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Teaching Complex Rather Than Simple Tasks: Balancing Intrinsic and Germane Load to Enhance Transfer of Learning

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SUMMARY

Research indicates that effective instructional methods for practicing simple tasks differ from effective methods for complex tasks. But unfortunately, load-reducing methods that work relatively well to reach high retention performance for complex tasks, such as low variability and complete guidance and feedback, are precisely those methods that hinder *transfer* of learning. This article presents a training design approach aimed at high transfer performance for complex tasks. The basic idea is that learning tasks should always be combined with methods that induce *germane* cognitive load, such as high variability and limited guidance or feedback. However, especially for novices, this can only be realised by decreasing *intrinsic* load early in training by manipulating the element interactivity of the learning tasks. Copyright © 2006 John Wiley & Sons, Ltd.

Recent instructional theories and practical educational approaches more and more stress on the use of complex 'real-life' tasks, which are expected to help learners to integrate the knowledge, skills and attitudes necessary for effective task performance in professional or daily life (Merrill, 2002). In contrast to simple tasks, such complex tasks have many different solutions, are ecologically valid, cannot be mastered in a single session and pose a very high load on the learner's cognitive system.

The main question of this article is: What are the implications of switching from simple tasks to complex tasks in education for the use of instructional methods? Because high cognitive load is a key characteristic of complex tasks, the research questions will be answered in the context of cognitive load theory (CLT; Sweller, 1988; Sweller, van Merriënboer, & Paas, 1998; van Merriënboer & Sweller, 2005). CLT distinguishes between extraneous, intrinsic and germane cognitive load. Extraneous load is load that is *not* necessary for learning; it typically results from badly designed instruction. Intrinsic load is determined by the interaction between the nature of the learning tasks and the expertise of the learner. It depends on the amount of *element interactivity* in the tasks that must be learned, which, in turn, depends on the expertise of the learner because what are numerous

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elements for a low-expertise learner may be only one or a few elements (i.e. chunks) for a high-expertise learner. Finally, germane load is load that directly contributes to learning, that is, to the learner's construction of cognitive structures and processes that improve performance.

In general, well-designed instruction should decrease extraneous load and optimise germane load, within the limits of total available capacity in order to prevent cognitive overload. However, this article is mainly about the situation that even after the removal of all sources of extraneous cognitive load, the element interactivity of the complex tasks is still too high to allow for efficient learning. Thus, it is about balancing intrinsic load, which is caused by dealing with the element interactivity in the tasks, and germane load, which is caused by genuine learning processes. The structure of our argument is as follows. First, we discuss research findings indicating that germane-load inducing instructional methods used for practicing simple tasks are not used for practicing complex tasks, at the cost of transfer of learning. Second, we argue that the element interactivity of learning tasks should be limited early in training to decrease their intrinsic load, so that germane-load inducing methods might be used right from the start of the training program. Third, implications for instructional design are discussed. The article ends with a discussion of main conclusions and future research issues.

TEACHING SIMPLE VS. COMPLEX TASKS

Research indicates that many instructional methods that work well for simple tasks do not work well for complex tasks, and vice versa (for overviews, see Bainbridge, 1997; Wulf & Shea, 2002). This section will first discuss the differential effects of germane-load inducing methods on learning simple and complex tasks. Second, we will argue that it would be a mistake to teach complex tasks without these methods because that yields a low *transfer* of training.

Instructional methods and task complexity

A first important germane-load inducing method affecting learning is practice variability and, in particular, the way that different versions of a learning task are scheduled over practice trials. A common distinction is between low and high contextual interference (HCI). In a practice schedule with low contextual interference (LCI; i.e. blocked practice), one version of a task is repeatedly practiced before another version of the task is introduced. Under HCI (i.e. random practice), all versions of the task are mixed and practiced in a random order. Contextual interference can be induced by varying the surface features of a task (e.g. context, representation), or the structural features of a task (e.g. underlying procedures; Quilici & Mayer, 1996). For simple tasks, a robust finding is that HCI results in less effective performance during practice (e.g. more time and/or more trials are necessary to reach a pre-specified level of performance), but higher performance during retention tests (for a review, see Magill & Hall, 1990). Possible explanations for the beneficial effects of HCI are that the different versions of a task reside together in working memory and can be compared and contrasted to each other to yield more elaborate representations in memory (Shea & Zimny, 1983), and that HCI conditions result in repeated forgetting of the action plan, resulting in reconstructive activities that eventually yield more accessible representations in memory (Lee & Magill, 1985). What the different explanations have in common is their assumption that random practice of different versions of a task induces *germane* learning processes that require more effort than does blocked practice, but yield cognitive representations that increase later transfer test performance.

