

Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching

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Evidence for the superiority of guided instruction is explained in the context of our knowledge of human cognitive architecture, expert–novice differences, and cognitive load. Although unguided or minimally guided instructional approaches are very popular and intuitively appealing, the point is made that these approaches ignore both the structures that constitute human cognitive architecture and evidence from empirical studies over the past half-century that consistently indicate that minimally guided instruction is less effective and less efficient than instructional approaches that place a strong emphasis on guidance of the student learning process. The advantage of guidance begins to recede only when learners have sufficiently high prior knowledge to provide “internal” guidance. Recent developments in instructional research and instructional design models that support guidance during instruction are briefly described.

Disputes about the impact of instructional guidance during teaching have been ongoing for at least the past half-century (Ausubel, 1964; Craig, 1956; Mayer, 2004; Shulman & Keisler, 1966). On one side of this argument are those advocating the hypothesis that people learn best in an unguided or minimally guided environment, generally defined as one in which learners, rather than being presented with essential information, must discover or construct essential information for themselves (e.g., Bruner, 1961; Papert, 1980; Steffe & Gale, 1995). On the other side are those suggesting that novice learners should be provided with direct instructional guidance on the concepts and procedures required by a particular discipline and should not be left to discover those pro-

cedures by themselves (e.g., Cronbach & Snow, 1977; Klahr & Nigam, 2004; Mayer, 2004; Shulman & Keisler, 1966; Sweller, 2003). Direct instructional guidance is defined as providing information that fully explains the concepts and procedures that students are required to learn as well as learning strategy support that is compatible with human cognitive architecture. Learning, in turn, is defined as a change in long-term memory.

The minimally guided approach has been called by various names including discovery learning (Anthony, 1973; Bruner, 1961); problem-based learning (PBL; Barrows & Tamblyn, 1980; Schmidt, 1983), inquiry learning (Papert, 1980; Rutherford, 1964), experiential learning (Boud, Keogh, & Walker, 1985; Kolb & Fry, 1975), and constructivist learning (Jonassen, 1991; Steffe & Gale, 1995). Examples of applications of these differently named but essentially pedagogically equivalent approaches include

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science instruction in which students are placed in inquiry learning contexts and asked to discover the fundamental and well-known principles of science by modeling the investigatory activities of professional researchers (Van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, in press). Similarly, medical students in problem-based teaching courses are required to discover medical solutions for common patient problems using problem-solving techniques (Schmidt, 1998, 2000).

There seem to be two main assumptions underlying instructional programs using minimal guidance. First they challenge students to solve “authentic” problems or acquire complex knowledge in information-rich settings based on the assumption that having learners construct their own solutions leads to the most effective learning experience. Second, they appear to assume that knowledge can best be acquired through experience based on the procedures of the discipline (i.e., seeing the pedagogic content of the learning experience as identical to the methods and processes or epistemology of the discipline being studied; Kirschner, 1992). Minimal guidance is offered in the form of process- or task-relevant information that is available if learners choose to use it. Advocates of this approach imply that instructional guidance that provides or embeds learning strategies in instruction interferes with the natural processes by which learners draw on their unique prior experience and learning styles to construct new situated knowledge that will achieve their goals. According to Wickens (1992, cited in Bernstein, Penner, Clarke-Stewart, Roy, & Wickens, 2003), for example,

large amounts of guidance may produce very good performance during practice, but too much guidance may impair later performance. Coaching students about correct responses in math, for example, may impair their ability later to retrieve correct responses from memory on their own. (p. 221)

This constructivist argument has attracted a significant following.

The goal of this article is to suggest that based on our current knowledge of human cognitive architecture, minimally guided instruction is likely to be ineffective. The past half-century of empirical research on this issue has provided overwhelming and unambiguous evidence that minimal guidance during instruction is significantly less effective and efficient than guidance specifically designed to support the cognitive processing necessary for learning.

THE CONSEQUENCES OF HUMAN COGNITIVE ARCHITECTURE FOR MINIMAL GUIDANCE DURING INSTRUCTION

Any instructional procedure that ignores the structures that constitute human cognitive architecture is not likely to be effective. Minimally guided instruction appears to proceed

with no reference to the characteristics of working memory, long-term memory, or the intricate relations between them. The result is a series of recommendations that most educators find almost impossible to implement—and many experienced educators are reluctant to implement—because they require learners to engage in cognitive activities that are highly unlikely to result in effective learning. As a consequence, the most effective teachers may either ignore the recommendations or, at best, pay lip service to them (e.g., Aulls, 2002). In this section we discuss some of the characteristics of human cognitive architecture and the consequent instructional implications.

Human Cognitive Architecture

Human cognitive architecture is concerned with the manner in which our cognitive structures are organized. Most modern treatments of human cognitive architecture use the Atkinson and Shiffrin (1968) sensory memory–working memory–long-term memory model as their base. Sensory memory is not relevant to the discussion here so it is not considered further. The relations between working and long-term memory, in conjunction with the cognitive processes that support learning, are of critical importance to the argument.

Our understanding of the role of long-term memory in human cognition has altered dramatically over the last few decades. It is no longer seen as a passive repository of discrete, isolated fragments of information that permit us to repeat what we have learned. Nor is it seen only as a component of human cognitive architecture that has merely peripheral influence on complex cognitive processes such as thinking and problem solving. Rather, long-term memory is now viewed as the central, dominant structure of human cognition. Everything we see, hear, and think about is critically dependent on and influenced by our long-term memory.

De Groot's (1945/1965) work on chess expertise, followed by Chase and Simon (1973), has served as a major influence on the field's reconceptualization of the role of long-term memory. The finding that expert chess players are far better able than novices to reproduce briefly seen board configurations taken from real games, but do not differ in reproducing random board configurations, has been replicated in a variety of other areas (e.g., Egan & Schwartz, 1979; Jeffries, Turner, Polson, & Atwood, 1981; Sweller & Cooper, 1985). These results suggest that expert problem solvers derive their skill by drawing on the extensive experience stored in their long-term memory and then quickly select and apply the best procedures for solving problems. The fact that these differences can be used to fully explain problem-solving skill emphasizes the importance of long-term memory to cognition. We are skillful in an area because our long-term memory contains huge amounts of information concerning the area. That information permits us to quickly recognize the characteristics of a situation and indicates to us, often unconsciously, what to do and when to do it. Without our huge store of information in long-term memory,

we would be largely incapable of everything from simple acts such as crossing a street (information in long-term memory informs us how to avoid speeding traffic, a skill many other animals are unable to store in their long-term memories) to complex activities such as playing chess or solving mathematical problems. Thus, our long-term memory incorporates a massive knowledge base that is central to all of our cognitively based activities.

