The Four-Component Instructional Design Model:

Multimedia Principles in Environments for Complex Learning

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Abstract

The Four-Component Instructional Design (4C/ID) 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 in which instruction is controlled by the system, the learner, or both; 22 multimedia principles are related to each of the four components and instructional control. Students may work on *learning tasks* in computer-simulated task environments such as virtual reality environments, serious games and high-fidelity simulators, where relevant multimedia principles primarily facilitate a process of inductive learning; they may study, share and discuss *supportive information* in hypermedia, microworlds and social media, where principles facilitate a process of elaboration and mindful abstraction; they may consult *procedural information* using mobile apps, augmented reality environments and on-line help systems, where principles facilitate a process of knowledge compilation; and, finally, they may be involved in *part-task practice* with drill & practice computer-based/app-based training programs and part-task trainers, where principles facilitate a process of psychological strengthening. Instructional control can be realized by adaptive multimedia systems, but electronic development portfolios can be helpful when learners are given partial or full control. Research implications and limitations of the presented framework are discussed.

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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), Baddeley's working memory model with a central executive and two slave systems, the visuospatial sketchpad and the phonological loop (1992; 1997), and Cowan's model of attention and memory (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 cognitive theory of multimedia learning (2009), Sweller's cognitive load theory (Sweller, Ayres, & Kalyuga, 2011; Van Merriënboer & Sweller, 2005), and Schnotz's integrated model of text and picture comprehension (2005). 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, 1997; Van Merriënboer, Clark, & de Croock, 2002; Van Merriënboer, Jelsma, & Paas, 1992; Van Merriënboer & Kirschner, 2013; Van Merriënboer, Kirschner, & Kester, 2003), and to discuss how this theory can be 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 tasks that are based on real-life tasks as the driving force for learning and thus as 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, 2012). 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 environments that are built from the four components, how instructional control can be organized in these environments, and how different media can be used to implement each component and instructional control. Second, the relationship between the four components and the assumed cognitive architecture is explained. This section describes a limited working memory and a virtually unlimited long term memory as the main memory systems, schema construction and schema automation as the processes that lay the foundation for meaningful learning, and monitoring and control as self-regulated learning processes that make it possible to give instructional control to the learner. Third, educational media and 22 multimedia principles are related to each of the four components and instructional control. 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 preferably 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.

This section will first describe the four components and their interrelationships in more detail. Second, the issue of instructional control is discussed: Is it the learner or is it the teacher or another intelligent agent who selects the learning tasks to work on? Finally, suitable media for implementing each of the four components and instructional control will be briefly discussed.

Four Components

***** INSERT FIGURE 1 ABOUT HERE *****

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 description*: 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 summative assessment of students' performance.

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 solve a problem in the domain. 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 *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.

Instructional Control

The schematic overview of the four components in Figure 1 might suggest that the same sequence of learning tasks needs to be presented to all learners. However, this is not and need not necessarily be the case. Rather than offering one-and-the-same educational program to all learners, a unique educational program can be offered with each learner receiving his or her own sequence of learning tasks adapted to individual needs, progress and preferences. If such individualization takes place, the question is who should be responsible for the selection of learning tasks and associated components: An external intelligent agent such as a teacher or multimedia application, the learner, or both? With system control, the teacher or another intelligent agent assesses the learner’s performance on previous tasks and based upon this appraisal selects the next learning task for a student to work on. With learner control, the ‘self-directed learner’ assesses his or her own performance on previous tasks and selects the next learning task from a set of available tasks (Corbalan, Kester, & van Merriënboer, 2011). Whether it is the teacher or the learner who selects the tasks, the selected tasks should be at an appropriate level of complexity, provide an optimal level of support and/or guidance, and exhibit a sufficient level of variability.

Obviously, giving full control to learners will only be effective if they have well developed self-directed learning skills, that is, if they are able to assess their own performance and plan their own future learning activities. If the learner lacks these skills, one might decide to help the learner not only to develop the domain-specific skills the training program is aiming at, but also to develop these self-directed learning skills. This can be reached through *shared control*, where the learner and the intelligent agent work together to plan an optimal learning trajectory (Corbalan, Kester, & Van Merriënboer, 2006). The same design principles that apply to complex learning apply to learning self-directed learning skills, namely variability, increasing complexity and, above all, decreasing support and guidance in a process of scaffolding (Van Merriënboer & Sluijsmans, 2009). We call this *second-order scaffolding* because it does not pertain to the domain-specific complex skill that is taught, but to the self-directed learning skills superimposed on it. Basically, it involves a gradual transition from system control to learner control. For example, a multimedia application may first present the learner with suitable learning tasks to work on, then present the learner with increasingly larger sets of pre-selected learning tasks from which the learners makes a final selection, and finally leave it up to the learner to select her or his own tasks. As another example, a teacher may first have frequent coaching meetings with the learner to discuss progress and selection of new learning tasks, then gradually decrease the frequency of those meetings, and finally leave it up to the learner to schedule such meetings only if necessary. It is precisely this type of second-order scaffolding that is essential for the development self-directed learning skills (Van Merriënboer & Kirschner, 2013).

Four Components, Instructional Control and Media

The different functions that are fulfilled by the four components as well as the realization of instructional control require the use of different types of media (see Table 1). Suitable media for learning tasks must allow learners to work on those tasks and will usually take the form of computer-simulated task environments. A low-fidelity simulation may take the form of textual case descriptions presented in a web-based course; a moderate-fidelity simulation may take the form of lifelike simulated characters (avatars) that the learner can interact with in a virtual reality environment (e.g., Second Life), and a high-fidelity simulation may take the form of a full-fledged operating room where medical residents treat a computerized mannequin who reacts just like a real patient. Suitable media for supportive information are hypermedia, microworlds, and social media. Hypermedia may present domain models in a highly interactive way and illustrate problem-solving approaches by showing expert models on video or via animated lifelike avatars. Microworlds offer a highly interactive approach to learning about domain models because learners can change the settings of particular variables and study the effects of those changes on other variables (De Jong & Van Joolingen, 1998). Social media offer learners the opportunity to share and discuss supportive information and to provide or receive cognitive feedback. Suitable media for procedural information are mobile apps, augmented reality environments, on-line help systems, and pedagogical agents. Mobile apps (on smartphones or tables) are particularly useful for presenting small displays of how-to information that tell learners during real-life task performance what to do in order to perform the routine aspects of the task at hand correctly. In augmented reality these how-to instructions can even be projected over the real world. Online help systems and pedagogical agents may fulfill a similar role in a computer-based learning environment. Finally, suitable media for part-task practice are traditional drill-and-practice computer-based or app-based training programs and part-task trainers.