The findings for contextual interference are less clear for complex tasks, which may be partly due to the fact that learners have difficulty to distinguish surface and structural features of such tasks (Ross & Kilbane, 1997). For complex tasks in sports, beneficial effects of HCI are not found at all, or only found for high-expertise learners but not for low-expertise learners (Hebert, Landin, & Solmon, 1996). Using drawing tasks, Albaret and Thon (1999) explicitly manipulated task complexity (number of line segments to draw) and studied the effects of contextual interference. As expected, they found that the positive effects of random practice decreased with task complexity, and that for the most complex task, blocked practice was even superior to random practice. It seems that complex tasks leave no processing capacity for the germane cognitive processes that help learners construct better cognitive representations.

A second germane-load inducing method relevant to the design of practice is providing guidance and feedback. For simple tasks, reducing the amount of guidance is typically beneficial to learning. For instance, physical guidance in learning motor skills (e.g. using a mechanical stop to indicate a target position, moving the performer's limb) is more effective when it is used for a limited number of trials than when it is used for a high proportion of trials, and guidance that focuses a learner's attention only on the external goal of a movement is more effective than guidance that focuses attention also on the specifics of the movement itself (Schmidt, 1991). Paas, Camp, and Rikers (2001) showed that providing limited guidance by loosely indicating the goal (i.e. the end point of the maze) is more effective in maze learning tasks than giving a precise description of the goal. Results indicate that for simple tasks, extensive guidance often has strong positive effects on performance during practice, but when it is withdrawn during tests learners who practiced with less or no guidance, perform better than learners who practiced with extensive guidance. Similarly, giving feedback on some of the practice tasks or on varying aspects of performance results in more effective learning than giving feedback on all tasks or all aspects of performance. Moreover, slightly delayed feedback is more effective than concurrent or immediate feedback (Balzer, Doherty, & O'Connor, 1989).

The findings for the effects of guidance and feedback on complex tasks, however, show another picture. For complex movements in sports, extensive physical assistance proved to be superior to limited physical assistance (Wulf, Shea, & Whitacre, 1998). For striking tasks, Guadagnoli, Dornier, and Tandy (1996) convincingly demonstrated that relatively long feedback summaries (i.e. delayed feedback) were most effective for teaching simple tasks to low-expertise and high-expertise learners, and teaching complex tasks to high-expertise learners, but single-task feedback (i.e. immediate feedback) was most effective for teaching complex tasks to low-expertise learners (i.e. a situation with high intrinsic cognitive load). These results suggest that neither limited guidance and feedback, nor alternation for the aspects of the task that receive feedback, has positive effects on learning complex tasks. In contrast, it seems that the intrinsic load imposed by the complex tasks leaves no processing capacity allowing learners to develop early in the learning process their own internal monitoring and feedback mechanisms or cognitive representations of how different task aspects interact with each other.

The transfer paradox

Research results on instructional methods and task complexity at first sight seem to imply that for complex tasks, instructional methods should *not* stimulate cognitive processes yielding germane cognitive load, because this may easily cause cognitive overload and hamper learning. Instead, it might be argued that for complex tasks, highly structured methods should be used that primarily facilitate performance because they take over part of the cognitive processing from the learner. We, however, do not support this conclusion because methods such as blocked practice, step-by-step guidance and frequent and complete feedback may indeed have a positive effect on the acquisition curve and performance on retention tests, but *not* on problem solving and transfer of learning.

