Does Discovery-Based Instruction Enhance Learning?

by

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Abstract

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Since Bruner's (1961) call for research into discovery-based learning, controversy has surrounded the efficacy of such a constructivist approach to instruction (e.g., Tobias & Duffy, 2009). For decades, research has investigated to what extent discovery-based instruction enhances learning tasks or conversely, detracts from them. Research has included wide varieties of domains and discovery-based instructional approaches. Samples have included both children and adults and both novices and experts within their specific domains. It seems that what the field needs is a definition of discovery learning from a practical perspective because a review of the literature reveals that although there might be an implied sense of what discovery learning is, the methodologies employed vary greatly. Furthermore, the characteristics of effective discovery methodology(s) need to be examined with careful consideration of the domain involved, the age of the sample, the comparison condition, and the outcome assessments. Therefore, two meta-analyses were conducted using a sample of 164 studies: the first examined the effects of unassisted discovery learning versus explicit instruction and the second examined the effects of enhanced and/or assisted discovery versus other types of instruction (e.g., explicit, unassisted discovery, etc.). Random effects analyses of 580 comparisons revealed that outcomes were favorable for explicit instruction when compared to unassisted discovery under most conditions, $d = -.38$ (95% CI = -.44/-.31). In contrast, analyses of 360 comparisons revealed that outcomes were favorable for enhanced discovery when compared to other forms of instruction, *d* = .30 (95% CI = .23/.36). The findings suggest that unassisted discovery does not benefit learners, whereas feedback, worked examples, scaffolding, and elicited explanations do.

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Chapter 1: Introduction to Discovery Learning

Within the past several decades, conventional rote learning has been largely abandoned in favor of learning approaches more closely aligned with Piagetian concepts of exploration, discovery, and invention (i.e., discovery learning). Allowing learners to interact with materials, to manipulate variables, to explore phenomena, and to attempt to apply principles affords them with opportunities to notice patterns, to discover underlying causalities, and to learn in ways that are seemingly more robust because learners can construct their own understandings. Such approaches to learning are thought to be within the category of constructivist pedagogies which, like Piaget (1980) and others, posit the child at the center of the learning process as they attempt to make sense of the world. However, the pedagogies derived from such a learner-centered perspective have varied greatly (Vianna & Stetsenko, 2006).

After reviewing the relevant literature thus far (i.e., spanning at least 75 years), it seems that a consistent operational definition of *discovery learning* has yet to be explicitly set forth (Klahr & Nigam, 2004). Based on the literature, a general explanation of discovery learning practices seems to be that the method is one in which a learner is not provided with the target information and must find it independently and with only the provided materials. There might be some level of assistance provided from an instructor or from the materials themselves but either would be minimal in its extent and systematically organized by the instructor to allow the learner to construct his/her own understanding. Such an active construction of knowledge on the part of the learner is thought to surpass other forms of knowledge acquisition for many reasons including motivational factors (e.g., Ausubel, 1963; Kagan, 1966) and improved cognitive processing (e.g., Chi, deLeeuw, Chiu, & LaVancher, 1994). However, there remains some debate concerning the limitations of such an approach to learning (e.g., Bruner, 1961; Kirschner, Sweller, & Clark, 2006; Klahr & Nigam, 2004; Mayer, 2004; Tobias & Duffy, 2009).

The Theories surrounding such Pedagogy

Piagetian processes involved in knowing. Piagetian concepts of exploration, invention, and discovery have been considered constructivist explanations of learning because when learning occurs such ways, it is the learner who is constructing new knowledge based at least in part on the learner's preexisting knowledge. Piaget explained that it was through interactions with their environments that children come to understand much of the world around them (Piaget, 1952, 1965, 1978). By trying to explain their experiences, children come to form schemas that subsequently predict, help to organize, and also explain their environments (Piaget, 1955). If/when their schemas or preconceptions fail to meet the demands of explaining new experiences (i.e., disequilibria), those schemas would then need to be modified (i.e., through accommodation of this new information/experience). When the preexisting schemas were sufficient (i.e., equilibria), the new information could be added as a new experience and schemas could be extended but would not need to be modified per se (i.e., through assimilation). He also warned that prematurely providing explanations to children instead of allowing them to invent their own explanations might keep them from ever understanding the phenomenon completely (Piaget, 1970).

