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Why Minimally Guided Teaching Techniques Do Not Work: A Reply to Commentaries

John Sweller
School of Education
University of New South Wales, Australia

Paul A. Kirschner
Research Centre Learning in Interaction
Utrecht University/Open University of The Netherlands, The Netherlands

Richard E. Clark
Rossier School of Education
University of Southern California

In this reply to commentaries on the Kirschner, Sweller, and Clark (2006) paper, we not only reemphasize the importance of randomized, controlled experimental tests of competing instructional procedures, but also indicate that altering one variable at a time is an essential feature of a properly controlled experiment. Furthermore, we also emphasize that variable must be relevant to the issue at hand with its effects explainable by our knowledge of human cognitive architecture. We reject the view that the presentation of relevant information should be reduced in favor of teaching learners how to find information. Lastly, we indicate that we believe a new educational psychology has been developed that has the potential to rapidly change our field.

From a historical perspective, the current controversies regarding cognitive processes and instructional procedures are predictable. New data and new conceptualizations have placed us in a transition period and transitions are frequently fraught with lack of understanding and controversy. The consensus that was forged more than a generation ago in the 1970s and 1980s lasted well into the 1990s, but has largely collapsed under the weight of its contradictions and a significant, increasing amount of data demonstrating a glaring need for change. A case study of that need is provided by the responses to Kirschner, Sweller, and Clark (2006). While the views offered in the rejoinders are thoughtful and considerate, the attempt by the authors to reconcile those views with the recent explosion of knowledge concerning cognitive processes results in a series of logical contradictions. We will begin by discussing the Schmidt, Loyens, van Gog, and Paas' (2007) response.

Correspondence should be addressed to John Sweller, School of Education, University of New South Wales, Sydney, NSW 2052, Australia. E-mail: j.sweller@unsw.edu.au

PROVIDING VERSUS DISCOVERING SOLUTIONS: RESPONSE TO SCHMIDT ET AL. (2007)

Schmidt et al. (2007) make clear that they concur with our major issue that the structures that constitute human cognitive architecture point to the importance of emphasizing guidance during learning. They deny that problem-based learning (PBL) is in conflict with our knowledge of human cognitive architecture and specifically deny that PBL is in conflict with the architecture commonly used by cognitive load theory (see Sweller & Sweller, 2006, for a recent version). Their disagreement with our contention that PBL deemphasizes guidance is surely in conflict with the essential purpose of the technique. Surely the *raison d'être* of PBL is to deemphasize direct instructional guidance? The website of the cradle of PBL (McMaster University—www-fhs.mcmaster.ca/mhsi/problem-.htm) still emphasizes that PBL is "self-directed." Guidance during problem solving requires giving a learner a problem and indicating a possible solution. Requiring that a learner discover a problem solution always reduces guidance compared to presenting the solution. The process of discovery is in conflict with our current knowledge of human cognitive architecture which assumes that working memory is severely limited in capacity when dealing with novel information sourced from the external environment but largely unlimited when dealing with familiar, organized information sourced from long-term memory. If this view of human cognitive architecture is valid, then by definition novices should not be presented with material in a manner that unnecessarily requires them to search for a solution with its attendant heavy working memory load rather than being presented with a solution.

At no point does the Schmidt et al. (2007) commentary address this critical point: we know that problem-solving search imposes a heavy extraneous cognitive load, so why, then, should we require learners to engage in problem-solving search? Learners could much more easily be given the information they are attempting to discover. This issue becomes obvious early in their commentary. When discussing the clinical psychology problem labeled "Little Monsters," the authors describe the usual PBL approach which involves "initial discussion", construction of a "tentative theory" resulting in "questions" and "dilemmas" to be resolved by further discussion and "studying sources of information." At no point in the two paragraphs following the presentation of the problem is there any mention of the effect of working memory and its limitations. What are the consequences of all of the above cognitive activities on a limited working memory? What would be the consequences of simply outlining a clear and effective solution, to the problem rather than having learners spend unnecessary time and effort on extraneous search activities? The worked-example effect makes quite clear the superiority of providing problem solutions over searching for them (e.g. Paas & van Gog, 2006).