This phenomenon has been called the 'transfer paradox' (see also Eaton & Cottrell, 1999; van Merriënboer, De Croock, & Jelsma, 1997). This paradox starts from the observation that particular instructional methods are often selected because they minimise the number of required practice items, the necessary time-on-task, or the learners' investment of effort to reach specific learning objectives. van Merriënboer et al. used the highly complex task of troubleshooting a simulated chemical factory, and learners had to learn to diagnose a limited set of possible errors (e.g. valve malfunctioning, leakage, broken controller, etc.). A highly structured, blocked practice schedule was found to be most efficient to learn to diagnose those particular errors. However, it yielded low transfer of learning as indicated by the fact that learners were not able to diagnose unfamiliar errors they did not encounter during practice. A random practice schedule was less efficient to learn to diagnose particular errors, because students needed more trials, more time on task, or more effort to reach the same level of performance for diagnosing those errors as the blocked group. But they were far better in diagnosing new errors that had not been practiced before. Thus, if one aims at transfer of learning, and at the ability to show performances that go beyond given learning objectives, it is better to practice errors in a random order. This phenomenon—where the methods that work best for reaching specific objectives are not the methods that work best for reaching transfer of learning—has important implications for the selection of instructional methods.

Methods that explicitly aim at transfer of learning should take two complementary dimensions of transfer into account. The first approach stresses that transfer may be partly explained by general or abstract knowledge that may be *interpreted* in the transfer situation (i.e. other use of the same—general—knowledge); the second approach stresses that transfer may be partly explained by the *application* of knowledge elements that are shared between the practice and the transfer situation (i.e. the same use of the same—specific—knowledge). Instructional methods that explicitly aim at transfer of learning must carefully balance both complementary dimensions, and facilitate the interpretive aspects of knowing for those aspects of a complex task that are different from problem to problem situation as well as facilitate the applicative aspects of knowing for those aspects of a complex task that are highly similar from situation to situation (van Merriënboer, 1997).

Whereas both transfer dimensions need to be carefully balanced, and adaptive experts score high on both dimensions (Gentner et al., 1997), it is important to note that instructional methods that explicitly aim for one or the other can also conflict with each other. The main problem is that starting with instructional methods that give priority to the applicative aspects of knowing (e.g. building routines), seriously hampers the later development of interpretive aspects of knowing. The methods constrain the problem spaces within which learners work, and then make it more difficult for them to generate creative solutions or 'think outside the box'. An example is provided by a study of Schwartz, Martin, and Pfaffman (2005), in which children learned to manipulate pieces to help solve fraction problems. One group learned with pie pieces with different sizes, with a focus on routine building because the pieces are easily seen as fractions of a whole; the other group learned with tile pieces of equal sizes, with a focus on interpretation because the pieces should be interpreted as parts of a whole rather than just units. For subsequent problem solving with new materials (beans, bars etc.), it was found that the interpretation group was better able to use the novel materials, showed better progress and eventually became more efficient than the routine-building group.

Concluding, methods such as blocked practice, step-by-step guidance and frequent and complete feedback may help to efficiently reach pre-specified objectives but yield low transfer of learning. In addition, they may block the later development of the second, interpretive dimension of transfer. Therefore, these load-reducing methods should not be used to teach complex tasks. But their counterparts (random practice, limited guidance, infrequent feedback), which are suitable to teach simple tasks, cannot be used without additional measures because otherwise they cause cognitive overload. In our opinion, there is only one solution to overcome this impasse: Reduce the intrinsic load of learning tasks in the early phases of training so that instructional methods that induce germane load can be applied right from the beginning.

LOW-TO-HIGH ELEMENT INTERACTIVITY AND INDUCING GERMANE LOAD

According to CLT, the complexity of a task is largely determined by its degree of element interactivity. High-element interactivity requires the learner to process several elements and their relationships simultaneously in working memory in order to learn the task. Low-element interactivity allows the learner to serially process only a few elements at a time. We first discuss approaches to lower intrinsic load early in learning. Second, we argue that this makes it possible to use instructional methods that induce germane load right from the start of a training program.