What are the instructional consequences of long-term memory? In the first instance and at its most basic, the architecture of long-term memory provides us with the ultimate justification for instruction. The aim of all instruction is to alter long-term memory. If nothing has changed in long-term memory, nothing has been learned. Any instructional recommendation that does not or cannot specify what has been changed in long-term memory, or that does not increase the efficiency with which relevant information is stored in or retrieved from long-term memory, is likely to be ineffective.

Working Memory Characteristics and Functions

Working memory is the cognitive structure in which conscious processing occurs. We are only conscious of the information currently being processed in working memory and are more or less oblivious to the far larger amount of information stored in long-term memory.

Working memory has two well-known characteristics: When processing novel information, it is very limited in duration and in capacity. We have known at least since Peterson and Peterson (1959) that almost all information stored in working memory and not rehearsed is lost within 30 sec and have known at least since Miller (1956) that the capacity of working memory is limited to only a very small number of elements. That number is about seven according to Miller, but may be as low as four, plus or minus one (see, e.g., Cowan, 2001). Furthermore, when processing rather than merely storing information, it may be reasonable to conjecture that the number of items that can be processed may only be two or three, depending on the nature of the processing required.

The interactions between working memory and long-term memory may be even more important than the processing limitations (Sweller, 2003, 2004). The limitations of working memory only apply to new, yet to be learned information that has not been stored in long-term memory. New information such as new combinations of numbers or letters can only be stored for brief periods with severe limitations on the amount of such information that can be dealt with. In contrast, when dealing with previously learned information stored in long-term memory, these limitations disappear. In the sense that information can be brought back from long-term memory to working memory over indefinite periods of time, the temporal limits of working memory become irrelevant. Similarly, there are no known limits to the amount of such information that can be brought into working memory from long-term memory. Indeed, the altered characteristics of

working memory when processing familiar as opposed to unfamiliar material induced Ericsson and Kintsch (1995) to propose a separate structure, long-term working memory, to deal with well-learned and automated information.

Any instructional theory that ignores the limits of working memory when dealing with novel information or ignores the disappearance of those limits when dealing with familiar information is unlikely to be effective. Recommendations advocating minimal guidance during instruction proceed as though working memory does not exist or, if it does exist, that it has no relevant limitations when dealing with novel information, the very information of interest to constructivist teaching procedures. We know that problem solving, which is central to one instructional procedure advocating minimal guidance, called inquiry-based instruction, places a huge burden on working memory (Sweller, 1988). The onus should surely be on those who support inquiry-based instruction to explain how such a procedure circumvents the well-known limits of working memory when dealing with novel information.

Implications of Human Cognitive Architecture for Constructivist Instruction

These memory structures and their relations have direct implications for instructional design (e.g., Sweller, 1999; Sweller, van Merriënboer & Paas, 1998). Inquiry-based instruction requires the learner to search a problem space for problem-relevant information. All problem-based searching makes heavy demands on working memory. Furthermore, that working memory load does not contribute to the accumulation of knowledge in long-term memory because while working memory is being used to search for problem solutions, it is not available and cannot be used to learn. Indeed, it is possible to search for extended periods of time with quite minimal alterations to long-term memory (e.g., see Sweller, Mawer, & Howe, 1982). The goal of instruction is rarely simply to search for or discover information. The goal is to give learners specific guidance about how to cognitively manipulate information in ways that are consistent with a learning goal, and store the result in long-term memory.

The consequences of requiring novice learners to search for problem solutions using a limited working memory or the mechanisms by which unguided or minimally guided instruction might facilitate change in long-term memory appear to be routinely ignored. The result is a set of differently named but similar instructional approaches requiring minimal guidance that are disconnected from much that we know of human cognition. Recommending minimal guidance was understandable when Bruner (1961) proposed discovery learning as an instructional tool because the structures and relations that constitute human cognitive architecture had not yet been mapped. We now are in a quite different environment because we know much more about the structures, functions, and characteristics of working and long-term memory; the relations between them; and their consequences

for learning and problem solving. This new understanding has been the basis for systematic research and development of instructional theories that reflect our current understanding of cognitive architecture (e.g., Anderson, 1996; Glaser, 1987). This work should be central to the design of effective, guided instruction.

Of course, suggestions based on theory that minimally guided instruction should have minimal effectiveness are worth little without empirical evidence. Empirical work comparing guided and unguided instruction is discussed after a review of the current arguments for minimal guidance.

THE ORIGINS OF CONSTRUCTIVISM AND THE CURRENT VIEW OF MINIMALLY GUIDED INSTRUCTION

Given the incompatibility of minimally guided instruction with our knowledge of human cognitive architecture, what has been the justification for these approaches? The most recent version of instruction with minimal guidance comes from constructivism (e.g., Steffe & Gale, 1995), which appears to have been derived from observations that knowledge is constructed by learners and so (a) they need to have the opportunity to construct by being presented with goals and minimal information, and (b) learning is idiosyncratic and so a common instructional format or strategies are ineffective. The constructivist description of learning is accurate, but the instructional consequences suggested by constructivists do not necessarily follow.

Most learners of all ages know how to construct knowledge when given adequate information and there is no evidence that presenting them with partial information enhances their ability to construct a representation more than giving them full information. Actually, quite the reverse seems most often to be true. Learners must construct a mental representation or schema irrespective of whether they are given complete or partial information. Complete information will result in a more accurate representation that is also more easily acquired. Constructivism is based therefore, on an observation that, although descriptively accurate, does not lead to a prescriptive instructional design theory or to effective pedagogical techniques (Clark & Estes, 1998, 1999; Estes & Clark, 1999; Kirschner, Strijbos, & Martens, 2004). Yet many educators, educational researchers, instructional designers, and learning materials developers appear to have embraced minimally guided instruction and tried to implement it.

Another consequence of attempts to implement constructivist theory is a shift of emphasis away from teaching a discipline as a body of knowledge toward an exclusive emphasis on learning a discipline by experiencing the processes and procedures of the discipline (Handelsman et. al., 2004; Hodson, 1988). This change in focus was accompanied by an assumption shared by many leading educators and discipline specialists that knowledge can best be learned or only learned

through experience that is based primarily on the procedures of the discipline. This point of view led to a commitment by educators to extensive practical or project work, and the rejection of instruction based on the facts, laws, principles and theories that make up a discipline's content accompanied by the use of discovery and inquiry methods of instruction. The addition of a more vigorous emphasis on the practical application of inquiry and problem-solving skills seems very positive. Yet it may be a fundamental error to assume that the pedagogic content of the learning experience is identical to the methods and processes (i.e., the epistemology) of the discipline being studied and a mistake to assume that instruction should exclusively focus on methods and processes.

