspect of a complex task in isolation, but also pay attention to the ability to *coordinate* these different aspects in real-life task performance. An important contribution of the 4C/ID-model is that is provides a whole-task methodology to deal with such integrated objectives. At the same time, the four components provide an organizing framework for instructional methods, including multimedia principles (cf. Table 1). At least, the 4C/ID-model points out to designers under which conditions, and for which components of a learning environment, particular multimedia principles should be considered.

The framework discussed in this chapter has several limitations. First, the 4C/ID-model may well be used to design multimedia learning environments, but if this is actually desirable in a particular situation is yet another question. Many factors determine the selection of media in instructional design, including *constraints* (e.g., manpower, equipment, time, money), *task requirements* (e.g., media attributes necessary for performing learning tasks and required response options for learners), and *target group characteristics* (size of the group, computer literacy, handicaps). The 4C/ID-model does not provide guidelines for this process of media selection. Second, when positioned in the general ADDIE model (Analysis, Design, Development, Implementation and Evaluation), the 4C/ID-model clearly focuses on analysis and design activities, and does neither provide specific guidelines for the development, production and construction of multimedia materials nor for their implementation and evaluation. And third, while we focused our discussion on the most prominent multimedia principles for each of the four blueprint components, this does not imply that particular principles cannot be important for other blueprint components.

For instance, the fidelity principle is particularly important to sequence learning tasks from working in low-fidelity to working in high-fidelity environments, but it may also be relevant to all other three components that, after all, also determine aspects of the learning environment. Likewise, the training-wheels principle and the individualization principle are not exclusively useful for the design of learning tasks, but may also be applied to gradually relax performance constraints and to control learner's progress during part-task practice. The self-pacing principle is particularly important to the design of supportive information, but may also be useful for the presentation of procedural information (e.g., giving students control over the pace of a demonstration, so that they can view it step-by-step, is more effective then presenting the demonstration as one uninterrupted streaming video). And finally, split attention, signaling and modality principles are particularly important for the presentation of procedural information, because this is typically presented while the learners work on their learning tasks, but the same principles may also be relevant to the design of complex pieces of supportive information.

To conclude, psychological knowledge about how people learn with multimedia is rapidly increasing and many findings from cognitive theory have been incorporated in instructional theories that yield useful guidelines for the design of instructional messages. Less is known about how to apply those guidelines in environments for complex learning that try to reach integrated learning goals by using a mix of traditional and new educational media. Future research must identify the real-life conditions under which particular principles do and do not work and, especially, develop higher-level principles that help designers to stretch multimedia design from the message design level to the course design level, where simulated task environments, hypermedia, EPSSs, drill & practice CBT programs and other (traditional) media should seamlessly link up with each other. Future research should also acknowledge that advanced networked multimedia systems enable people to learn in ways that were inconceivable in the past. In order to make scientific progress in the field of multimedia learning, we should both study how good old-fashioned learning principles inform the design of artifacts and how implicit design principles in advanced technological artifacts affect the way in which people learn.

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Glossary

Completion-strategy principle. Sequencing learning tasks from worked examples that students must study, via completion tasks with incomplete solutions that must be finished, to conventional problems that must be solved has a positive effect on inductive learning and transfer.

Component-fluency principle. Training routine aspects, or, consistent components of a task up to a very high level of automaticity, in addition to training the whole task, has a positive effect on learning (in particular, strengthening) and transfer of the whole task.

Elaboration. A category of learning processes by which learners connect new information to knowledge that they already have available in memory. It is a form of schema construction that is especially important for learning supportive information using, for instance, hypermedia.

Fidelity principle. Sequencing learning tasks in such a way that they are first performed in an environment that does not try mimic the real task environment (i.e., low fidelity) and later performed in environments that more and more resemble the real environment (i.e., increasing fidelity) has a positive effect on inductive learning and transfer.

Individualization principle. Adapting the difficulty and the amount of available support of learning tasks to the level of expertise of individual learners has a positive effect on inductive learning and transfer.

Induction. A category of learning processes, including generalization and discrimination, by which learners mindfully abstract away from their concrete experiences. It is a form of schema construction that is especially important for learning from learning tasks in real or simulated task environments.

Knowledge compilation. A category of learning processes by which learners embed new information in highly domain-specific schemata that directly steer behavior. It is a form of schema automation that is especially important for learning procedural information from, for instance, electronic performance support systems (EPSS).

Learning task. A meaningful whole-task experience that is typically based on a real-life task and promotes inductive learning. Learning tasks are performed in a real or simulated task environment.

Modality principle. Replacing a written explanatory text and another source of visual information such as a diagram (unimodal) with a spoken explanatory text and a visual source of information (multimodal) has a positive effect on knowledge compilation and transfer.

Part-task practice. Additional exercises to train a particular routine aspect up to a very high level of automation through strengthening. Drill & practice computer-based training is a suitable medium for part-task practice.

Procedural information. Information that is relevant for learning the routine aspects of learning tasks through knowledge compilation. This information is typically presented during task performance by electronic performance support systems (EPSS).

Redundancy principle. Replacing multiple sources of information that are self-contained (i.e., they can be understood on their own) with one source of information has a positive effect on elaborative learning and transfer.

Self-explanation principle. Prompting learners to self-explain new information by asking them, for instance, to identify underlying principles has a positive effect on elaborative learning and transfer.

Self-pacing principle. Giving learners control over the pace of instruction, which may have the form of transient information (e.g. animation, video), has a positive effect on elaborative learning and transfer.

Sequencing principle. Sequencing learning tasks from simple to complex, instead of presenting them in their full complexity at once, has a positive effect on inductive learning and transfer.

Signaling principle. Focusing learners' attention on the critical aspects of learning tasks or presented information reduces visual search and has a positive effect on knowledge compilation and transfer.

Spatial split-attention principle. Replacing multiple sources of information (frequently pictures and accompanying text) with a single, integrated source of information has a positive effect on knowledge compilation and transfer.

Strengthening. A category of learning processes responsible for the fact that domain-specific schemata accumulate strength each time they are successfully applied. It is a form of advanced schema automation that is especially important for (over)learning on the basis of part-task practice with, for instance, drill & practice computer based training.

Supportive information. Information that is relevant for learning the problem-solving and reasoning aspects of learning tasks through elaboration and understanding. This information is typically presented before learners start to work on the learning tasks, by hypermedia that stress relations between pieces of knowledge.

Temporal split-attention principle. Presenting multiple sources of information (e.g., mutually referring pictures and text) at the same time, instead of one by one, has a positive effect on knowledge compilation and transfer.

Training wheels principle. Sequencing learning tasks in such a way that learners' performance is first constrained (i.e., unproductive actions are blocked), and then slowly loosening the constraints until none has a positive effect on inductive learning and transfer.

Variability principle. Organizing learning tasks in such a way that they differ from each other on dimensions that also differ in the real world has a positive effects on inductive learning and transfer.