In the first paragraph of the section entitled "Effective Learning According to Cognitive Load Theory (CLT)," Schmidt et al. (2007) do mention the worked-example effect, but at no point do they relate the effect to PBL. Indeed, the worked-example effect is ignored in the rest of the paper. If problem solving is ineffective as a learning device as suggested by the worked-example effect, why does it suddenly become effective when used in PBL? Why is the worked-example effect relevant to instruction except when that instruction is based on PBL? It is contradictory to both accept the validity of the worked-example effect and then not accept its consequences in the case of PBL.

Schmidt et al. (2007) use a previous experimental study on students learning the processes of osmosis to support their argument (Schmidt, De Grave, De Volder, Moust, & Patel, 1989). In Experiment 2 of this paper, one group was asked to discuss why red blood cells placed in pure water expand and burst while the same cells placed in salt water shrink. Learners had little or no prior knowledge. Next, they studied a text on osmosis followed by a knowledge test. A control group discussed an unrelated problem followed by the osmosis text and the test. The group that discussed the blood problem performed better on the test, a result interpreted as indicating the importance of activating prior knowledge through discussion.

We have no doubt that considering a relevant problem prior to instruction and a test is superior to considering an *irrelevant* problem. Yet the real question is not whether providing learners with the problem of a blood cell in pure or salt water and letting them discuss it is superior to providing them with an irrelevant problem to discuss (i.e., the control condition that the authors chose), but whether discussing that problem without appropriate guidance for a fixed time is better than being presented with that problem along with a clear explanation of its solution for the same fixed time—in other words, a worked example that provides "direct instructional guidance" which we 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" (Kirschner et al., 2006, p. 75). Such a comparison would constitute an appropriate controlled experiment if one wishes to compare the effects of instructional methods providing more or less guidance; and that, we assume, is what Schmidt et al. (2007) were attempting to do. We hope that few readers today would have doubts concerning the results of such an experiment.

In the sub-section *Group Discussion*, Schmidt et al. (2007) refer to an experiment that they indicate was referred to by Schmidt (1993). From our reading of Schmidt (1993) and Schmidt et al. (2007), the procedure and results of that experiment are indistinguishable from Experiment 1 of Schmidt et al. (1989). (Our two paragraphs above refer to Experiment 2 of Schmidt et al., 1989). Accordingly, we will comment on Experiment 1 of Schmidt et al. (1989). That experiment tested a hypothesis similar to that of Experiment 2. In Experiment 1, participants who had prior experience with the topic of osmosis were used. Again, the aim was to see if discussing the blood-cells-in-water problem would be beneficial compared to discussing an irrelevant problem. Unlike Experiment 2, participants were not provided with instruction concerning osmosis, but they relied on their previous knowledge. As was the case in Experiment 2, discussing a relevant problem was superior to discussing an irrelevant problem despite the fact that "Recording the discussion verified that no information was provided from which the subjects could derive insights into the underlying mechanisms of either problem" (p. 612). We wonder how a group that had been directly and explicitly provided insights into the underlying mechanisms of osmosis by being presented with the osmosis problem along with its solution might have performed. A comparison of such groups with a PBL group would provide a direct test of the PBL hypothesis. The worked-example effect provides a clear expectation of the result of such a comparison: The learners provided with direct instructional guidance could be expected to learn more concerning osmosis and its underlying mechanisms.