Shulman (1986; Shulman & Hutchings, 1999) contributed to our understanding of the reason why less guided approaches fail in his discussion of the integration of content expertise and pedagogical skill. He defined *content knowledge* as "the amount and organization of the knowledge per se in the mind of the teacher" (Shulman, 1986, p. 9), and *pedagogical content knowledge* as knowledge "which goes beyond knowledge of subject matter per se to the dimension of subject knowledge for teaching" (p. 9). He further defined *curricular knowledge* as "the pharmacopoeia from which the teacher draws those tools of teaching that present or exemplify particular content" (p. 10). Kirschner (1991, 1992) also argued that the way an expert works in his or her domain (epistemology) is not equivalent to the way one learns in that area (pedagogy). A similar line of reasoning was followed by Dehoney (1995), who posited that the mental models and strategies of experts have been developed through the slow process of accumulating experience in their domain areas.

Despite this clear distinction between learning a discipline and practicing a discipline, many curriculum developers, educational technologists, and educators seem to confuse the teaching of a discipline as inquiry (i.e., a curricular emphasis on the research processes within a science) with the teaching of the discipline by inquiry (i.e., using the research process of the discipline as a pedagogy or for learning). The basis of this confusion may lie in what Hurd (1969) called the rationale of the scientist, which holds that a course of instruction in science

should be a mirror image of a science discipline, with regard to both its conceptual structure and its patterns of inquiry. The theories and methods of modern science should be reflected in the classroom. In teaching a science, classroom operations should be in harmony with its investigatory processes and supportive of the conceptual, the intuitive, and the theoretical structure of its knowledge. (p. 16)

This rationale assumes

that the attainment of certain attitudes, the fostering of interest in science, the acquisition of laboratory skills, the learning of scientific knowledge, and the understanding of the nature of science were all to be approached through the

methodology of science, which was, in general, seen in inductive terms. (Hodson, 1988, p. 22)

The major fallacy of this rationale is that it makes no distinction between the behaviors and methods of a researcher who is an expert practicing a profession and those students who are new to the discipline and who are, thus, essentially novices.

According to Kyle (1980), scientific inquiry is a systematic and investigative performance ability incorporating unrestrained thinking capabilities after a person has acquired a broad, critical knowledge of the particular subject matter through formal teaching processes. It may not be equated with investigative methods of science teaching, self-instructional teaching techniques, or open-ended teaching techniques. Educators who confuse the two are guilty of the improper use of inquiry as a paradigm on which to base an instructional strategy.

Finally, Novak (1988), in noting that the major effort to improve secondary school science education in the 1950s and 1960s fell short of expectations, went so far as to say that the major obstacle that stood in the way of “revolutionary improvement of science education ... was the obsolete epistemology that was behind the emphasis on ‘inquiry’ oriented science” (pp. 79–80).

RESEARCH COMPARING GUIDED AND UNGUIDED INSTRUCTION

None of the preceding arguments and theorizing would be important if there was a clear body of research using controlled experiments indicating that unguided or minimally guided instruction was more effective than guided instruction. In fact, precisely as one might expect from our knowledge of human cognition and the distinctions between learning and practicing a discipline, the reverse is true. Controlled experiments almost uniformly indicate that when dealing with novel information, learners should be explicitly shown what to do and how to do it.

A number of reviews of empirical studies have established a solid research-based case against the use of instruction with minimal guidance. Although an extensive review of those studies is outside the scope of this article, Mayer (2004) recently reviewed evidence from studies conducted from 1950 to the late 1980s comparing pure discovery learning, defined as unguided, problem-based instruction, with guided forms of instruction. He suggested that in each decade since the mid-1950s, when empirical studies provided solid evidence that the then popular unguided approach did not work, a similar approach popped up under a different name with the cycle then repeating itself. Each new set of advocates for unguided approaches seemed either unaware of or uninterested in previous evidence that unguided approaches had not been validated. This pattern produced discovery learning, which gave way to experiential learning, which gave way to prob-

lem-based and inquiry learning, which now gives way to constructivist instructional techniques. Mayer (2004) concluded that the “debate about discovery has been replayed many times in education but each time, the evidence has favored a guided approach to learning” (p. 18).

Current Research Supporting Direct Guidance

Because students learn so little from a constructivist approach, most teachers who attempt to implement classroom-based constructivist instruction end up providing students with considerable guidance. This is a reasonable interpretation, for example, of qualitative case studies conducted by Aulls (2002), who observed a number of teachers as they implemented constructivist activities in their classrooms. He described the “scaffolding” that the most effective teachers introduced when students failed to make learning progress in a discovery setting. He reported that the teacher whose students achieved all of their learning goals spent a great deal of time in instructional interactions with students by

simultaneously teaching content and scaffolding-relevant procedures ... by (a) modeling procedures for identifying and self-checking important information ... (b) showing students how to reduce that information to paraphrases ... (c) having students use notes to construct collaborations and routines, and (d) promoting collaborative dialogue within problems. (p. 533)

Stronger evidence from well-designed, controlled experimental studies also supports direct instructional guidance (e.g., see Moreno, 2004; Tuovinen & Sweller, 1999). Hardiman, Pollatsek, and Weil (1986) and Brown and Campione (1994) noted that when students learn science in classrooms with pure-discovery methods and minimal feedback, they often become lost and frustrated, and their confusion can lead to misconceptions. Others (e.g., Carlson, Lundy, & Schneider, 1992; Schauble, 1990) found that because false starts are common in such learning situations, unguided discovery is most often inefficient. Moreno (2004) concluded that there is a growing body of research showing that students learn more deeply from strongly guided learning than from discovery. Similar conclusions were reported by Chall (2000), McKeough, Lupart, and Marini (1995), Schauble (1990), and Singley and Anderson (1989). Klahr and Nigam (2004), in a very important study, not only tested whether science learners learned more via a discovery versus direct instruction route but also, once learning had occurred, whether the quality of learning differed. Specifically, they tested whether those who had learned through discovery were better able to transfer their learning to new contexts. The findings were unambiguous. Direct instruction involving considerable guidance, including examples, resulted in vastly more learning than discovery. Those relatively few

students who learned via discovery showed no signs of superior quality of learning.

Cognitive load. Sweller and others (Mayer, 2001; Paas, Renkl, & Sweller, 2003; Sweller, 1999, 2004; Winn, 2003) noted that despite the alleged advantages of unguided environments to help students to derive meaning from learning materials, cognitive load theory suggests that the free exploration of a highly complex environment may generate a heavy working memory load that is detrimental to learning. This suggestion is particularly important in the case of novice learners, who lack proper schemas to integrate the new information with their prior knowledge. Tuovinen and Sweller (1999) showed that exploration practice (a discovery technique) caused a much larger cognitive load and led to poorer learning than worked-examples practice. The more knowledgeable learners did not experience a negative effect and benefited equally from both types of treatments. Mayer (2001) described an extended series of experiments in multimedia instruction that he and his colleagues have designed drawing on Sweller's (1988, 1999) cognitive load theory and other cognitively based theoretical sources. In all of the many studies he reported, guided instruction not only produced more immediate recall of facts than unguided approaches, but also longer term transfer and problem-solving skills.