Knowing within formal education vs. rote learning. Piaget (1962) had similar explanations of the acquisition of formal education and whereas the emphasis was still on the learner's capacity to explain to understand, Piaget appreciated the cooperative nature of formal education (i.e., the instructor, the dialogue of instruction, etc.). He suggested that it would be of great benefit to instructors to know the learner's spontaneous thoughts, not in an effort to overcome them, but in an effort to utilize them systematically to bring the learner meaningfully into the cooperative acquisition of this new information and/or intellectual task. It seems that for Piaget, the processes involved in formal education were similar to any other acquisition of understanding (i.e., tentative explanation to the self, the consequent building of schemas, and the experiences of equilibria or disequilibria thereafter). The processes that were thought to be different by Piaget in formal education as opposed to common knowledge acquisition were seemingly the media of introduction, organization, and reorganization of the information to be acquired, through cooperative interaction with the instructor and the learner's preexisting knowledge, as well as with the new information (Piaget, 1965). In other words, the instructor might introduce the situation/experience to be explained and, whereas it was still up to the learner to explain it to himself/herself, formal education makes the task a more-or-less cooperative effort.

Piaget (1955) illustrated the importance of learners explaining things to themselves, a concept overlooked by more conventional pedagogies (e.g., rote learning). Rote learning can be accomplished simply by memorizing provided information and reiterating that information when appropriate. Arguably, there does not need to be an understanding on the part of the rote learner. Whereas such an approach might work for lower level educational tasks (e.g., memorizing multiplication tables), more meaningful learning typically requires explanation. Although it could be argued that even explanations can be taught in a rote fashion, it could also be argued that at minimum provided explanations need to be interpreted by the learner by his/her own analyses of them to be meaningful to him/her. At the point at which the learner interprets such an explanation or provides his/her own explanation, he/she can gain insight into how that explanation might fit other circumstances or when that explanation might be insufficient (i.e., an outcome unlikely if the learner merely memorizes explanations in a rote fashion). Such would be an occasion of discovery and consequently, his/her understanding could be more salient than if that explanation was simply memorized verbatim without active consideration of it and furthermore, he/she might be better prepared for subsequent learning experiences within that domain. Thus, the emphasis is placed on the active part of the learner in the acquisition of that new knowledge (Piaget, 1980). The active learning involved does not imply mere effort or attention but active consideration on the appropriate aspects of that information and a sustained consideration of it until the learner sufficiently makes sense of it in his/her own way.

The warnings of John Dewey. Whereas some of Piaget's claims seem to suppose that human beings have an ability to think and to reason that develops more-or-less through maturation, Dewey's (1910) claims as to how people think and potentially come to know point out the flaws in such processes. Dewey claimed that natural intelligence and that which is referred to as thinking can lead a thinker to misconceptions and that those misconceptions can be furthered by untrained experience into an accumulation of fixed false beliefs (1910, p. 21). Consequently, Dewey emphasized the need for thinking to be trained or regulated by education (to be discussed subsequently). Dewey seemed to have constructivist ideas of pedagogy in that Dewey agreed that it is the thinker who needs to be actively engaged with the information to connect it to things that are to the thinker, *surely known* (p. 26). In other words, thinkers or learners construct new understandings or accept new information only when it is inferentially appraised as warranted because of the information they already know. However, Dewey claimed that to carry out this appraisal process properly, thinkers needed to be trained as to how to think, how to attend to the relevant details, how to consider all of the causal elements within a situation, and more generally, how to overcome the shortcomings of what are seemingly more natural reasoning processes.

The warnings of Jerome Bruner. As constructivist perspectives of pedagogy emerged, Bruner (1961) and some of his contemporaries (Ausubel, 1964; Ballew, 1967; Craig, 1965; Guthrie, 1967; Kagan, 1966; Kendler, 1966; Kersh, 1958, 1962; Ray, 1961; Scandura, 1964; Wittrock, 1963; Worthen, 1968) advocated learning situations that elicited explanations from learners and that provided opportunities for learners to gain insights into their domains of study. Bruner emphasized that such discovery-based learning could enhance the entire learning experience and consequently, he has been cited repeatedly as being a proponent of such teaching methods. However, he also remarked that such discovery could not be made a priori or without at least some base of knowledge in the domain in question. Thus, what seems to have been largely ignored were Bruner's warnings that there are limitations to such an approach, as with any other.