Finally, Schmidt et al. (2007) also introduce a specific type of PBL, namely, cooperative PBL. Referring to group discussion they state that, ". . . activating and sharing prior knowledge among group members" (p. 95) decreases intrinsic cognitive load. If cooperative PBL is an effective and efficient instructional strategy, it will at best increase germane load with a concomitant (though not necessarily equal) decrease in extraneous load. By their own definition, intrinsic cognitive load "is determined by the degree to which the elements of the to-be-learned information can, or cannot, be understood in isolation" (p. 93). Cooperation or collaboration, however, imposes costs in terms of cognitive load in that the coordination and execution of communication and interaction in groups is, in itself, often a cognitively taxing experience. If the communication and coordination of the problem-solving process in the group (i.e., the interaction processes) proceeds effectively and efficiently, this will only add new germane load to the already existent intrinsic, germane, and extraneous load caused by PBL (i.e., trying to solve the problem, looking for relevant information, evaluating alternative solutions, etc.). It is likely that the evidence supporting collaborative learning is due, in large part, to the failure to provide adequate levels of guidance in instruction. In a vacuum, learners are sometimes able to provide collaborative guidance but the cognitive cost of collaboration is high. When the interaction is not effective and/or efficient, then a worst case scenario arises, namely that a cognitively taxing pedagogy is compounded by extra, and solely, extraneous load caused by poor interaction and the extra coordination needed. This is, in our opinion, not a very pretty picture. While we may want students to learn to cooperate and collaborate, why not teach those skills separately in a guided fashion?

Unlike many researchers who favor PBL or indeed, take constructivist teaching positions, Schmidt et al. (2007) are aware of the critical importance of taking human cognitive architecture into account when devising instructional procedures. More importantly in the present context, we share their concern that instructional procedures need to be tested using randomized, controlled experiments. Nevertheless, we do not believe the studies they cite provide a test of the PBL hypothesis that addresses its effectiveness over minimally guided instruction. The closest available studies are concerned with the worked-example effect and the results of those studies are unambiguous: PBL is ineffective compared with instruction that provides direct, explicit information.

AMOUNT AND TYPE OF GUIDANCE: A REPLY TO HMELO-SILVER, DUNCAN, AND CHINN (2007)

Hmelo-Silver et al. (2007) also agree with us that instructional guidance is important and also agree with what Schmidt et al. (2007) feel—that PBL emphasizes instructional guidance. Hmelo-Silver et al. (2007) do not distinguish between PBL and inquiry learning (IL), but insist both are different than discovery learning. Historically, discovery learning in its pure form was slowly jettisoned and replaced by "guided discovery" as the full disaster of pure discovery became apparent. Similarly, the more recent emphasis on the "scaffolding" supported by Schmidt et al. (2007) and Hmelo-Silver (2007) for PBL and IL has been forced by evidence concerning the ineffectiveness of "pure" PBL and IL without scaffolding. Yet we are still unable to detect the differences between guided discovery and PBL and/or IL with scaffolding. Furthermore, while scaffolding, like all guidance for novices, is better than no scaffolding, the ultimate scaffold, providing learners with all information needed including a complete problem solution—either prior to a task or just-in-time during a task—is better still.

In their section entitled "The Use of Scaffolding in PBL and IL," Hmelo-Silver et al. (2007) describe a large range of effective scaffolds. We agree that the different scaffolds are effective compared to no scaffolding. However, the only scaffolds they seem to ignore are providing learners with a problem and a problem-solving procedure that can be used for generating this solution. In other words, both a fully worked out example of a solution (i.e., task support) and the process-related information used to reach the solution is necessary for the design of suitable learning tasks and the associated instructional support and guidance structures (Van Merriënboer & Kirschner, 2007).

Hmelo-Silver et al. (2007) make minimal reference to human cognitive architecture. They indicate, correctly, that scaffolding reduces working memory load. However, in common with other supporters of constructivist teaching, they make no attempt to indicate how failing to provide learners with a problem solution assists in transferring that solution to long-term memory. As indicated in Kirschner et al. (2006), we believe the aim of learning is to increase knowledge in long-term memory. The techniques favored by Hmelo-Silver et al. (2007) were developed in an era when it was thought that the central component of human cognition was not knowledge in long-term memory, but rather the ability to devise novel, general problem-solving and thinking strategies. IL was intended to foster this skill. The failure over many decades to isolate a single, novel, teachable, general problem-solving or thinking strategy has inhibited that pursuit. As a consequence, there is a discord, indeed a contradiction, between the aims of IL and the processes our cognitive architecture support. That architecture is focused on accumulating integrated knowledge (i.e., schemas) in long-term memory (e.g., Sweller & Sweller, 2006). Mayer (1987) posited that general problem-solving strategies usually fail, but that domain-specific strategies are more successful. Specifically he noted that "to solve [mathematical] problems requires the acquisition of large amounts of domain-specific knowledge" (p. 109). In contrast, IL focuses, at least in part, on teaching general problem-solving strategies, but despite half a century of effort, no sophisticated, teachable general problem-solving strategies have been isolated. We must learn domain-specific solutions to specific problems and the best way to acquire domain-specific problem-solving strategies is to be given the problem with its solution, leaving no role for IL.