Worked examples. A worked example constitutes the epitome of strongly guided instruction, whereas discovering the solution to a problem in an information-rich environment similarly constitutes the epitome of minimally guided discovery learning. The worked-example effect, which is based on cognitive load theory, occurs when learners required to solve problems perform worse on subsequent test problems than learners who study the equivalent worked examples. Accordingly, the worked-example effect, which has been replicated a number of times, provides some of the strongest evidence for the superiority of directly guided instruction over minimal guidance. The fact that the effect relies on controlled experiments adds to its importance.

The worked-example effect was first demonstrated by Sweller and Cooper (1985) and Cooper and Sweller (1987), who found that algebra students learned more studying algebra worked examples than solving the equivalent problems. Since those early demonstrations of the effect, it has been replicated on numerous occasions using a large variety of learners studying an equally large variety of materials (Carroll, 1994; Miller, Lehman, & Koedinger, 1999; Paas, 1992; Paas & van Merriënboer, 1994; Pillay, 1994; Quilici & Mayer, 1996; Trafton & Reiser, 1993). For novices, studying worked examples seems invariably superior to discovering or constructing a solution to a problem.

Why does the worked-example effect occur? It can be explained by cognitive load theory, which is grounded in the human cognitive architecture discussed earlier. Solving a problem requires problem-solving search and search must occur

using our limited working memory. Problem-solving search is an inefficient way of altering long-term memory because its function is to find a problem solution, not alter long-term memory. Indeed, problem-solving search can function perfectly with no learning whatsoever (Sweller, 1988). Thus, problem-solving search overburdens limited working memory and requires working memory resources to be used for activities that are unrelated to learning. As a consequence, learners can engage in problem-solving activities for extended periods and learn almost nothing (Sweller et al., 1982).

In contrast, studying a worked example both reduces working memory load because search is reduced or eliminated and directs attention (i.e., directs working memory resources) to learning the essential relations between problem-solving moves. Students learn to recognize which moves are required for particular problems, the basis for the acquisition of problem-solving schemas (Chi, Glaser, & Rees, 1982). When compared to students who have solved problems rather than studied worked examples, the consequence is the worked-example effect.

There are conditions under which the worked-example effect is not obtainable. First, it is not obtainable when the worked examples are themselves structured in a manner that imposes a heavy cognitive load. In other words, it is quite possible to structure worked examples in a manner that imposes as heavy a cognitive load as attempting to learn by discovering a problem solution (Tarmizi & Sweller, 1988; Ward & Sweller, 1990). Second, the worked-example effect first disappears and then reverses as the learners' expertise increases. Problem solving only becomes relatively effective when learners are sufficiently experienced so that studying a worked example is, for them, a redundant activity that increases working memory load compared to generating a known solution (Kalyuga, Chandler, Tuovinen, & Sweller, 2001). This phenomenon is an example of the expertise reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003). It emphasizes the importance of providing novices in an area with extensive guidance because they do not have sufficient knowledge in long-term memory to prevent unproductive problem-solving search. That guidance can be relaxed only with increased expertise as knowledge in long-term memory can take over from external guidance.

Process worksheets. Another way of guiding instruction is the use of process worksheets (Van Merriënboer, 1997). Such worksheets provide a description of the phases one should go through when solving the problem as well as hints or rules of thumb that may help to successfully complete each phase. Students can consult the process worksheet while they are working on the learning tasks and they may use it to note intermediate results of the problem-solving process.

Nadolski, Kirschner, and van Merriënboer (in press), for example, studied the effects of process worksheets with law students and found that the availability of a process worksheet had positive effects on learning task performance,

indicated by a higher coherence and more accurate content of the legal case being developed. Learners receiving guidance through process worksheets outperformed learners left to discover the appropriate procedures themselves.

RESEARCH ON EDUCATIONAL MODELS FAVORING MINIMAL GUIDANCE DURING INSTRUCTION IN VARIOUS SETTINGS

Having discussed both the human cognitive architecture responsible for learning and current research supporting direct instruction through guidance, this section discusses a number of the alternative educational models that see and use minimal guidance as an approach to learning and instruction.

Experiential Learning at Work

Kolb (1971) and Kolb and Fry (1975) argued that the learning process often begins with a person carrying out a particular action and then seeing or discovering the effect of the action in this situation. The second step is to understand these effects in the particular instance so that if the same action was taken in the same circumstances it would be possible to anticipate what would follow from the action. Using this pattern, the third step would be to understand the general principle under which the particular instance falls. They also suggested a number of learning styles that they hypothesized would influence the way that students took advantage of experiential situations.

Attempts to validate experiential learning and learning styles (Kolb, 1971, 1984, 1999) appear not to have been completely successful. Iliff (1994), for example, reported in “a meta-analysis of 101 quantitative LSI studies culled from 275 dissertations and 624 articles that were qualitative, theoretical, and quantitative studies of ELT and the Kolb Learning Style Inventory” (Kolb, Botatzis, & Mainemelis, 1999, p. 20) correlations classified as low ($< .5$) and effect sizes that were weak (.2) to medium (.5). He concluded that the magnitude of these statistics is not sufficient to meet standards of predictive validity to support the use of the measures or the experiential methods for training at work. Similarly, Ruble and Stout (1993), citing a number of studies from 1980 through 1991, concluded that the Kolb Learning Style Inventory (KLSI-1976) has low test–retest reliability, that there is little or no correlation between factors that should correlate with the classification of learning styles, and that it does not enjoy a general acceptance of its usefulness, particularly for research purposes.

Roblyer (1996) and Perkins (1991) examined evidence for minimally guided pedagogy in instructional design and instructional technology studies. Both researchers concluded that the available evidence does not support the use of minimal guidance and both suggested that some form of stronger guidance is necessary for both effective learning and transfer.

Individual Differences in Learning From Instruction

Constructivist approaches to instruction are based, in part, on a concern that individual differences moderate the impact of instruction. This concern has been shared by a large body of aptitude–treatment interaction (ATI) studies that examine whether the effects of different instructional methods are influenced by student aptitudes and traits (e.g., Cronbach & Snow, 1977; Kyllonen & Lajoie, 2003; Snow, Corno, & Jackson, 1996). Much of this work provides a clear antecedent to the expertise reversal effect, discussed earlier, according to which instructional methods that are effective for novices become less effective as expertise increases.