One of the commonly ignored warnings is that the learner's mind has to be prepared for discovery (Bruner, 1961). Although Bruner suggested that learning by discovery does not necessarily involve the acquisition of new information but that the learner might gain insights which transform the learner's understanding through new organizations of previously learned information, the preparation that Bruner emphasized was not merely an existing knowledge base regarding the domain of study. The prepared mind for Bruner was one with experience in the process of discovery itself, which seems similar to Dewey's (1910) claim that training is required for proper thinking:

> The narrative of teaching is of the order of the conversation. The next move in the development of competence is the internalization of the narrative and its "rules of

> generation" so that the child is now capable of running off the narrative on [his/her] own. (p. 28)

Although Bruner referred to a child, the same might be said of all learners: the act of discovery is a scripted tool for making sense of something on one's own. The steps and procedures of that script are not intuitive to a learner - as Dewey (1910) points out and Bruner further emphasizes in the quote below - because they are part of a culture (e.g., a culture of formal education):

> It goes without saying that, left to [himself/herself], the child will go about discovering things for [himself/herself] within limits. It also goes without saying that there are certain forms of child rearing, certain home atmospheres that lead some children to be their own discoverers more than other children. (p. 22)

Activity theory. The issue of discovery learning procedures being perhaps an internalized, scripted tool that is provided by a culture of formal education echoes some activity theories of education found within more post-Vygotskian psychology (Arievitch & Stetsenko, 2000; Karpov & Haywood, 1998; Stetsenko & Arievitch, 2002; Vianna & Stetsenko, 2006; Vygotsky, 1978; Wertsch, 1981). And in fact, Bruner (1961) credits Vygotsky (1934) for that insight. Within post-Vygotskian psychology and/or the Kharkov School of psychology, which is most often associated with Leontiev's activity theory (Cole, 1980; Yasnitsky & Ferrari, 2008), tools are cultural artifacts that help people (i.e., learners) to develop higher mental functions which are by definition, culturally mediated (Cole & Wertsch, 1996; Karpov & Haywood, 1998; Stetsenko & Arievitch, 2002). On a global scale, these tools are cultural artifacts like language, moral reasoning, and other guiding principles that help individuals of those shared cultures coordinate with each other and with their physical worlds. At a more specific level, these tools can be understood to be those processes employed during everyday activities that allow members of a culture to consider and to act on their environments. Vygotsky claimed that the tool (i.e., thought process) is internalized and then replaces preexisting natural processes whose work can now be accomplished exclusively with that tool (Karpov & Haywood, 1998). Bruner echoed that claim when he wrote that the child, if left to himself/herself, will go about discovering things within limits but that the child who has been familiarized with the narrative of teaching and has internalized that narrative can now teach or discover things on his/her own. Dewey (1910) also made such a claim when he wrote that natural (i.e., untrained) thinking is likely to lead to misconceptions. Bruner furthered his explanation when he points out that certain home atmospheres rear children with abilities to discover more than others do, illustrating that such ability does not arise out of cognitive development alone. Bruner's consideration of the influence of home environments also draws attention to a micro-level consideration of the historicity (Engestrom, 1999) of the child, of the parents' sociocultural position, and the influence of their cultural position on the types of tools they use when attempting to explain phenomena.