When Hmelo-Silver et al. (2007) state, "In PBL, students learn content, strategies, and self-directed learning skills through collaboratively solving problems, reflecting on their experiences, and engaging in self-directed inquiry," which strategies and which self-directed learning skills are being referred to (p. 100)? What is an example of a "flexible thinking skill" and where is the evidence that it can be taught (p. 102)? How does one teach "sense making" (p. 101)? Has anyone ever tested whether learners who learn sense making, however defined, through inquiry-based techniques are better at sense making in a novel environment than learners who are presented the same information via, for example, problems and their solutions? Where does the newly learned sense-making skill reside; in long-term memory? Is that where a flexible teaching skill resides as well? If we can describe these skills, why can we not teach them directly and explicitly? In our experience, they are rarely if ever described, let alone taught. If self-directed learning skills means learning to use the internet or learning to use a library, those skills can and should be taught directly and explicitly.

The question arises as to whether these thinking and sense-making skills constitute more than domain-specific knowledge. In trying to acquire complex cognitive skills, the beginner tries to understand the task. Understanding a task has occurred when the learner understands the substantive structure of a domain (Kirschner, 1992). Beginners learn to observe and to understand what a task involves and how a task is carried out (i.e., through the use of worked out examples or modeling examples and cases). What they know determines what they see; an empty mind sees little and understands even less (Wellington, 1981). Experience does not give concepts meaning, if anything "concepts give experience meaning" (Theobald, 1968).

There is overwhelming evidence that providing a learner with a problem solution enhances learning, as we suggest, compared to having them discover the solution themselves (with or without assistance via scaffolding). Hmelo-Silver et al. (2007) suggest that the "modeling" used by PBL and inquiry-based learning is very similar to worked examples (p. 102). We agree and to the extent that PBL and inquiry-based learning use modeling, we support the procedures. Our difficulty lies in the insistence on the use of unnecessary problem-solving search as a teaching tool. As far as we can see, modeling seems to be a very minor part of PBL and IL in most of the papers cited by Hmelo-Silver et al. (2007).

Hmelo-Silver et al. (2007) also cite several studies that they claim support an IL position. While many of those studies are valuable for other reasons, as far as we can see, all seem fatally flawed as examples of studies that provide support for the claim that an IL procedure is as effective as or more effective than a fully guided learning procedure. For example, Schwartz and Bransford (1998) found that learners who tried to explain a pattern of results from a real memory experiment learned more from a subsequent lecture on the material than students who were simply provided with a summary of the results. Hmelo-Silver et al. (2007) claim that this result provides evidence for an IL approach (see p. 103). We doubt this claim. Learners provided with the summary did not have access to the raw data and those data appeared to contain considerable amounts of important information essential to understanding the results. From our perspective, an appropriate control would be for both groups to have access to the raw data with one group asked to analyze the data and the other group *provided* with an appropriate analysis. We hypothesize that those provided with a detailed, appropriate analysis should outperform those required to provide their own analysis. Because that comparison was not made, this study, which is important for a variety of other reasons, cannot be used to provide evidence for the value of inquiry-based teaching over direct instruction.