Cronbach and Snow’s (1977) review of ATI research described a number of replicated ordinal and disordinal interactions between various instructional methods and aptitudes. One of the most common ATI findings according to Kyllonen and Lajoie (2003) was “that strong treatments benefited less able learners and weaker treatments benefited more able learners” (p. 82). This conclusion anticipated the now recognized scaffolding effect.

In the instructional methods described by Cronbach and Snow (1977) strong treatments implied highly structured instructional presentations where explicit organization of information and learning support were provided. The weaker treatments were relatively unstructured and so provided much less learning support. The aptitude measures used in the research reviewed by Cronbach and Snow were varied but usually involved some measure of specific subject matter knowledge and measures of crystallized and fluid ability. Snow and Lohman (1984) encouraged research that attempts to understand the cognitive processes demanded by specific learning goals. They argued for a concern with describing the cognitive processes required to learn specific classes of tasks, how those processes are reflected in learner aptitudes, and how characteristics of instructional treatments might compensate for students with lower relevant aptitude by providing needed cognitive processes to help them achieve learning and transfer goals.

Knowing Less After Instruction

A related set of findings in the ATI research paradigm was described by Clark (1989). He reviewed approximately 70 ATI studies and described a number of experiments in which lower aptitude students who choose or were assigned to unguided, weaker instructional treatments receive significantly lower scores on posttests than on pretest measures. He argued that the failure to provide strong learning support for less experienced or less able students could actually produce a measurable loss of learning. The educational levels represented in the studies reviewed ranged from elementary classrooms to university and work settings and included a variety of types of problems and tasks. Even more distressing is the

evidence Clark (1982) presented that when learners are asked to select between a more or a less unguided version of the same course, less able learners who choose less guided approaches tend to like the experience even though they learn less from it. Higher aptitude students who chose highly structured approaches tended to like them but achieve at a lower level than with less structured versions but did not suffer by knowing less after than before instruction. Clark hypothesized that the most effective components of treatments help less experienced learners by providing task-specific learning strategies embedded in instructional presentations. These strategies require explicit, attention-driven effort on the part of learners and so tend not to be liked, even though they are helpful to learning. More able learners, he suggested, have acquired implicit, task-specific learning strategies that are more effective for them than those embedded in the structured versions of the course. Clark pointed to suggestive evidence that more able students who select the more guided versions of courses do so because they believe that they will achieve the required learning with a minimum of effort. Studies described by Woltz (2003) are a recent and positive example of ATI research that examines the cognitive processing required for learning tasks. He provided evidence that the same learner might benefit from stronger and weaker treatments depending on the type of learning and transfer outcome desired.

Empirical Evidence About Science Learning From Unguided Instruction

The work of Klahr and Nigam (2004), discussed earlier, unambiguously demonstrated the advantages of direct instruction in science. There is a wealth of such evidence. A series of reviews by the U.S. National Academy of Sciences has recently described the results of experiments that provide evidence for the negative consequences of unguided science instruction at all age levels and across a variety of science and math content. McCray, DeHaan, and Schuck (2003) reviewed studies and practical experience in the education of college undergraduates in engineering, technology, science, and mathematics. Gollub, Berthenthal, Labov, and Curtis (2003) reviewed studies and experience teaching science and mathematics in high school. Kilpatrick, Swafford, and Findell (2001) reported studies and made suggestions for elementary and middle school teaching of mathematics. Each of these and other publications by the U.S. National Academy of Sciences amply document the lack of evidence for unguided approaches and the benefits of more strongly guided instruction. Most provide a set of instructional principles for educators that are based on solid research. These reports were prepared, in part, because of the poor state of science and mathematics education in the United States. Finally, in accord with the ATI findings and the expertise reversal effect, Roblyer, Edwards, and Havriluk (1997) reported that teachers have found that discovery learning is successful only

when students have prerequisite knowledge and undergo some prior structured experiences.

Medical Problem-Based Learning Research

All in all, a lack of clarity about the difference between learning a discipline and research in the discipline coupled with the priority afforded to unbiased observation in the best inductivist and empiricist tradition has led many educators to advocate a problem-based method as the way to teach a discipline (Allen, Barker, & Ramsden, 1986; Anthony, 1973; Barrows & Tamblyn, 1980; Obioma, 1986). Not only did PBL seem to mesh with ideas in, for example, the philosophy of science, but it also fit well with progressive learner-centered views emphasizing direct experience and individual inquiry. Cawthron and Rowell (1978) stated that it all seemed to fit. The logic of knowledge and the psychology of knowledge coalesced under the umbrella term *discovery*. Why, he asked, should educators look further than the traditional inductivist and empiricist explanation of the process?

In an attempt to rescue medical students from lectures and memory-based recall exams, approximately 60 medical schools in North America have adopted PBL in the past two decades. This variant of constructivist instruction with minimal guidance, introduced at the McMaster University School of Medicine in 1969, asks medical students to work in groups to diagnose and suggest treatment for common patient symptoms. PBL student groups are supervised by a clinical faculty member who is directed not to solve problems for the students but instead to offer alternatives and suggest sources of information.

The best known survey of the comparisons of PBL with conventional medical school instruction was conducted by Albanese and Mitchell (1993). Their meta-analysis of the English language literature of the effectiveness of PBL produced a number of negative findings concerning its impact, including lower basic science exam scores, no differences in residency selections, and more study hours each day. They reported that although PBL students receive better scores for their clinical performance, they also order significantly more unnecessary tests at a much higher cost per patient with less benefit. There was an indication in their review that increased clinical practice evaluation scores may have been due to the fact the PBL students are required to spend more time in clinical settings.

Berkson (1993) also reviewed much of the literature on PBL and arrived at many of the same conclusions as Albanese and Mitchell (1993). She reviewed studies where the problem-solving ability of PBL students was compared with the same ability in conventionally trained students and found no support for any differences, and so failed to replicate the clinical advantage found by Albanese and Mitchell. Colliver (2000) reviewed existing studies comparing the effectiveness of PBL in medicine to conventional medical school curricula. He concluded that PBL studies show no statistical effect on the

performance of medical students on standardized tests or on instructor-designed tests during the first 2 years of medical school. Also important for medical educators has been the constant finding in research summaries that PBL is not more effective but is more costly than traditional instruction. Of course, some supporters of PBL are aware of its limitations. Hmelo-Silver (2004) placed strong question marks concerning the general validity of PBL. According to her,

Certain aspects of the PBL model should be tailored to the developmental level of the learners ... there may be a place for direct instruction on a just-in-time basis. In other words, as students are grappling with a problem and confronted with the need for particular kinds of knowledge, a lecture at the right time may be beneficial. ... Some techniques such as procedural facilitation, scripted cooperation, and structured journals may prove useful tools in moving PBL to other settings. (pp. 260–261)

Two major components of PBL are the explicit teaching of problem-solving strategies in the form of the hypothetico-deductive method of reasoning (Barrows & Tamblyn, 1980), and teaching of basic content in the context of a specific case or instance. Proponents argue that problem-centered education is superior to conventional education. Students taught problem-solving skills, in particular through the use of the hypothetico-deductive method, and given problems to practice those skills learn in a more meaningful way. It is assumed that because students are exposed to problems from the beginning, they have more opportunity to practice these skills, and that by explicitly applying the hypothetico-deductive method they learn to analyze problems and search for explanations, improving their comprehension of clinical problems (Norman & Schmidt, 1992). According to Patel, Arocha, and Leccisi (1995), “although these ideas seem intuitively appealing, the efficacy of these methods of clinical training is questionable” (p. XXX). Patel and colleagues argued that the hypothetico-deductive method may not be the most efficient way of solving clinical problems (Groen & Patel, 1985; Patel, Arocha, & Kaufman, 1994).