Explanation, the scientific method, and pedagogy. Constructivism is a theory of how people learn or know about the world but it is not a theory of pedagogy, per se (Schwartz, Lindgren, & Lewis, 2009). The claim that a learner needs to construct his/her own understanding in order to know, does not imply that he/she cannot benefit from a provided explanation. Conversely, being provided with an explanation does not guarantee that the learner will come to know and understand that which is being explained. If we consider that formal explanations are not tools by themselves but that the process of arriving at those explanations independently is a culturally given tool (Karpov & Haywood, 1998), then that explanation whether provided by a conversational partner or by one's self, has a huge impact on development (Chi, deLeeuw, Chiu,

& LaVancher, 1994; Hickling & Wellman, 2001; Keil, 2006; Lombrozo, 2006). Formal education teaches its students, implicitly if not explicitly, that explanation requires a great deal of active engagement with the phenomenon, efforts to understand all parts of it, and that there are specific characteristics that explanations should have. For example, they should be as general and yet as specific as possible. Explanations often require conditionality and that any such conditionality should be explicitly set forth within them. They should be as simply worded as is possible and certain types should be transferable from the general to the specific and back again with as few modifications as possible. Lastly, explanations need to meet the demands of the thinker confronted by that which requires explanation; that is, the explanation is a conversation between the questions that the mind poses in the presence of that which is to be explained, and what the explainer already knows. This process of explaining might not be inherent in human thinking (e.g., Dewey's claims, explanatory stereotypes of out-groups, explanatory failings such as the fundamental attribution error) but almost all students of formal education can distinguish their better explanations of things from those that fall short of the ideal. Thus, pedagogy designed to explain *how* to explain might be better than pedagogy designed simply to explain (Karpov & Haywood, 1998).

Dewey (1910) makes similar assertions when he explains that arriving at proof using controlled inference (i.e., that following from trained thinking) can be a difficult task, unnatural to the ways untrained minds work. For the trained thinker, arriving at the proof of a claim is, at times, a hands-on activity so that the claim can be tried out empirically; at other times, reasoning and inference without testing might appreciate a claim but any such assent to the claim is held tentatively at best if the claim is only examined hypothetically. However, the untrained thinker does not appreciate claims in such a way; he/she needs to be taught through education:

> While it is not the business of education to prove every statement made, any more than to teach every possible item of information, it is its business to cultivate deep-seated and effective habits of discriminating tested beliefs from mere assertions, guesses, and opinions; to develop a lively, sincere, and open-minded preference for conclusions that are properly grounded, and to ingrain into the individual's working habits methods of inquiry of reasoning appropriate to the various problems that present themselves. (p. 28)

The example of explanations is a complex one because even decent explanations often fall short of the ideal because the explainer fails to appreciate all of the influential factors present in the phenomenon (i.e., what Davydov refers to as empirical learning; Karpov & Haywood, 1998). However, the culture of formal education (i.e., specifically, science) also has a tool to assist a learner in the utilization of this tool of explaining (e.g., the control of variables strategy or scientific method). Holding all other factors constant while manipulating a select few is a way for someone who hopes to explain something to find out which factor(s) influence some occurrence (Klahr, 2009). However, this is not a visceral method of making sense of the world. It seems that a more intuitive method involves some quick-fix explanations based on experiences that might not have been understood properly and that are heavily tainted by presumptions, falsehoods, and perhaps superstition (Dewey, 1910). Once the scientific method is learned however, it potentially will replace those earlier methods of attempt as activity theory suggests (Stetsenko & Arievitch, 2002).

In sum, the tool of formal explanation and the tool commonly referred to as the scientific method are both tools of the culture of education that need to be introduced to, and understood by the learner to be utilized independently and effectively later. Teaching students about the tools and how to use them effectively probably begins as a dialogue or conversation between the instructor and student, as suggested by Vygotsky (Arievitch & Stetsenko, 2000; Stetsenko & Arievitch, 2002) and Bruner (1961), and then comes to be internalized by the learner who can then independently run off the coordinated discussion (i.e., as inner speech) between what he/she already knows from previous experience and what he/she knows of the present materials/situation. Furthermore, the learner can then modify the tool to fit with personal experience and the intended task and over time, that tool can be enhanced, modified, or altogether replaced as learners transcend the tool's original purpose and find new applications for it or new methods for those same applications (Lektorsky, 1991 from Engestrom, 1999). This might be the most practical pedagogical advice to be derived from constructivist theories: teach students how to learn by use of the proper tools and at the advice of Dewey and activity theorists, do not make those tools a mere mechanism that is devoid of meaning. The pedagogy should not only teach students how to use the tools but also when and why they are important and useful by marrying concepts to procedures (Karpov & Haywood, 1998). Dewey (1910) emphasized that the activity (i.e., or tool) should be understood by learners to be useful not only in its intentional goal but appreciated at every step of the process.