Low-to-high element interactivity

Basically, there are two ways to sequence tasks from low to high element interactivity. First, the number of elements and interactions between elements may be initially reduced by simplifying the tasks, after which more and more elements and interactions are added. This resembles a part-whole approach. Second, the number of elements and interactions between elements may be immediately presented in their full complexity, but the learner has to take more and more interacting elements into account when performing the tasks. This resembles a whole-part approach.

Using a part-whole approach, many studies indicate that learners benefit from learning tasks that are sequenced from simple, with relatively little interacting elements, to complex, with all interacting elements that are necessary for complete understanding. For instance, Mayer and Moreno (2003) discuss studies that show better transfer test performance when students first had to study which components make up a system, and only then how the system works. Kester, Kirschner, and van Merriënboer (2004a, 2004b; in press) studied the effects of presenting information necessary to solve a complex task.

They found that not presenting all information at once leads to better transfer test performance. Pollock, Chandler, and Sweller (2002) and Clarke, Ayres, and Sweller (2005) considered mathematical learning tasks and found that, especially for low-expertise learners and high-element interactivity materials, first presenting isolated elements and only then the interacting elements yields higher transfer test performance than presenting all elements simultaneously from the start. Finally, Ayres (2006) also used mathematical learning tasks and found that especially low-expertise learners benefit from the initial reduction in element interactivity, whereas high-expertise learners benefit from high-element interactivity materials used right from the start.

The second option, a whole-part approach, is to present high-element interactivity materials in their full complexity right from the beginning, but use learning tasks that focus the learner's attention on particular subsets of interacting elements. One way to emphasise varying interacting elements of a learning task is to constrain learners' performance, either through forcing them to behave as an expert would do by requiring them to successfully complete a particular problem-solving phase before entering a next phase (Dufresne, Gerace, Thibodeau-Hardiman, & Mestre, 1992) or through the use of particular task formats such as worked examples and completion tasks. Worked examples focus the learner's attention on elements that represent correct solution steps only, so that they do not have to worry about potential solution steps that are not relevant for the task at hand. Completion tasks present a partial solution that must be completed by the learner. Like worked examples, they constrain the learner's performance because not all potential solution steps need to be taken into consideration. Many studies indicate that low-expertise learners learn more from studying worked examples or from completing partial solutions than from independently performing the equivalent conventional tasks (for an overview, see Atkinson, Derry, Renkl, & Wortham, 2000). Furthermore, Kalyuga, Chandler, Tuovinen, and Sweller (2001) found that this effect reverses for high-expertise learners. Thus, to accommodate the learner's increase in expertise during practice, task formats with low element interactivity (worked examples, completion tasks) should be gradually replaced by conventional tasks with high element interactivity. To ensure a smooth transition, one may start with worked examples, continue with completion tasks and end with conventional tasks in an instructional strategy known as the 'completion strategy' (see also Renkl & Atkinson, 2003; van Merriënboer, 1990).

Inducing germane load

Next to a low-to-high element interactivity sequencing strategy that frees up cognitive capacity, learning should be promoted by simultaneously implementing germane-load inducing methods. As discussed earlier, practice variability and limited guidance and feedback are promising germane-load inducing methods. Paas and van Merriënboer (1994) investigated variability in combination with worked examples and found that learners who received a training sequence of high-variability worked examples invested less time and mental effort in practice and attained a better transfer performance than learners who received a sequence of low-variability worked examples. van Merriënboer, Schuurman, De Croock, and Paas (2002) obtained similar results showing that a training combining the 'completion strategy' with HCI yielded higher transfer test performance than a training combining it with LCI.

With regard to limited guidance and feedback as methods to induce germane cognitive load, a study of Renkl (2002) indicated that using guidance, in the form of a minimalist description of the probabilistic rule that was used in a worked example provided, had beneficial effects on learning. In addition, Renkl and Atkinson (2003) studied the use of self-explanation prompts in combination with the 'completion strategy' in the domain of statistics (probability). During studying, the worked examples guided the learners by asking them which probability rule was applied in each solution step. They found a strong effect on transfer test performance for learners who received the self-explanation prompts compared to learners who did not receive these prompts. Robins and Mayer (1993) presented sets of worked examples in a training ordered by type and accompanied by feedback that described the problem types. They found superior transfer test performance for learners who received sets of worked examples together with infrequent feedback. These studies all suggest that once the task complexity is reduced by lowering the element interactivity as a function of learner expertise, that is, by using a simple-to-complex sequence or performance constraints, implementing germane-load inducing methods has beneficial effects on transfer test performance. The next section discusses how these methods to lower intrinsic load and to induce germane load could be reflected in an instructional design model that aims at transfer of learning.