In the medical domain, Patel, Groen, and Norman (1993) showed that teaching basic science within a clinical context may have the disadvantage that once basic science knowledge is contextualized, it is difficult to separate it from the particular clinical problems into which it has been integrated. They showed that students trained in a PBL curriculum failed to separate basic science knowledge from the specific clinical knowledge associated with particular patients. Although PBL students generated more elaborate explanations, they had less coherent explanations and more errors. If students have difficulty separating the biomedical knowledge they have learned from the particular clinical cases associated with that knowledge, it is not surprising that when given a different problem they bring to bear on the new problem some irrelevant biomedical knowledge.

This appears to persist after training. In a study of the effect of undergraduate training in PBL—as opposed to a conventional curriculum—on the performance of residents on the organization of clinical and biomedical knowledge and the use of reasoning strategies, Patel et al. (1995) found that participants trained in PBL retained the backward-directed reasoning pattern, but did not seem to acquire forward-directed reasoning, which is a hallmark of expertise. This finding means that something in PBL may hinder the development of the forward reasoning pattern.

Experts use schema-based pattern recognition to determine the cause of a patient’s illness. According to Elstein (1994) knowledge organization and schema acquisition are more important for the development of expertise than the use of particular methods of problem solving. In this regard, cognitive research has shown that to achieve expertise in a domain, learners must acquire the necessary schemata that allow them to meaningfully and efficiently interpret information and identify the problem structure. Schemata accomplish this by guiding the selection of relevant information and the screening out of irrelevant information.

Patel et al. (1995) concluded that the negative results

can be accounted for by the effect of splitting of attention resources and the high working memory load on schema acquisition during problem solving. In solving clinical problems, subjects must attend to the current diagnostic hypothesis, the data in the problem presented to them, and any intermediate hypothesis between the diagnosis and the patient data (e.g., a pathophysiological process underlying the signs and symptoms). If we consider that more than one hypothesis has been generated, the cognitive resources needed for maintaining this information in working memory must be such that few cognitive resources are left for acquiring the problem schema. Although problems can be solved successfully using the hypothetico-deductive method, the scarcity of attentional and memory resources may result in the students having difficulties learning problem schemata in an adequate manner. It is possible to hypothesize that one of the reasons for the failure of PBLC subjects to acquire a forward-directed reasoning style as found in this study may be the use of problem solving strategies, such as the hypothetico-deductive method, as a learning strategy.

This is completely in line with our claim that the epistemology of a discipline should not be confused with a pedagogy for teaching or learning it. The practice of a profession is not the same as learning to practice the profession.

CONCLUSIONS

After a half-century of advocacy associated with instruction using minimal guidance, it appears that there is no body of research supporting the technique. In so far as there is any evidence from controlled studies, it almost uniformly supports

direct, strong instructional guidance rather than constructivist-based minimal guidance during the instruction of novice to intermediate learners. Even for students with considerable prior knowledge, strong guidance while learning is most often found to be equally effective as unguided approaches. Not only is unguided instruction normally less effective; there is also evidence that it may have negative results when students acquire misconceptions or incomplete or disorganized knowledge.

Although the reasons for the ongoing popularity of a failed approach are unclear, the origins of the support for instruction with minimal guidance in science education and medical education might be found in the post-*Sputnik* science curriculum reforms such as Biological Sciences Curriculum Study, Chemical Education Material Study, and Physical Science Study Committee. At that time, educators shifted away from teaching a discipline as a body of knowledge toward the assumption that knowledge can best or only be learned through experience that is based only on the procedures of the discipline. This point of view appears to have led to unguided practical or project work and the rejection of instruction based on the facts, laws, principles, and theories that make up a discipline's content. The emphasis on the practical application of what is being learned seems very positive. However, it may be an error to assume that the pedagogic content of the learning experience is identical to the methods and processes (i.e., the epistemology) of the discipline being studied and a mistake to assume that instruction should exclusively focus on application. It is regrettable that current constructivist views have become ideological and often epistemologically opposed to the presentation and explanation of knowledge. As a result, it is easy to share the puzzlement of Handelsman et al. (2004), who, when discussing science education, asked: "Why do outstanding scientists who demand rigorous proof for scientific assertions in their research continue to use and, indeed defend on the bias of intuition alone, teaching methods that are not the most effective?" (p. 521). It is also easy to agree with Mayer's (2004) recommendation that we "move educational reform efforts from the fuzzy and unproductive world of ideology—which sometimes hides under the various banners of constructivism—to the sharp and productive world of theory-based research on how people learn" (p. 18).