***** INSERT TABLE 1 ABOUT HERE *****

With regard to instructional control, individualization through system control requires adaptive multimedia systems. For example, many ‘intelligent tutoring systems’ contain an intelligent agent for selecting learning tasks that best fit the needs of individual learners (Nkambou, Bordeau, & Mizoguchi, 2010). But as indicated above, 4C/ID will more often realize individualization through shared control, where the responsibility for the selection of new learning tasks is gradually transferred from the adaptive system/teacher to the learner in a process of second-order scaffolding. As self-directed learning skills further develop, the learner gets increasingly more responsibility over the learning cycle (i.e., assessment, identify learning needs, select new learning tasks). Electronic development portfolios can keep track of all the tasks that have been performed by an individual learner and store assessment results for these tasks. They are a useful tool to support second-order scaffolding because both teachers and learners can use the information in the electronic development portfolio to reflect on progress, to identify learning needs and points of improvement, and to plan future learning (Kicken, Brand-Gruwel, Van Merriënboer, & Slot, 2009a).

Cognitive Architecture and Meaningful Learning

The 4C/ID-model assumes that all human knowledge is stored in cognitive schemas. It further supposes a cognitive architecture that is broadly accepted in the psychological literature and for which ample empirical support is available. This architecture is also assumed by cognitive load theory (Sweller, Ayres, & Kalyuga, 2011) and 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 schemas that vary in their degree of richness (i.e., number of elements and interconnections between those elements) and their level of automation. This section will first describe the memory systems distinguished in this architecture. Second, it will discuss learning processes that are related to the construction or reconstruction of schemas (i.e., induction and elaboration) and the automation of schemas (i.e., knowledge compilation and strengthening). Third, self-regulated learning processes that are directly relevant for instructional control will be briefly discussed.

Memory Systems

To begin with, all novel information must be processed in working memory to construct cognitive schemas 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, 1997). 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 schemas, *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 schemas, by combining elements consisting of lower-level schemas into higher-level schemas. These schemas organize and store knowledge, but also heavily reduce working memory load because even highly complex schemas 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 schemas, but also the automation of schemas 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 schemas; their consultation of procedural information, repeated performance of routine aspects of learning tasks, and drill on part-task practice helps them to *automate* schemas. 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 schemas by—often mindfully—abstracting away from concrete learning tasks (component 1), and elaboration, which refers to the construction of schemas 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 schemas (see Holland, Holyoak, Nisbett, & Thagard, 1989). When learners generalize or abstract away from well-designed learning tasks, they construct schemas 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 learners who are working in either a real or simulated task environment (also called ‘mindful abstraction’; Perkins & Salomon, 1989).

The *elaboration* of new supportive information refers to those cognitive activities that integrate new information with cognitive schemas 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 schemas that may provide a cognitive structure for understanding the information in general terms, and for concrete schemas or cases that may provide a useful analogy. These schemas are connected to the new information, and elements from the retrieved schemas 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 that is presented to them in books, lectures, hypermedia, microworlds or social media.

With regard to schema automation, a distinction is made between knowledge compilation, which refers to the preliminary automation of schemas 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 schemas that directly steer behavior, that is, evoke particular actions under particular conditions. How-to instructions that are provided by an instructor, mobile app, augmented reality, on-line help system or pedagogical agent may be used to yield an initial solution, and compilation is the process that creates highly specific schemas 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 schemas, 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 schemas accumulate strength each time they are successfully applied. The improvement that results from strengthening requires long periods of 'overtraining' (Palmeri, 1999) in part-task trainers or with drill-and-practice computer-based or app-based training programs.

Self-Regulated Learning

Instructional control can only be safely given to learners when they have well-developed self-directed learning skills. Otherwise, system control is the preferred approach or, alternatively, shared control may gradually transfer the responsibility over the learning cycle from the system to the learner (i.e., second-order scaffolding) so that the learner can develop self-directed learning skills. In the cognitive architecture, self-directed learning skills are closely related to *self-regulated learning*. Important sub processes in self-regulated learning are monitoring and control: Monitoring is the term used to refer to the thoughts learners have about their own cognition, and based on these metacognitive thoughts learners respond to the environment or adapt their behavior, which is termed control (Zimmerman & Schunk, 2001). Self-regulated learning can be studied at the level of distinct information elements (e.g., Do I understand this concept? Do I need to study it again?), topics or tasks (e.g., Do I comprehend this topic? Do I need to restudy particular pieces of this text?), and sequences of tasks (e.g., Am I making sufficient progress? Which tasks can help me to improve my performance?). The 4C/ID-model emphasizes the development of self-regulated learning skills at the task-sequence level (i.e., self-directed learning), because choice over own learning trajectories is becoming increasingly important in many educational settings. Then, learners must –learn to– monitor how well they performed on one or more learning tasks after completion (referred to as *self-assessment* to distinguish it from monitoring during task performance), and they must –learn to– control their future learning by selecting suitable new tasks. Adaptive multimedia systems which make, for example, a pre-selection of suitable tasks and electronic development portfolios which gather assessment results and keep track of learner progress can support the development of these self-directed learning skills.