Hmelo-Silver et al. (2007) describe several large-scale studies in which learners are presented an entirely new curriculum, the results of which can be compared with an existing curriculum. In all cases, the new curriculum uses versions of PBL or inquiry-based learning. The Cognition and Technology Group at Vanderbilt (1992) and Lynch, Kuipers, Pyke, and Szesze (2005) provide examples. Both studies presented learners with a completely new curriculum. Studies such as these are frequently valuable, but can never be used to support a particular teaching procedure such as inquiry-based learning for two basic reasons. First, we do not know the extent to which teachers in the conventional classrooms used IL techniques and second, we do not know the extent to which the results are due to the new curriculum itself. If one group of students is taught using new curriculum materials while the other group uses older, possibly inferior materials, that differential information alone can generate the learning differences found. If we want to test the effectiveness of IL we should run experiments in which only one variable is varied at a time, at least in the first instance, and that variable needs to be the relevant variable.

Most of the studies that Hmelo-Silver et al. (2007) cite as providing evidence for PBL or inquiry-based learning used an experimental design in which one group of students was presented with PBL or inquiry-based learning while another group was provided with lectures, written material, discussions, or other forms of more conventional instructions. We believe such experimental designs are almost useless in determining effective instructional procedures. Altering one variable at a time is a *sine qua non* of an effective experiment. Is a lecture better than a discussion of a problem? A good lecture is likely to be superior on most measures to a poor discussion of a problem while a good discussion of a problem is just as likely to be better than a poor lecture. We all know of lectures in which the possibility of students learning anything useful other than avoiding the lecturer is slim. We might expect that meta-analyses of such studies would yield mixed, ambiguous results, precisely the findings of the meta-analyses cited by Hmelo-Silver et al. (2007). (It might be noted that this failure to use controlled experiments appropriately is not restricted to this field. The early days following the introduction of computers in education are replete with studies attempting to prove that the new technology was superior to lectures or books with a similar lack of success for the same reasons. A good lecture is almost always going to be superior to poor computer-based instruction and vice-versa.)

Nothing in the previous paragraph should be interpreted as indicating that proper, randomized, controlled experiments cannot be run or even that they are particularly difficult to run. Such experiments can and have been used to directly test the consequences of solving problems compared to having answers provided to the same problems. The worked-example effect is directly relevant to the current debate. It is tested by having one group of learners solve problems while another group is presented exactly the same problems under exactly the same conditions with one exception: rather than solving the problems themselves they are presented with the solutions. Any differences among groups on subsequent test problems (including it must be emphasized, transfer problems) must be due to this factor because all other factors are controlled for.

Hmelo-Silver et al. (2007) indicate that there are few experimental studies comparing explicit instruction on the one hand and PBL and inquiry-based learning on the other. This assertion is not strictly true. Even if one excludes those studies with uninterpretable results due to faulty controls, there is a large body of literature testing the effects of providing learners with solutions as opposed to having them search for solutions themselves. That literature, on the worked-example effect (see Kirschner et al. 2006, p. 80), has provided unambiguous results and has been studiously ignored by most researchers approaching the issue from a constructivist teaching viewpoint.

Notwithstanding any of the above, we genuinely welcome the shift by the constructivist teaching research community to a position acknowledging the importance of explicit instruction, at least under some circumstances. From the 1970s to early 1990s, that position was anathema. In that sense, the contribution of Hmelo-Silver et al. (2007) is valuable and may signal an emerging consensus.

DIRECT, EXPLICIT INSTRUCTIONAL GUIDANCE VERSUS DISCOVERY OR INQUIRY

In many ways, both Schmidt et al. (2007) and Hmelo-Silver et al. (2007) support our argument that direct instructional guidance is of the ultimate importance. Both papers stress that modern PBL/IL are very structured with strong scaffolding and as we understand their argument, that the more structured they are, the better they work. If there is a disagreement, it is that both commentaries stop short of what we see as the ultimate conclusion, namely, a need for the major instructional emphasis to be on direct, explicit instruction such as worked examples, case studies as modeling examples, or just tuition (see Van Merriënboer & Kirschner, 2007, for a detailed argument for scaffolding). Weak guidance forces learners to rely on weak problem-solving strategies and for at least two decades, weak problem-solving strategies have been known to impose a heavy, extraneous cognitive load (e.g. Van Merriënboer, Kirschner, & Kester, 2003).