REFERENCES

- Albanese, M., & Mitchell, S. (1993). Problem-based learning: A review of the literature on its outcomes and implementation issues. *Academic Medicine*, 68, 52–81.
- Allen, J. B., Barker, L. N., & Ramsden, J. H. (1986). Guided inquiry laboratory. *Journal of Chemical Education*, 63, 533–534.
- Anderson, J. R. (1996). ACT: A simple theory of complex cognition. *American Psychologist*, 51, 355–365.
- Anthony, W. S. (1973). Learning to discover rules by discovery. *Journal of Educational Psychology*, 64, 325–328.
- Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. Spence & J. Spence (Eds.), *The psychology of learning and motivation* (Vol. 2, pp. 89–195). New York: Academic.
- Aulls, M. W. (2002). The contributions of co-occurring forms of classroom discourse and academic activities to curriculum events and instruction. *Journal of Educational Psychology*, 94, 520–538.
- Barrows, H. S., & Tamblyn, R. M. (1980). *Problem-based learning: An approach to medical education*. New York: Springer.
- Berkson, L. (1993). Problem-based learning: Have the expectations been met? *Academic Medicine*, 68(Suppl.), S79–S88.
- Bernstein, D. A., Penner, L. A., Clarke-Stewart, A., Roy, E. J., & Wickens, C. D. (2003). *Psychology* (6th ed.). Boston: Houghton-Mifflin.
- Boud, D., Keogh, R., & Walker, D. (Eds.). (1985). *Reflection: Turning experience into learning*. London: Kogan Page.
- Brown, A., & Campione, J. (1994). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229–270). Cambridge, MA: MIT Press.
- Bruner, J. S. (1961). The art of discovery. *Harvard Educational Review*, 31, 21–32.
- Carlson, R. A., Lundy, D. H., & Schneider, W. (1992). Strategy guidance and memory aiding in learning a problem-solving skill. *Human Factors*, 34, 129–145.
- Carroll, W. (1994). Using worked examples as an instructional support in the algebra classroom. *Journal of Educational Psychology*, 86, 360–367.
- Cawthron, E. R., & Rowell, J. A. (1978). Epistemology and science education. *Studies in Science Education*, 5, 51–59.
- Chall, J. S. (2000). *The academic achievement challenge*. New York: Guilford.
- Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, 4, 55–81.
- Chi, M., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence* (pp. 7–75). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Clark, R. E. (1982). Antagonism between achievement and enjoyment in ATI studies. *Educational Psychologist*, 17, 92–101.
- Clark, R. E. (1989). When teaching kills learning: Research on mathematics. In H. N. Mandl, N. Bennett, E. de Corte, & H. F. Freidrich (Eds.), *Learning and instruction: European research in an international context* (Vol. II). London: Pergamon.
- Clark, R. E., & Estes, F. (1998). Technology or craft: What are we doing? *Educational Technology*, 38(5), 5–11.
- Clark, R. E., & Estes, F. (1999). The development of authentic educational technologies. *Educational Technology*, 37(2), 5–16.
- Colliver, J. A. (2000). Effectiveness of problem-based learning curricula: Research and theory. *Academic Medicine*, 75, 259–266.
- Cooper, G., & Sweller, J. (1987). The effects of schema acquisition and rule automation on mathematical problem-solving transfer. *Journal of Educational Psychology*, 79, 347–362.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 24, 87–114.
- Craig, R. (1956). Directed versus independent discovery of established relations. *Journal of Educational Psychology*, 47, 223–235.
- Cronbach, L. J., & Snow, R. E. (1977). *Aptitudes and instructional methods: A handbook for research on interactions*. New York: Irvington.
- De Groot, A. D. (1965). *Thought and choice in chess*. The Hague, Netherlands: Mouton. (Original work published 1946)
- Dehoney, J. (1995). Cognitive task analysis: Implications for the theory and practice of instructional design. *Proceedings of the Annual National Convention of the Association for Educational Communications and Technology (AECT)*, 113–123. (ERIC Document Reproduction Service No. ED 383 294)
- Dewey, J. (1938). *Experience and education*. New York: Simon & Schuster.
- Egan, D. E., & Schwartz, B. J. (1979). Chunking in recall of symbolic drawings. *Memory and Cognition*, 7, 149–158.

- Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, 102, 211–245.
- Estes, F., & Clark, R. E. (1999). Authentic educational technologies: The lynchpin between theory and practice. *Educational Technology*, 37(6), 5–13.
- Glaser, R. (1987). Further notes toward a psychology of instruction. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. III). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Gollub, J. P., Berthenthal, M., Labov, J., & Curtis, C. (Eds.). (2003). *Learning and understanding: Improving advanced study of mathematics and science in U.S. high schools*. Washington, DC: National Academies Press.
- Handelsman, J., Egert-May, D., Beichner, R., Bruns, P., Change, A., DeHaan, R., et al. (2004). Scientific teaching. *Science*, 304, 521–522.
- Hardiman, P., Pollatsek, A., & Weil, A. (1986). Learning to understand the balance beam. *Cognition and Instruction*, 3, 1–30.
- Hodson, D. (1988). Experiments in science and science teaching. *Educational Philosophy and Theory*, 20, 53–66.
- Illiff, C. H. (1994). *Kolb's learning style inventory: A meta-analysis*. Unpublished doctoral dissertation, Boston University, Boston.
- Jeffries, R., Turner, A., Polson, P., & Atwood, M. (1981). Processes involved in designing software. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 255–283). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Jonassen, D. (1991). Objectivism vs. constructivism. *Educational Technology Research and Development*, 39(3), 5–14.
- Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). Expertise reversal effect. *Educational Psychologist*, 38, 23–31.
- 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.
- Kilpatrick, J., Swafford, J., & Findell, B. (Eds.). (2001). *Adding it up: Helping children learn mathematics*. Washington, DC: National Academies Press.
- Kirschner, P. A. (1991). *Practicals in higher science education*. Utrecht, Netherlands: Lemma.
- Kirschner, P. A. (1992). Epistemology, practical work and academic skills in science education. *Science and Education*, 1, 273–299.
- Kirschner, P. A., Strijbos, J.-W., & Martens, R. L. (2004). CSCL in higher education: A framework for designing multiple collaborative environments. In J.-W. Strijbos, P. A. Kirschner, & R. L. Martens (Eds.), *What we know about CSCL in higher education*. Dordrecht, Netherlands: Kluwer.
- Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effects of direct instruction and discovery learning. *Psychological Science*, 15, 661–667.
- Kolb, D. A. (1971). *Individual learning styles and the learning process* (Working Paper No. 535–71). Cambridge, MA: Sloan School of Management, Massachusetts Institute of Technology.
- Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Englewood Cliffs, NJ: Prentice-Hall.
- Kolb, D. A. (1999). *Learning Style Inventory, version 3*. Boston: TRG Hay/McBer, Training Resources Group.
- Kolb, D. A., Boyatzis, R. E., & Mainemelis, C. (1999). *Experiential learning theory: Previous research and new directions*. Cleveland, OH: Case Western Reserve University.
- Kolb, D. A., & Fry, R. (1975). Toward an applied theory of experiential learning. In C. Cooper (Ed.), *Studies of group process* (pp. 33–57). New York: Wiley.
- Kyle, W. C., Jr. (1980). The distinction between inquiry and scientific inquiry and why high school students should be cognizant of the distinction. *Journal of Research on Science Teaching*, 17, 123–130.
- Kyllonen, P. C., & Lajoie, S. P. (2003). Reassessing aptitude: Introduction to a special issue in honor of Richard E. Snow. *Educational Psychologist*, 38, 79–83.
- Mayer, R. (2001). *Multi-media learning*. Cambridge, UK: Cambridge University Press.
- Mayer, R. (2004). Should there be a three-strikes rule against pure discovery learning? The case for guided methods of instruction. *American Psychologist*, 59, 14–19.
- McCray, R., DeHaan, R. L., & Schuck, J. A. (Eds.). (2003). *Improving undergraduate instruction in science, technology, engineering, and mathematics: Report of a workshop*. Washington, DC: National Academies Press.
- McKeough, A., Lupart, J., & Marini, A. (Eds.). (1995). *Teaching for transfer: Fostering generalization in learning*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
- Miller, C., Lehman, J., & Koedinger, K. (1999). Goals and learning in microworlds. *Cognitive Science*, 23, 305–336.
- Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81–97.
- Moreno, R. (2004). Decreasing cognitive load in novice students: Effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science*, 32, 99–113.
- Nadolski, R. J., Kirschner, P. A., & van Merriënboer, J. J. G. (in press). Optimising the number of steps in learning tasks for complex skills. *British Journal of Educational Psychology*.
- Novak, J. D. (1988). Learning science and the science of learning. *Studies in Science Education*, 15, 77–101.
- Obioma, G. O. (1986). Expository and guided discovery methods of presenting secondary school physics. *European Journal of Science Education*, 8, 51–56.
- Paas, F. (1992). Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach. *Journal of Educational Psychology*, 84, 429–434.
- Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. *Educational Psychologist*, 38, 1–4.
- Paas, F., Renkl, A., & Sweller, J. (2004). Cognitive load theory: Instructional implications of the interaction between information structures and cognitive architecture. *Instructional Science*, 32, 1–8.
- Paas, F., & van Merriënboer, J. (1994). Variability of worked examples and transfer of geometrical problem solving skills: A cognitive-load approach. *Journal of Educational Psychology*, 86, 122–133.
- Papa, F. J., & Harasym, P. H. (1999). Medical curriculum reform in North America, 1765 to the present: A cognitive science perspective. *Academic Medicine*, 74, 154–164.
- Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books.
- Perkins, D. N. (1991). Technology meets constructivism: Do they make a marriage? *Educational Technology*, 13, 18–23.
- Peterson, L., & Peterson, M. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, 58, 193–198.
- Pillay, H. (1994). Cognitive load and mental rotation: Structuring orthographic projection for learning and problem solving. *Instructional Science*, 22, 91–113.
- 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.
- Roblyer, M. D. (1996). The constructivist/objectivist debate: Implications for instructional technology research. *Learning and Leading With Technology*, 24, 12–16.
- Roblyer, M. D., Edwards, J., & Havriluk, M. A. (1997). *Integrating educational technology into teaching* (2nd ed.). Upper Saddle River, NJ: Prentice-Hall.
- Ruble, T. L., & Stout, D. E. (1993, March). Learning styles and end-user training: An unwarranted leap of faith. *MIS Quarterly*, 17, 115–117.
- Salomon, G. (1979). *Interaction of media, cognition and learning*. San Francisco, CA: Jossey-Bass.
- Schauble, L. (1990). Belief revision in children: The role of prior knowledge and strategies for generating evidence. *Journal of Experimental Child Psychology*, 49, 31–57.