IMPLICATIONS FOR INSTRUCTIONAL DESIGN

van Merriënboer's four-component instructional design model (4C/ID-model, 1997; van Merriënboer, Clark, & De Croock, 2002; van Merriënboer, Kirschner, & Kester, 2003) claims that learning environments for complex tasks can always be described in four components:

1. *Learning tasks*, which are preferably based on real-life tasks and fulfill the role of a backbone for the training program.
2. *Supportive information*, which is made available to learners because it helps them to perform the problem-solving and reasoning aspects of learning tasks. It mainly concerns information on how the domain is organised and how problems in the domain can be systematically approached by the learner.
3. *Procedural information*, which is presented to learners because it helps them to perform the routine aspects of learning tasks. It mainly concerns procedural steps that precisely specify under which conditions particular actions must be taken by the learner.
4. *Part-task practice*, which may provide learners with additional practice for routine aspects of the complex task that need to be developed to a very high level of automaticity (e.g. children practicing the multiplication tables).

Three basic prescriptions of the 4C/ID-model correspond with the main principles discussed in the previous sections. First, the model suggests to order learning tasks in so-called *task classes*, where earlier task classes have lower element interactivity than later task classes (i.e. a whole-part approach). Even the first task class contains whole and meaningful tasks (i.e. the most essential interacting elements) so that the learners may quickly develop a holistic vision of the whole task that is then gradually embellished in subsequent task classes. Learning tasks within a particular task class are equivalent in the sense that they can be performed on the basis of the same body of knowledge; each subsequent, more complex task class requires more knowledge or more embellished knowledge for effective performance than the preceding, simpler task classes. Second, when learners start to work on tasks in a new, more complex task class, it is essential to initially focus their attention on those elements that are most important for learning. This may be reached by first constraining and then more and more relaxing their performance, or by starting with worked examples, continuing with completion tasks, and ending with conventional tasks. Third and probably most important, the combination of ordering learning tasks in simple-to-complex task classes with scaffolding learners within a task class, enables the use of instructional methods that evoke a germane cognitive load. Thus, learning tasks should always, right from the beginning of the training program, show high variability of practice, give limited guidance to learners and provide them with infrequent feedback on varying aspects of performance.

The three other components of the 4C/ID-model explicitly take the two transfer dimensions into account. Supportive information relates to the idea that transfer is explained by general or abstract information that may be interpreted by a task performer to solve a new problem situation. Conceptual models (what is this?), structural models (how is this built?), causal models (how does this work?) and cognitive strategies (how should I approach this task?) provide this kind of information. Procedural information and part-task practice mainly relate to the idea that transfer may be explained by the application of knowledge elements that are shared between the practice and the transfer situation. Procedural information tells the learner, precisely when it is needed, how to perform routine aspects of the learning tasks. Part-task practice may provide additional practice needed to develop knowledge elements that allow the learner to perform routine aspects at a high level of automaticity.

DISCUSSION

In this article, we argued that the increasing focus of instructional design theories on the use of complex 'real-life' tasks has important implications for the use of instructional methods. Even after removal of all sources of extraneous load, these tasks are often so cognitively demanding that it is impossible to use transfer enhancing instructional methods right from the start of the training program. Therefore, we proposed a two-stage approach. First, intrinsic load is decreased early in training by manipulating the element interactivity of the learning tasks. Second, learning tasks are immediately combined with methods that induce germane cognitive load, such as high variability of practice and limited guidance and feedback.