Much of our response to the Schmidt et al. (2007) and Hmelo-Silver et al. (2007) commentaries have focused on methodological issues. We have suggested that the experiments used in the commentaries to support PBL/IL procedures fail to provide reasonable tests because they either do not provide an adequate manipulation of key variables and/or lack adequate controls for confounds. This issue is similar to the criticism that Clark (1983, 2001) made concerning the design of experiments used as evidence indicating that some media were more effective in promoting learning than others. Clark suggested that instructional methods, not media, influenced learning and that methods were not controlled in most media experiments. Similarly, the results of experiments comparing PBL/IL with other techniques have been compromised by a plethora of uncontrolled variables. We welcome the opportunity to discuss experimental evidence that, for example, an accurate and well-designed worked example is less effective than providing novice or intermediate-level learners with a problem and resources for solving a problem. That evidence is missing.

WHETHER TEACHING SHOULD EMPHASIZE CONTENT OR INQUIRY SKILLS: A REPLY TO KUHN (2007)

In contrast to Schmidt et al. (2007) and Hmelo-Silver et al. (2007), Kuhn (2007) presents a point of view with which we very strongly disagree. Because scientific theories develop and change and because new findings are continually being presented, Kuhn (2007) believes we should deemphasize the teaching of scientific theories and findings in favor of learning the methods of science. She suggests we should consider, "... whether to teach knowledge at all" (p. 110). Rather, we should "teach ... the skills of knowledge acquisition" (p. 110). She does not describe any of the critical thinking skills she favors or how to teach them or how they might relate to human cognitive architecture. Indeed, she makes no mention of human cognitive architecture, implying by omission, for example, that a limited working memory is an irrelevant instructional consideration. She is, of course, correct in indicating that if scientific theories and findings are either deemphasized or not taught, then the procedures we recommend become unimportant. We assume teachable/learnable science to consist of knowledge of the theories and findings of science, including knowledge of how to solve domain-specific problems. If knowledge of the theories and findings of science are of little importance when teaching science, then our recommendations on how that knowledge is best acquired also will be of little importance.

Kuhn (2007) does not wish to completely eliminate science knowledge from the curriculum. She says, "... we want children to acquire some rudimentary understanding of the physical and biological world around them" (p. 111). She implies that this understanding is a minor aspect of what society should want students to learn of science. We respectfully disagree. If understanding the world has only a minor role in science teaching as suggested by Kuhn (2007), what is its purpose? According to Kuhn (2007) it is to "... offer opportunities for exploration" (p. 110). In turn, we offer opportunities for exploration by teaching IL: "... inquiry skills is a worthwhile educational goal" (p. 111). We should encourage students to "... use their minds well" (p. 110) but the means by which we should teach students to use their minds well is by teaching them inquiry skills. Kuhn (2007), in common with most other supporters of IL, does not describe any inquiry skills, let alone provide evidence that teaching the skills has benefits. If we cannot describe a single, novel, general inquiry skill a half century after the concept of IL was introduced to the field, and if we are not to emphasize the theories and findings of physical and biological science, we unnecessarily limit what is to be taught in the science classroom.

We appreciate, of course, that science educators are faced with a huge, constantly changing discipline and that one possible solution to this problem has been to down-play theories and findings to be replaced by the more constant, inquiry-based methodology of science. We agree we should teach students what a scientific experiment is but the most important knowledge in devising a novel scientific experiment is knowledge of the relevant theories and findings of an area. The need for knowledge of science theories and findings is not obviated simply because theories and findings are dynamic and knowing how to engage in research is not a substitute for knowing the content of science.

There are adverse consequences to down-playing knowledge of scientific theories and findings. Novak (1988) stated it eloquently and succinctly noting that the major effort to improve secondary school science education in the 1950s and 1960s (i.e., ChemStudy chemistry, PSSC physics, BSCS biology) fell short of expectations, and that the major obstacle that stood in the way of the expected "revolutionary improvement of science education ... was the obsolete epistemology that was behind the emphasis on 'enquiry' oriented science" (p. 79–80).