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

As discussed in the previous sections, 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 (cf. Table 2). In addition, the way instructional control is realized has also implications for the use of multimedia systems and multimedia principles. These media and principles are discussed in the next sections.

Learning Tasks and Learning in Computer-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, such as a virtual reality (VR) environment, a serious game, or a high-fidelity simulator. According to the 4C/ID-model, the multimedia application must offer the learner the opportunity to perform learning tasks that are somehow based on real-life tasks, but the fidelity can range from low (e.g., working on authentic cases in a web-based course) to very high (virtual reality technologies with VR-helmets and data gloves). Table 2 summarizes the main multimedia principles (1-6) that should be taken into account in computer-simulated task environments and provides for each principle an example of how it could be applied.

***** INSERT TABLE 2 ABOUT HERE *****

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 the ‘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, for example, Devolder, Pynoo, Voet, Adang, Vercruysse, & Duyck, 2009).

Several studies confirm the sequencing principle (e.g., Clarke, Ayres & Sweller, 2005; Limniou & Whitehead, 2010; Musallam, 2010; Mayer, Mathias, & Wetzell, 2002; Pollock, Chandler, & Sweller, 2002). A study of Ayres (2006), however, indicates that the pretraining effect might only occur when learners master the pretraining content to a sufficient degree before moving on to a more complex task. Kester, Kirschner, and Van Merriënboer (2004a; 2004b; 2005) 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).

Physical-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 the opportunity to perform the tasks, with no attempts to mimic the real task environment (i.e., low fidelity). The physical-fidelity principle indicates that for novice learners, a high fidelity task environment often contains irrelevant details that may deteriorate learning (e.g., Fulgham, 2008; Gulikers, Bastiaens, & Martens, 2005; Scheiter, Gerjets, Huk, Imhof, & Kammerer, 2009).

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 task environment (see also Maran & Glavin, 2003).

Training-wheels principle. Even performing relatively easy learning tasks in a low-fidelity environment is difficult for novice learners, because they are still ‘whole’ tasks that require the coordination of many different constituent skills. A way to support these 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 or functional-fidelity 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. A study of Mulder, Lazonder, and de Jong (2011) in the same domain also confirmed the training-wheels principle. They compared two types of model progression to a control condition in an inquiry learning environment and found that model progression enhanced task 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. Moreover, studies in user-interface design found suboptimal results for training-wheels interfaces (e.g., Bannert, 2000; Schimpf & Spannagel, 2011; Spannagel, Girwidz, Löthe, Zendler, & Schroeder, 2008). This indicates that the effectiveness of a training-wheels approach strongly depends on how it is designed.

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.

Variability principle. The variability principle indicates that learning tasks must be sufficiently different from each other to allow for the construction of general, abstract schemas 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; Corbalan, Kester & Van Merriënboer, 2009). Predominantly positive results are also found for contextual interference, which is a special type of variability referring to the way in which differences between tasks are divided across acquisition tasks (e.g., de Croock & Van Merriënboer, 2007; de Croock, Van Merriënboer & Paas, 1998; Helsdingen, Van Gog, & Van Merriënboer, 2011a, 2011b; Olina, Reiser, Huang, Lim, & Park, 2006; Van Merriënboer, Schuurman, de Croock, & Paas, 2002). Low contextual interference is produced by a blocked practice schedule, in which the skills necessary for performing one type of task (e.g., diagnosing one particular type of error) are practised before continuing to another type of task (e.g., AAA, BBB, CCC, …). High contextual interference is produced by a random practice schedule, in which different types of tasks are sequenced in a random order (e.g., CABBCABAC...). High contextual interference prohibits a quick and smooth mastery of the skills being trained, but potentially yields higher transfer test performance because learners are promoted to construct general cognitive schemas.

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. 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).

Collaboration principle. According to the collaboration principle complex learning tasks should preferably be assigned to groups instead of individuals. Due to limitations of working memory capacity these complex tasks readily exceed an individual's capacity while groups can share the task-load. This allows the individuals in a group to achieve higher learning outcomes (Kirschner, Paas, & Kirschner, 2009).

The collaboration principle has been confirmed in several studies. Kirschner, Paas, Kirschner, and Janssen (2011) compared the learning outcomes of individuals who studied worked examples (i.e., a low load activity) or solved problems (i.e., a high load activity) either alone or in a group. They found that individuals learned better from worked examples while the individuals in a group learned better from problem solving. Johnson, Archibald, and Tenenbaum (2010) investigated a social annotation tool in English classes and showed that learners who used this tool in small teams achieved a higher reading comprehension and meta-cognitive skill acquisition than learners who used this tool individually. Weinberger, Stegmann, and Fischer (2010) found an advantage for learners in scripted groups over both learners in non-scripted groups and individual learners in learning to argue.

In the 4C/ID-model, the collaboration principle can be incorporated in the design of learning tasks. If learning tasks are complex, they can be assigned to groups (e.g., project work) instead of individuals because the task-load is then shared amongst group members. Well-organized groups can provide both first-order scaffolding that helps learners to acquire the domain-specific skills, and second-order scaffolding that helps them to develop the self-regulated and self-directed learning skills that our present and future society require.

Completion-strategy principle. The completion strategy (Van Merriënboer, 1990; Van Merriënboer & de Croock, 1992) or fading-guidance strategy (Renkl, Atkinson, & Grosse, 2004) 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 than from solving the equivalent problems (for an overview, see Atkinson, Derry, Renkl, & Wortham, 2000). In addition, performing completion tasks that require learners to complete partial solutions enhances learning as compared to solving the equivalent conventional problems (for an overview, see Sweller, Van Merriënboer, & Paas, 1998). Moreover, the completion strategy proved to be very effective in facilitating transfer of learning (Renkl & Atkinson, 2003; Renkl, Atkinson, & Grosse, 2004; Schwonke, Renkl, Krieg, Wittwer, Aleven, & Salden, 2009).