Our analysis points out three important directions for future research. First, the assumed interaction between intrinsic-load reducing methods and germane-load inducing methods has only been empirically confirmed for a limited number of concrete instructional methods. More research is needed to show that the interaction holds across a wide variety of methods. Second, more research is needed with highly complex real-life tasks performed in ecologically valid settings. Particular instructional methods such as variability might then have unexpected effects, for instance because it is difficult for learners to distinguish between the surface and structural features of such tasks. Finally, progress must be made with regard to the measurement of cognitive load. Especially instruments that allow researchers to disentangle changes in cognitive load into changes in intrinsic load on the one hand, and germane load on the other hand, would be very helpful to the in-depth analysis of research findings.

From a practical viewpoint, probably the most important point to consider when designing training programs for complex tasks is that the intrinsic load of a task depends on the expertise of the learner. The higher the expertise, the lower the intrinsic load. In a flexible and adaptive educational program, it should be possible to take differences between individual learners into account when suitable learning tasks are selected. Thus, a high-ability student may proceed much faster from low- to high-element interactivity tasks than a low-ability student, and also need less learning tasks to complete the program.

REFERENCES

Albaret, J. M., & Thon, B. (1999). Differential effects of task complexity on contextual interference in a drawing task. *Acta Psychologica, 100*, 9–24.

Atkinson, R. K., Derry, S. J., Renkl, A., & Wortham, D. (2000). Learning from examples: Instructional principles from the worked examples research. *Review of Educational Research, 70*, 181–214.

Ayres, P. (2006). Impact of reducing intrinsic cognitive load on learning in a mathematical domain. *Applied Cognitive Psychology, 20*, 287–298 (this issue).

Bainbridge, L. (1997). The change in concepts needed to account for human behaviour in complex dynamic tasks. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans, 27*, 351–359.

Balzer, W. K., Doherty, M. E., & O'Connor, R. (1989). Effects of cognitive feedback on performance. *Psychological Bulletin, 106*, 410–433.

Clarke, T., Ayres, P., & Sweller, J. (2005). The impact of sequencing and prior knowledge on learning mathematics through spreadsheet applications. *Educational Technology, Research and Development, 53*, 15–24.

Dufresne, R. J., Gerace, W. J., Thibodeau-Hardiman, P., & Mestre, J. P. (1992). Constraining novices to perform expertlike problem analyses: Effects on schema acquisition. *The Journal of the Learning Sciences, 2*, 307–331.

Eaton, D., & Cottrell, D. (1999). Structured teaching methods enhance skill acquisition but not problem-solving abilities: An evaluation of the 'silent run through'. *Medical Education, 33*, 19–23.

Gentner, D., Brem, S., Ferguson, R. W., Markman, A. B., Levidow, B. B., Wolff, P., & Forbus, K. D. (1997). Analogical reasoning and conceptual change: A case study of Johannes Kepler. *Journal of the Learning Sciences, 6*, 3–40.

Guadagnoli, M. A., Dornier, L., & Tandy, R. D. (1996). Optimal length for summary knowledge of results: The influence of task-related experience and complexity. *Research Quarterly for Exercise and Sport, 67*, 239–248.

Hebert, E. P., Landin, D., & Solmon, M. A. (1996). Practice schedule effects on the performance and learning of low- and high-skilled students: An applied study. *Research Quarterly for Exercise and Sport, 67*, 52–58.

Kalyuga, S., Chandler, P., Tuovinen, J., & Sweller, J. (2001). When problem solving is superior to studying worked examples. *Journal of Educational Psychology, 93*, 579–588.

Kester, L., Kirschner, P. A., & van Merriënboer, J. J. G. (2004a). Just in time presentation of different types of information in learning statistics. *Instructional Science, 32*, 233–252.

Kester, L., Kirschner, P. A., & van Merriënboer, J. J. G. (2004b). Information presentation and troubleshooting in electrical circuits. *International Journal of Science Education, 26*, 239–256.

Kester, L., Kirschner, P. A., & van Merriënboer, J. J. G. (in press). Just-in-time information presentation: Improving transfer performance and learning efficiency of a complex troubleshooting skill. *Contemporary Educational Psychology.*

Lee, T. D., & Magill, R. A. (1985). Can forgetting facilitate skill acquisition? In D. Goodman, R. B. Wilberg, & I. M. Franks (Eds.), *Differing perspectives on memory, learning and control* (pp. 3–22). Amsterdam, The Netherlands: Elsevier North Holland.