A DEEPER EXPLICATION OF GUIDANCE NEEDED

Despite our differences, we hope that the current dialog will encourage instructional researchers to engage in a deeper consideration and explication of instructional "guidance." We suggest that it would be much more effective if in the future we focus on improving our understanding of how we can more precisely determine the amount and type of guidance required by different learners through the careful design of systematic instructional experiments. This issue is reflected in many of the recent studies that support new instructional design theories and models (see Clark, Nguyen, & Sweller, 2006; Merrill, 2002; Van Merrienboer & Kirschner, 2007, for examples).

We also realize that when researchers develop specific approaches to instructional design, give that approach a label, and work with practitioners to implement the approach, the temptation is to defend the approach and resist evidence that its fundamental method may be flawed and in need of change. It is our view that the strong empirical evidence supporting cognitive load theory should be incorporated into all instructional methods even if this change requires a major revision of a popular instructional program. New theory and evidence has compelled the development of cognitive load theory. In the next section, we briefly describe a major, emerging conceptual change based on evolutionary biology that we believe has dramatic implications for the entire field of educational psychology, including the issues discussed in this reply to comments.

A NEW EDUCATIONAL PSYCHOLOGY IS EMERGING

For several decades, educational psychology has been dominated by the view that direct explicit instruction is inferior to various combinations of discovery learning or "immersion" in the procedures of a discipline. This view was both attractive and plausible on the grounds that the bulk of what we learn outside of educational institutions is learned either by discovery or immersion. For example, we do not need to go to school to learn to listen or speak, recognize faces, learn general problem-solving techniques, or learn about basic social interactions. We do not need formal instruction to acquire knowledge in these areas because we have acquired it through immersion in life experiences. It seemed to follow that if we organized the disciplines taught in educational institutions appropriately, surely they also could be learned as effortlessly as, for example, a first language. Extending this argument further, it seemed reasonable to expect that we should base the pedagogy for teaching and learning in the natural sciences on the epistemology of the natural scientist (Kirschner, 1992; Kirschner et al., 2006).

This view, in spite of the questions raised in the 1980s, was sufficiently attractive to be impervious to the near total lack of supporting evidence from randomized, controlled experiments. Theories such as cognitive load theory argued that the failure to find empirical evidence for the superiority of indirect instruction was because without direct, explicit instruction, working memory was overwhelmed by the need to engage in search through a wilderness of possibilities. But while cognitive load theory could point to the empirical evidence from controlled studies supporting this view, it was unable to explain why in some basic areas not taught in educational institutions, immense amounts could be learned without explicit instruction.

Recent work by Geary (2002, 2005, in press) provides some of the missing pieces of the scientific jigsaw. Some knowledge, that Geary called biologically primary knowledge, is not learned consciously because we have evolved to acquire that knowledge easily and automatically. The examples of learning a first language, recognizing faces, learning general problem-solving techniques (including inquiry), or learning about basic social interactions fall into this category. It is possible that the well-known working memory limitations simply do not apply when acquiring this knowledge. Huge amounts of such knowledge can be learned and stored directly in long-term memory without the restrictions imposed by a limited working memory.

In contrast, we have not evolved to effortlessly acquire the biologically secondary knowledge such as the operation of a base 10 number system or scientific theories that are characteristically taught in educational institutions. That information passes through working memory and so requires conscious effort. It must be explicitly taught; indeed we invented educational institutions in order to teach such knowledge, and the manner in which it is taught needs to take into account the characteristics of working memory, long-term memory and the relations between them. Cognitive load theory, based on the relations between working and long-term memory, only applies to biologically secondary, not biologically primary, knowledge (Sweller, in press; Sweller & Sweller, 2006). Educational recommendations cannot assume that procedures that work for biologically primary information will work for biologically secondary information. There is no theoretical reason to suppose or empirical evidence to support the notion that constructivist teaching procedures based on the manner in which humans acquire biologically primary information will be effective in acquiring the biologically secondary information required by the citizens of an intellectually advanced society. That information requires direct, explicit instruction.

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