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 be 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 in Hypermedia, Microworlds and Social Media

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, microworlds and social media may take over—part of—those functions. Hypermedia 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. Microworlds offer learners the opportunity to experiment in a domain and discover the principles that apply in this domain. Social media offer the opportunity to share and discuss supportive information with other learners and experts. As indicated before, it is critical that students elaborate and deeply process the supportive information; it is thus of utmost importance to provoke deep processing through asking questions, stimulating reflection, and promoting discussion. Principles 7-13 in Table 2 summarize the main multimedia principles that should be taken into account in hypermedia systems, microworlds and social media and provide illustrations of their application.

Prior knowledge activation principle. The prior knowledge activation (PKA) principle holds that subsequent learning is enhanced when prior knowledge is activated beforehand. PKA facilitates elaboration based on prior knowledge, which enhances the integration of new knowledge into the existing knowledge base. This enhances recall and comprehension of the new knowledge by making it more accessible (De Grave, Schmidt, & Boshuizen, 2001).

Different PKA strategies have proven to be effective, for example, problem analysis (e.g., De Grave et al., 2001; Schmidt, de Volder, de Grave, Moust, & Patel, 1989), perspective taking (e.g., Anderson, Pichert, & Shirey, 1983; Goetz, Schallert, Reynolds, & Radin, 1983), mobilisation (e.g., Machiel-Bongaerts, Schmidt, & Boshuizen, 1993, 1995) and concept mapping (Gurlitt, Dummel, Schuster, & Nückles, 2012; Gurlitt, Renkl, Motes, & Hauser, 2006; Gurlitt &

Renkl, 2008). In addition, next to verbal instructions, static or dynamic pictorial representations can be used for PKA. Wetzels (2009) showed that the effectiveness of pictures, animations, and verbal representations is mediated by the learner's prior knowledge. Pictures become more beneficial than animations as prior knowledge increases. Since mentally animating static pictures results in more constructive prior knowledge activation than viewing animations, however, learners need sufficient prior knowledge to engage in such mental animation.

All instructional methods for supportive information presentation provided by the 4C/ID model are directed at elaboration, that is, establishing meaningful relations between new information and prior knowledge. In addition, the 4C/ID model advocates an inductive strategy for information presentation which incorporates the prior knowledge activation principle. An inductive information presentation strategy works from concrete illustrations or examples, which aim to activate relevant prior knowledge, toward the general and abstract information.

Multimedia principle. The multimedia principle states that learning is improved when text and pictures are presented as compared to text alone. It is argued that pictures and text evoke different cognitive processes that result in a rich mental representation of the learning content which aids retention and comprehension (Mayer, 2009).

The multimedia principle is well-researched and confirmed (Mayer, 2009). Nevertheless, research also shows that its effectiveness is dependent on factors like: the learning content (e.g., De Westelinck, Valcke, De Craene, & Kirschner, 2005; Corradi, Elen, & Clarebout, 2012); the type of pictures (e.g., Sung & Mayer, 2012); the type of task (e.g., Van Genuchten, Scheiter, & Schüler, 2012), and so forth. Therefore sometimes adding pictures to text does not improve learning and the presentation of text alone is more efficient (Rasch & Schnotz, 2009).

The 4C/ID model subscribes the importance of the multimedia principle for schema construction and elaboration and therefore, the supportive information is preferably presented in a multimedia format.

Dynamic visualizations principle. Dynamic visualizations (e.g., animations, video) of processes and mechanisms that change over time can, under particular conditions, have a positive effect on elaborative learning and transfer (Ainsworth & VanLabeke, 2004), especially when they are designed in accordance with other multimedia principles (Plass, Homer, & Hayward, 2009) and/or deal with human movement (Imhof, Scheiter, Edelmann, & Gerjets, 2012).

An important factor that mediates the effects of dynamic visualizations on learning is prior knowledge. Kalyuga (2008) compared the learning of low prior-knowledge learners and high prior-knowledge learners for both static and dynamic visualizations. He found an 'expertise reversal effect' (Kalyuga, Ayres, & Chandler, 2003; Kalyuga, Chandler, & Sweller, 2000), indicating that low prior-knowledge learners learned more from static visualizations while high prior-knowledge learners learned better with dynamic visualizations. Schnotz and Rasch (2005) found similar results. Eye-tracking techniques (e.g., Jarodzka, Scheiter, Gerjets, & Van Gog, 2010) and thinking-aloud protocols (e.g., Kühl, Scheiter, Gerjets, & Gemballa, 2011) are used to gain more insight in the conditions under which dynamic visualization enhance learning.

In the 4C/ID-model, the dynamic visualizations principle will primarily apply to the presentation of modelling examples that are part of the supportive information (e.g., a video demonstration showing an expert who models task performance). The dynamic visualization principle seems to be especially important when an expert models locomotor behavior.

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.

Several studies found evidence for the redundancy effect. For example, Lee and Kalyuga (2011) used concurrent visual presentations of characters and pinyin (a phonetic system), as well as their auditory pronunciations to learn Chinese and found that this hampered learning for more experienced learners. Moussa-Inaty, Ayres, and Sweller (2012) found a deteriorating effect on learning English listening skills of simultaneously reading and listening to the same spoken material, and Liu, Lin, Tsai, and Paas (2012) presented text with pictures on a mobile device together with real objects outside the device and found that this hindered learning. Mayer and Johnson (2008; see also Moreno & Mayer, 2002), however, showed that in some cases redundant information enhances learning. They included brief redundant information in narrated slides to direct learners' attention to important information without causing extraneous load and this improved learning.

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.

Coherence principle. According to the coherence principle, there is better retention and transfer when 'seductive details' such as background music and non-essential video clips are excluded from a training program (see for a review and meta-analysis, Rey, 2012). Although more research is necessary to fully explain the coherence principle, the principle itself is very robust (Rey, 2012). Nevertheless, factors such as time pressure in the learning or test phase, the type of seductive details, cognitive load imposed by the learning material, and the learning domain, can influence the extent to which the seductive details negatively affect learning (Rey, 2012).