- Schmidt, H. G. (1983). Problem-based learning: Rationale and description. *Medical Education*, 17, 11–16.
- Schmidt, H. G. (1998). Problem-based learning: Does it prepare medical students to become better doctors? *The Medical Journal of Australia*, 168, 429–430.
- Schmidt, H. G. (2000). Assumptions underlying self-directed learning may be false. *Medical Education*, 34, 243–245.
- Schraagen, J. M., Chipman, S., & Shalin, V. (2000). *Cognitive task analysis*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
- Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, 15, 4–14.
- Shulman, L. S., & Hutchings, P. (1999, September–October). The scholarship of teaching: New elaborations, new developments. *Change*, 11–15.
- Shulman, L., & Keisler, E. (Eds.). (1966). *Learning by discovery: A critical appraisal*. Chicago: Rand McNally.
- Singley, M. K., & Anderson, J. R. (1989). *The transfer of cognitive skill*. Cambridge, MA: Harvard University Press.
- Snow, R. E., Corno, L., & Jackson, D. N., III. (1994). Individual differences in conation: Selected constructs and measures. In H. F. O'Neil & M. Drillings (Eds.), *Motivation: Theory and research* (pp. 71–99). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Snow, R. E., & Lohman, D. F. (1984). Toward a theory of cognitive aptitude for learning from instruction. *Journal of Educational Psychology*, 76, 347–376.
- Steffe, L., & Gale, J. (Eds.). (1995). *Constructivism in education*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12, 257–285.
- Sweller, J. (1999). *Instructional design in technical areas*. Camberwell, Australia: ACER Press.
- Sweller, J. (2003). Evolution of human cognitive architecture. In B. Ross (Ed.), *The psychology of learning and motivation* (Vol. 43, pp. 215–266). San Diego, CA: Academic.
- Sweller, J. (2004). Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science*, 32, 9–31.
- Sweller, J., & Cooper, G. A. (1985). The use of worked examples as a substitute for problem solving in learning algebra. *Cognition and Instruction*, 2, 59–89.
- Sweller, J., Mawer, R., & Howe, W. (1982). The consequences of history-cued and means-ends strategies in problems solving. *American Journal of Psychology*, 95, 455–484.
- Sweller, J., van Merriënboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, 10, 251–296.
- Tarmizi, R., & Sweller, J. (1988). Guidance during mathematical problem solving. *Journal of Educational Psychology*, 80, 424–436.
- Trafton, J. G., & Reiser, R. J. (1993). The contribution of studying examples and solving problems to skill acquisition. In *Proceedings of the 15th Annual Conference of the Cognitive Science Society* (pp. 1017–1022). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Tuovinen, J. E., & Sweller, J. (1999). A comparison of cognitive load associated with discovery learning and worked examples. *Journal of Educational Psychology*, 91, 334–341.
- Van Joolingen, W. R., de Jong, T., Lazonder, A. W., Savelsbergh, E. R., & Manlove, S. (in press). Co-Lab: Research and development of an online learning environment for collaborative scientific discovery learning. *Computers in Human Behavior*.
- Van Merriënboer, J. J. G. (1997). *Training complex cognitive skills*. 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(2), 39–64.
- Ward, M., & Sweller, J. (1990). Structuring effective worked examples. *Cognition and Instruction*, 7, 1–39.
- Wickens, C. D. (1989). Attention and skilled performance. In D. H. Holding (Ed.), *Human skills* (pp. 70–105). New York: Wiley.
- Winn, W. (2003). Research methods and types of evidence for research in educational psychology. *Educational Psychology Review*, 15, 367–373.
- Woloschuk, W., Harasym, P., Mandin, H., & Jones, A. (2000). Use of scheme-based problem solving: An evaluation of the implementation and utilization of schemes in a clinical presentation curriculum. *Medical Education*, 34, 437–442.
- Woltz, D. J. (2003). Implicit cognitive processes as aptitudes for learning. *Educational Psychologist*, 38, 95–104.