Magill, R. A., & Hall, K. G. (1990). A review of the contextual interference effect in motor skill acquisition. *Human Movement Science, 9*, 241–289.

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist, 38*, 43–52.

Merrill, M. D. (2002). First principles of instruction. *Educational Technology, Research and Development, 50*, 43–59.
Paas, F., & van Merriënboer, J. J. G. (1994). Variability of worked examples and transfer of geometrical problem-solving skills: A cognitive load approach. *Journal of Educational Psychology, 86*, 122–133.
Paas, F., Camp, G., & Rikers, R. (2001). Instructional compensation for age-related cognitive declines: Effects of goal specificity in maze learning. *Journal of Educational Psychology, 93*, 181–186.
Pollock, E., Chandler, P., & Sweller, J. (2002). Assimilating complex information. *Learning and Instruction, 12*, 61–86.
Quilici, J. L., & Mayer, R. E. (1996). Role of examples in how students learn to categorize statistics word problems. *Journal of Educational Psychology, 88*, 144–161.
Renkl, A. (2002). Worked-out examples: Instructional explanations support learning by self-explanation. *Learning and Instruction, 12*, 529–556.
Renkl, A., & Atkinson, R. K. (2003). Structuring the transition from example study to problem solving in cognitive skill acquisition: A cognitive load perspective. *Educational Psychologist, 38*, 15–22.
Robins, S., & Mayer, R. E. (1993). Schema training in analogical reasoning. *Journal of Educational Psychology, 85*, 529–538.
Ross, B. H., & Kilbane, M. C. (1997). Effects of principle explanation and superficial similarity on analogical mapping in problem solving. *Journal of Experimental Psychology—Learning, Memory & Cognition, 23*, 427–440.
Schmidt, R. A. (1991). *Motor control and learning: A behavioral emphasis* (2nd ed.). Champaign, IL: Human Kinetics.
Schwartz, D. L., Martin, L., & Pfaffman, J. (2005). How mathematics propels the development of physical knowledge. *Journal of Cognition and Development, 6*, 65–88.
Shea, J. B., & Zimny, S. T. (1983). Context effects in learning movement information. In R. A. Magill (Ed.), *Memory and the control of action* (pp. 345–366). Amsterdam, The Netherlands: Elsevier North Holland.
Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12*, 257–285.
Sweller, J., van Merriënboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10*, 251–296.
van Merriënboer, J. J. G. (1990). Strategies for programming instruction in high school: Program completion vs. program generation. *Journal of Educational Computing Research, 6*, 265–285.
van Merriënboer, J. J. G. (1997). *Training complex cognitive skills: A four-component instructional design model for technical training*. Englewood Cliffs, NJ: Educational Technology Publications.
van Merriënboer, J. J. G., Clark, R. E., & De Croock, M. B. M. (2002). Blueprints for complex learning: The 4C/ID-model. *Educational Technology, Research and Development, 50*, 39–64.
van Merriënboer, J. J. G., De Croock, M. B. M., & Jelsma, O. (1997). The transfer paradox: Effects of contextual interference on retention and transfer performance of a complex cognitive skill. *Perceptual and Motor Skills, 84*, 784–786.
van Merriënboer, J. J. G., Kirschner, P. A., & Kester, L. (2003). Taking the load of a learners' mind: Instructional design for complex learning. *Educational Psychologist, 38*, 5–13.
van Merriënboer, J. J. G., Schuurman, J. G., De Croock, M. B. M., & Paas, F. (2002). Redirecting learners' attention during training: Effects on cognitive load, transfer test performance, and training efficiency. *Learning and Instruction, 12*, 11–37.
van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review, 17*, 147–177.
Wulf, G., & Shea, C. H. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin & Review, 9*, 185–211.
Wulf, G., Shea, C. H., & Whitacre, C. A. (1998). Physical guidance benefits in learning a complex motor skill. *Journal of Motor Behavior, 30*, 367–380.