In instruction designed according to the 4C/ID model, the coherence principle is of importance for the development of hypermedia and social media environments used to deliver the supportive information. Such environments should be free of seductive details and help the learner to focus on the relevant information.

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. Research shows, however, that self-explanation enhances learning from multimedia content as well (e.g., Berthold, Eysenck, & Renkl, 2009; Cho & Jonassen, 2012; Johnson & Mayer, 2010). In any event, the effectiveness of self-explanation prompts is depending on the learners' prior knowledge (e.g., Leppink, Broers, Imbos, Van der Vleuten, & Berger, 2012; Roelle & Berthold, in press; Yeh, Chen, Hung, & Hwang, 2010) and on the type of prompt, for instance, gap-filling self-explanation prompts lead to higher learning outcomes than model-revision self-explanation prompts (Nokes, Hausmann, VanLehn, & Gershman, 2011).

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. 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. Höffler and Schwartz (2011) found that self-pacing fostered learning from animations while system-pacing enhanced learning from static pictures. Hatsidimitris and Kalyuga (2013) showed that adding a timeline scrollbar to an animation facilitated retention and comprehension for domain novices but not for more experienced learners.

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 Learning from Mobile Apps and On-Line Help

Procedural information primarily aims at schema automation through knowledge compilation. The traditional media for procedural information are the teacher and all kinds of job aids 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 quickly taken over by mobile apps (on smartphones or tablets), augmented reality environments, on-line help systems and pedagogical agents. Such systems provide procedural information on request of the learner (e.g., mobile apps, on-line help) or on their own initiative. For example, in an augmented reality environment 'how-to' instructions and prerequisites can be projected when the learner is looking at a particular display or control in the real environment, or a pedagogical agent can give unsolicited advice precisely when students need it for their work on the learning tasks. Table 2 summarizes the main multimedia principles (14-18) that should be taken into account in mobile apps, augmented reality, on-line help systems and pedagogical agents and provides some examples of how they can be applied.

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 (Leahy, Chandler, & Sweller, 2003).

The modality principle is supported by a meta-analysis of Ginns (2005). This study also showed that the higher the complexity (i.e., element interactivity) of the learning material, the stronger the modality effect. In addition, a stronger modality effect is observable with system-paced instruction as compared to learner-paced instruction. More empirical support for the modality principle is found by Schmidt-Weigand, Kohnert, and Glowalla (2010) and Kühl, Scheiter, Gerjets, and Edelmann (2011). A study of Seufert, Schütze, and Brünken (2009) indicated a stronger modality effect for low-prior knowledge than for high-prior knowledge learners.

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, at least, when the learning task contains visual elements. If the learning task contains no visual elements (e.g., playing a musical instrument), it might be better to provide visual just-in-time instructions (cf. the conductor of an orchestra).

Temporal split-attention principle. The temporal split-attention principle (or temporal contiguity principle; Mayer & Moreno, 2003) 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. This principle is strongly supported by a meta-analysis of Ginns (2006). Especially for complex learning material, it is better to present mutually referring information sources concurrently.

According to 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 (cf. contingent tutoring). 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 (2004a; see also Kester, Kirschner, & Van Merriënboer, 2004b) 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 (or the spatial contiguity principle; 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 (for a meta-analysis, see Ginns, 2006). Eye-tracking studies seem to indicate that a split-attention information presentation format hampers learning because learners tend to neglect the visualizations (e.g., pictures, animations) in favour of processing the accompanying text (Johnson & Mayer, 2012; Schmidt-Weigand et al., 2010). Integrated information presentation formats, in contrast, stimulate learners to further integrate both information sources (Johnson & Mayer, 2012).

In the context of the 4C/ID-model, Kester, Kirschner and Van Merriënboer (2005) 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. 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 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.

Research shows that signaling enhances learners' appreciation of the learning material (Sung & Mayer, 2012) and their learning (e.g., Mautone & Mayer, 2001; Tabbers, Martens, & Van Merriënboer, 2004). Relatively new techniques such as eye-tracking can be used to enhance the effectiveness of signaling. Boucheix, Lowe, Putri, and Groff (2013) used eye tracking to study to what extent the learners obeyed the signaling while Van Gog, Jarodzka, Scheiter, Gerjets, and Paas (2009), and Jarodzka, Van Gog, Dorr, Scheiter, and Gerjets (2013) integrated an expert's eye movements in modeling examples to direct learner's attention to important parts of the example with positive effects on learning. .

The 4C/ID-model holds that 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.

Segmentation principle. The segmentation principle holds that splitting up a dynamic visualization (animation, video etc.) in meaningful parts or segments has a positive effect on learning and transfer. Both the pauses that arise when segmenting dynamic visualizations and the cues that can be derived from the meaningful chunks that are formed seem to cause the beneficial effects of segmentation (Spanjers, Van Gog, Wouters, & Van Merriënboer, 2012). Furthermore, segmentation prevents that learners experience a too high cognitive load while processing the transient information conveyed by the dynamic visualisation. Therefore, segmentation is particularly useful for low prior-knowledge learners (e.g., Khacharem, Spanjers, Zoudji, Kalyuga, & Ripoll, 2012; Spanjers, Wouters, Van Gog, & Van Merriënboer, 2011) and might be most effective when the learners themselves exert control over it (Hassanabadi, Robatjazi, & Savoji, 2011).

The 4C/ID model uses the segmentation principle for just-in-time information presentation. How-to instructions or demonstrations to help learners perform routine aspects of tasks need to be presented step-by-step in meaningful chunks. This will help to prevent learners get cognitively overloaded by this transient information which hampers knowledge compilation.

Part-task Practice in Drill & Practice Computer Based or App 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 still a successful type of educational software, and many of these programs now also become available through mobile apps. For the training of perceptual motor skills, part-task trainers fulfill the same function. The computer is sometimes abused for its use of drill, but most critiques seem to miss the point. They contrast drill & practice 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 2 gives an example of the application of the component fluency principle (19), that is, the most important multimedia principle in drill & practice programs and part-task trainers.

Component-fluency principle. The component-fluency principle indicates that drill and practice on one or more routine aspects of a task (i.e., part-task practice) 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’. This is confirmed in a meta-analysis of Wickens, Hutchins, Carolan, and Cumming (2013) who found that part-task practice generally produces negative transfer when the parts need to be performed concurrently in the whole task but not when they need to be performed in sequence. Part-task practice within the context of the whole task (i.e., variable-priority training of the whole task), in contrast, is a successful technique.

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.

Instructional Control by Adaptive Systems and Electronic Development Portfolios

Instructional control aims to set an optimal learning trajectory for each learner. In the 4C/ID model it mainly relates to the selection of new learning tasks, although instructional control can also be varied for the other three components (see Van Merriënboer & Kirschner, 2013). Traditionally, instructional control is with the teacher, who can either give all learners the same learning tasks or assess individual learners in order to give them their own, individualized sequence of learning tasks, or with the learner, who is then acting as a self-directed learner and selecting his or her own learning tasks. When learners and teachers discuss learner progress and make decisions on future learning in, for example, coaching meetings, portfolios or other documents with assessment and progress results can inform these decisions. In multimedia learning environments, the function of the teacher as assessor and selector of new learning tasks can be taken over by adaptive systems or intelligent tutoring systems. Then, it is the system that keeps track of learner progress and selects new tasks. A drawback of this approach, however, is that the learner does not have the opportunity to develop self-directed learning skills. Electronic development portfolios can help to share control between teachers and learners and facilitate the development of self-directed learning skills such as self-assessing performance, identifying own learning needs, and selecting tasks that fulfil these needs. Table 2 summarizes the main multimedia principles (20-22) that should be taken into account in adaptive multimedia systems and electronic development portfolios.

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 (Corbalan, Kester, & Van Merriënboer, 2008; Salden, Paas, & Van Merriënboer, 2006). 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, 2005; 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.

Second-order scaffolding principle. The second-order scaffolding principle refers to a gradual shift from system control to learner control (i.e., *shared control*; Corbalan et al., 2008), where the learner receives increasing responsibility over the assessment of learning and the selection of new tasks, which has a positive effect on the development of self-directed learning skills (Van Merriënboer & Kirschner, 2013). Scaffolding is currently seen as a combination of learner support and guidance and the fading of that support and guidance, as in a scaffold that supports the construction of a new building and that is slowly taken away as the building nears completion. Because irrelevant, ineffective, excessive, or insufficient support and guidance can hamper the learning process (by adding extraneous cognitive load to the learner), it is critical to determine the right type and amount of learner support and guidance needed and to fade it at the appropriate time and rate (Taminiau, 2013). In the 4C/ID-model, second-order scaffolding is used the help learners develop self-directed learning skills. For example, learners may first receive learning tasks that are adapted to their individual needs; then receive advice on how to select these tasks from a small set of preselected suitable tasks, and finally independently select new tasks from all available tasks.

Development portfolio principle. Electronic development portfolios help learners and their coaches to assess learning and to select suitable learning tasks and they may have a positive effect on the development of both domain-specific and self-directed learning skills. Electronic development portfolios (Kicken, Brand-Gruwel, Van Merriënboer, & Slot, 2009a, 2009b; Van Merriënboer & Van der Vleuten, 2012) take over administrative duties and computational tasks to provide overviews and summaries, detect conflicts between different assessors, give vertical and horizontal assessments (i.e., in order, on one aspect of performance or overall performance), and so forth. They include scoring rubrics that allow an assessor (or the learner) to assess the learner's (or their own) performance on one or more learning tasks. To improve the informative value of the portfolio, scoring rubrics need not be limited to quantitative ratings of particular aspects of performance, but may also include narrative reports which might be given by the assessor in a separate text box, or multimedia information, including spoken messages, photographs, and video fragments uploaded into the portfolio. The same development portfolio with the same scoring rubrics and thus the same standards should be used throughout the curriculum so that the learner is confronted with all relevant standards from the start of the educational program. The portfolio should be discussed in regular coaching meetings. The main aim of such meetings is to reflect on the work on previous learning tasks and identify future opportunities for performance improvement. In the 4C/ID-model, development portfolios in combination with coaching meetings are used when a high level of learner control is provided and the learners need to develop self-directed learning skills.

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 environments are typically build around a computer-simulated task environment (e.g., serious game, virtual reality environment, high-fidelity simulator) that offers the opportunity to perform learning tasks (component 1). They may further make use of hypermedia, microworlds and social media that allow learners to actively study, share and discuss supportive information (component 2); mobile apps, augmented reality, on-line help systems and pedagogical agents providing procedural information specifying how to perform routine aspects of complex tasks (component 3) and, finally, drill & practice computer-based or app-based programs or part-task trainers 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).

In addition, learning environments based on 4C/ID allow for three different types of instructional control. If system control is applied, adaptive multimedia systems may take over instructional control from the teacher and select learning tasks that best fit the needs of each individual learner. If learner control is applied, an electronic development portfolio may inform learners and, if desired, their coaches on assessment results and learner progress and so help them to plan future learning trajectories. If shared control is applied, second-order scaffolding ensures that the control is gradually moving from system control to learner control, so that the learner can develop self-directed learning skills. Each of the four components and the realization of instructional control 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 and curriculum 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 as well as self-regulated learning processes have all 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 –self-regulated– 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 and instructional control, including related multimedia principles (cf. Table 2). At least, the 4C/ID-model points out to designers under which conditions, and for which aspects 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 and for the realization of instructional control, this does not imply that particular principles cannot be important for other blueprint components.

For instance, the physical-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 is not exclusively useful for the design of learning tasks, but may also be applied to gradually relax performance constraints during part-task practice. 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, and sometimes try to develop self-directed learning skills, 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 and curriculum design level, where either adaptive or non-adaptive computer-simulated task environments (VR, serious games, high-fidelity simulators), hypermedia, microworlds, social media, mobile apps, augmented reality, on-line help systems, drill & practice computer-based and app-based programs, part-task trainers, and electronic development portfolios should seamlessly link up with each other. 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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Table 1

Multimedia for Realizing Each of the Four Components and Instructional Control

Components and Instructional Control	Aim of Related Media	Example Media
Learning tasks	Provide the learner an environment to work on the learning tasks.	Computer-simulated task environments, high-fidelity simulators, virtual reality environments, serious games
Supportive information	Provide information on the domain and SAPs; provide cognitive feedback.	Hypermedia (e.g., Internet), microworlds, social media (e.g., Facebook)
Procedural information	Provide how-to instructions and prerequisites; provide corrective feedback.	Mobile apps, augmented reality environments, on-line help systems, pedagogical agents
Part-task practice	Provide additional practice for routine aspects of learning tasks.	Drill & practice computer-based/app-based training, part-task trainers
Instructional control	Assess learner performance and keep track of progress in order to select suitable future learning tasks.	Adaptive multimedia systems, electronic development portfolios

Table 2

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

Multimedia Principle	Example
Learning Tasks: Computer-Simulated Task Environments, Virtual Reality, Serious Games and High-Fidelity Simulators	
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. Physical-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. 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.

4. 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.
5.Collaboration principle	For medical students who are confronted with a complex health problem which requires a multidisciplinary approach for reaching an acceptable solution it is better to work in a small group instead of alone.
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 re-design blueprints for the renovation of buildings, and finally let them design blueprints for new buildings.
Supportive Information: Hypermedia, Microworlds and Social Media	
7. Prior knowledge principle	For physiotherapy students who need to learn about blood circulation, first present them a picture of the heart and ask them to bring to mind everything they know about the anatomy and functioning of the heart.
8. Multimedia principle	For students who need to learn how lightning develops, present pictures or an animation on how lighting develops together with an explanatory text or narration.

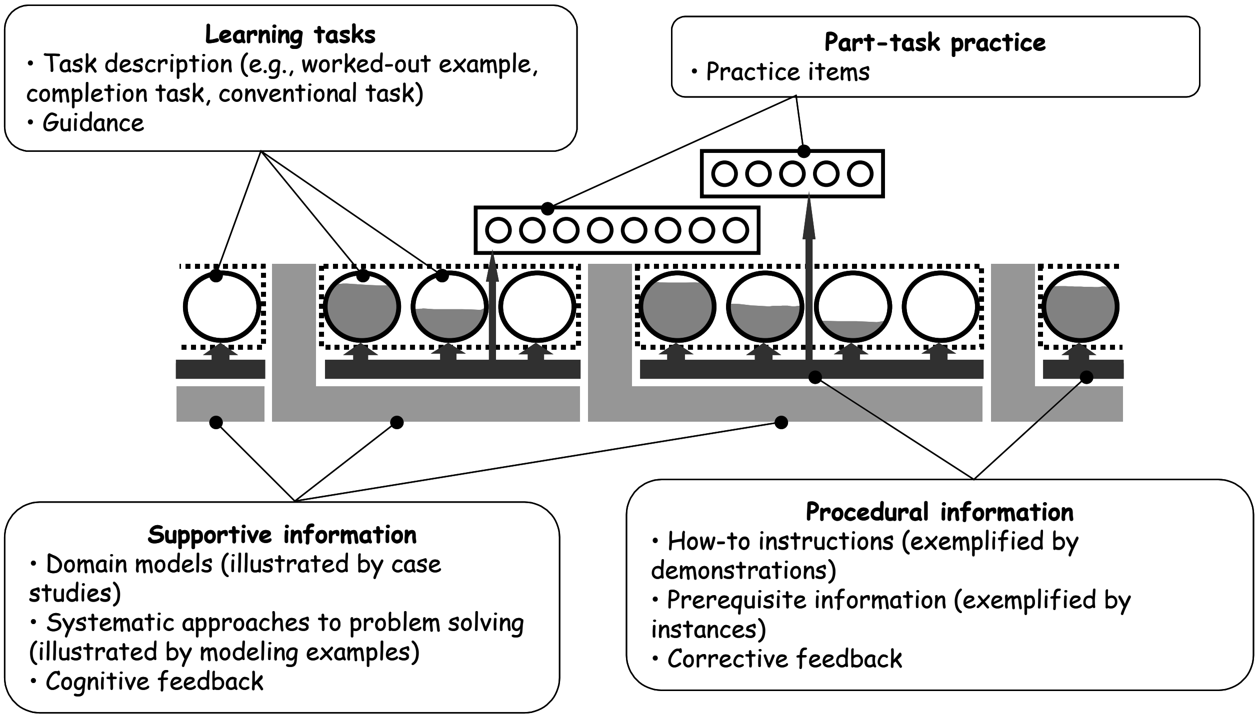
9. Dynamic visualizations principle	For biology students who need to learn about fish locomotion patterns, present videos or animations that show swimming fish.
10. Redundancy principle	For students in econometrics who learn to explain periods of economic growth, first present a qualitative model (allows 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.
11. Coherence principle	For history students who need to learn about the Second World War in a hypermedia environment, only present relevant learning material without, for example, music to dramatize the instructional message or irrelevant pictures to soften it.
12. 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 underlying mechanism to themselves or to their peers.
13. 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: Mobile Apps, Augmented Reality, On-line Help Systems and Pedagogical Agents	
14. 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
15. 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.
16. 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.
17. 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.
18. Segmentation principle	For cooks in training who need to specialize in molecular cooking, present the instruction video on how to make, for example, a 'golden christmas tiramisu' in meaningful cuts.

Part-task Practice: Drill & Practice Computer-Based/App-Based Training and Part-Task Trainers	
19. 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.
Instructional Control: Adaptive Systems and Electronic Development Portfolios	
20. 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 (adaptation).
21. Second-order scaffolding principle	For biology students who need to learn the inheritance rules of Mendel as well as self-directed learning skills, first present them with suitable learning tasks (system control), then present them with a subset of suitable learning tasks to choose from (shared control), and, finally, present them the complete task database to choose their own tasks from (learner control).
22. Development portfolio principle	For students in hairdressing in an on-demand learning environment, collect information on their progress in an electronic development portfolio and use this portfolio to assess their progress and give advice on their future learning trajectory.

Figure Caption

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


Learning tasks
• Task description (e.g., worked-out example, completion task, conventional task)
• Guidance
Part-task practice
• Practice items
Supportive information
• Domain models (illustrated by case studies)
• Systematic approaches to problem solving (illustrated by modeling examples)
• Cognitive feedback
Procedural information
• How-to instructions (exemplified by demonstrations)
• Prerequisite information (exemplified by instances)
• Corrective feedback

Glossary

Adaptive multimedia system. In the context of 4C/ID, a system that assesses and keeps track of learner progress in order to select learning tasks in such a way that their difficulty, level of support and guidance, and available real-world features are optimized to the needs of the individual learner.

Augmented reality environment. An environment generating a composite view that is a combination of the real scene viewed by the learner and additional information generated by the computer. It is very suitable for the just-in-time presentation of procedural information.

Coherence principle. Excluding all irrelevant but sometimes seductive details (e.g., music, embellishments) that are extraneous to learning has a positive effect on elaborative learning and transfer.

Collaboration principle. Working in a team or group, rather than individually, has a positive effect on inductive learning and transfer when learning tasks are highly complex.

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.

Computer-simulated task environment. A computer-based task environment which enables learners to perform learning tasks. Examples are virtual reality environments (e.g., Second Life), serious games and high-fidelity simulators.

Development portfolio principle. An electronic development portfolio helps learners and their coaches to keep track of progress and select suitable learning tasks; it has a positive effect on the development of both domain-specific and self-directed learning skills.

Drill & practice computer-based/app-based training. Applications that provide part-task practice and allow a learner to practice routine aspects of a task (e.g., multiplication tables, spelling rules, dexterity) up to a very high level of automaticity.

Dynamic-visualizations principle. Dynamic visualizations (e.g., animations, video) of processes and mechanisms that change over time can, under particular conditions, have a positive effect on elaborative learning and transfer, especially when they are designed in accordance with other multimedia principles and/or deal with human movement.

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 example, hypermedia or serious games.

Electronic development portfolio. An assessment instrument used to gather assessment results over time. It provides information on learner progress and may be used by both teachers and learners to identify learning needs and select suitable new learning tasks.

High-fidelity simulator. A simulation of a task environment that not only behaves like the real task environment but also looks, feels and smells like the real environment.

Hypermedia. Computer-based media (text, images, videos, animations etc.) that can be navigated through clicking hyperlinks. It is an extension of hypertext. The Internet can be seen as a giant hypermedia system.

Individualization principle. Adapting the contents, difficulty and 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 computer-simulated task environments.

Instructional control. Control over the sequence of instruction, e.g., the specific learning tasks the learner will be working on. A distinction can be made between system control, learner control and shared control.

Knowledge compilation. A category of learning processes by which learners embed new information in highly domain-specific schemas that directly steer behavior. It is a form of schema automation that is especially important for learning procedural information from, for instance, mobile apps and online help systems.

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.

Microworld. A simulation of a conceptual domain that offers a highly interactive approach to the presentation of supportive information because learners can change the settings of particular variables and study the effects of those changes on other variables.

Mobile apps. A type of application software designed to run on a mobile device, such as a smartphone or tablet computer. They are very suitable to present procedural information during task performance.

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.

Multimedia principle. Adding graphics to words or, inversely, adding words to graphics has a positive effect on elaborative learning and transfer because students learn better from words and pictures than from words/pictures alone.

On-line help systems. Systems that provide immediate on-screen instructions on request of the learner. They are very suitable to present procedural information during task performance.

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/app-based training is a suitable medium for part-task practice.

Part-task trainer. A device that permits selected routine aspects of a task to be practiced independently of other aspects of the whole task. As the name indicates, it is suitable for part-task practice.

Pedagogical agents. Intelligent agents that support human learning by interacting with learners in computer-based learning environments. They are particularly useful for presenting procedural information but can also give advice on other aspects of learning.

Physical-fidelity principle. Sequencing learning tasks in such a way that they are first performed in an environment that does not try to 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.

Prior-knowledge principle. The activation of prior knowledge through individual or collaborative brainstorm or discussion has positive effects on elaborative learning and transfer.

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 mobile apps or on-line help systems.

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.

Second-order scaffolding principle. A gradual shift from system control to learner control (i.e., through shared control), where the learner receives increasingly more responsibility over the assessment of learning and the selection of new tasks, has a positive effect on the development of self-directed learning skills.

Segmentation principle. Splitting up an explanatory dynamic visualization (animation, video demonstration etc.) in meaningful parts or segments has a positive effect on knowledge compilation 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.

Self-regulated learning. Learning that is guided by the learner's thinking about own learning processes; accurate monitoring/self-assessment and control over future learning activities enable a process of self-directed learning.

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.

Serious games. Computer-simulated task environments that include gaming elements and so make it more appealing for learners to work on learning tasks.

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.

Social media. Internet-based applications that allow for the creation, sharing and discussion of user-generated content (e.g., Facebook, Wikipedia, YouTube). They are useful to share and discuss supportive information.

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 schemas 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 effect on inductive learning and transfer.

Virtual reality environment. A computer-simulated task environment that simulates the learner's presence in places in the real world (e.g., military simulation of an actual scene of battle) or in places in an imaginary world (e.g., Second Life). They enable learners to work on learning tasks.