Although Dewey did not refer to such thought processes as tools, he emphasized that good thinking is a distinct piece of mental machinery separate from observation, memory, imagination, and common-sense judgments and that the method of good thinking consists of a set of operations that can be applied to numerous subjects (1910, p. 45). Consequently, it seems reasonable to assume that there is some degree of agreement amongst Dewey, Bruner (1961), and Vygotsky and his followers (Arievitch & Stetsenko, 2000; Karpov & Haywood, 1998). Good thinking, proper reasoning and explanation, and perhaps discovery are processes that need to be taught to students. Followers of Davydov refer to learning these processes (i.e., cognitive tools) as *theoretical learning* which students engage in while trying to solve problems (Karpov & Haywood, 1998). Consequently, these tools not only help to solve the current problem that students are tackling, but these tools are also learned as procedural knowledge and can be used subsequently in other domains. Furthermore, theoretical learning can replace more natural, *empirical learning* (e.g., discovery learning by induction) which often is deficient because it relies heavily on the more salient but often unimportant features of problems to be solved (Karpov & Haywood, 1998; Stetsenko & Arievitch, 2002). The theoretical learning approach attempts to teach students how to be independent thinkers and consequently, learners, and does not presume that students already know how to learn independently. “The child as an independent learner is considered to be a result, rather than a premise of the learning process” (Kozulin, 1995, p. 121).

Although there is some resistance to concepts like *learning to learn* (e.g., Schwartz, Lindgren, & Lewis, 2009; Sweller, 2009; Wise & O’Neill, 2009) because it does not map neatly onto cognitive architecture and there is little evidence of general cognitive skills that are generalizable from the moment that they are learned, engaging learners in goal-directed interactions that expose them to more complex forms of thinking about the given situation (e.g., in the form of dialogue while discussing a problem to be solved) might lead to the type of theoretical learning suggested by followers of Davydov. Similarly, concerned researchers who are aware of the shortcomings of constructivist-based instruction also suggest teaching critical thinking and reasoning skills (Schwartz, Lindgren, & Lewis, 2009), reading support tools (Herman & Gomez, 2009), and the control of variables strategy (Klahr, 2009) and then allowing learners to gain practice in applying those newly learned tools/procedures. Although their concerns are expressed with regard to the amount of direct instruction necessary to facilitate accurate construction on the part of the learner when working independently, it is worth noting here the similarity between their suggestions and those of Davydov’s followers: critical thinking and reasoning skills, reading support tools, and the control of variables strategy are all seemingly the fruits of theoretical learning.

Motivation and involvement. Bruner (1961) claimed that independent discovery increased the learner’s competence motivation and that cyclically, that increase in competence motivation would encourage the learner to try to learn things independently in the future. Other explanations as to why discovery methods are superior range from practical reasons to personal reasons. Kendler (1966) claimed that discovery methods should be superior because they require learners to explain things in their own language patterns. If learners typically have difficulty understanding the instructor’s explanations because of his/her unique language patterns, then the ability to avoid having to translate explanations could be motivation to explain them to themselves. Kagan (1966) claimed that discovery methods should be superior because the learner experiences discovery methods as being the most rewarding. Kagan referred to Festinger’s cognitive dissonance theory and explained that it was a result of the hard work on the part of the learner to achieve that understanding, that the learner considered understandings arrived at in this way the most rewarding. In this explanation, the learner is motivated to use discovery methods because they are experienced to be the most rewarding, albeit the most demanding. A similar explanation was provided by Ausubel (1963), a staunch defender of expository teaching methods, who agreed that under certain conditions discovery methods should be somewhat superior because of the motivation and effort involved in them. However, effort and/or activity do not lead to learning in all cases (Mayer, 2009).

The ongoing debate. After a heated debate at the 2007 annual convention of the American Educational Research Association, leading proponents of constructivist instruction (e.g., discovery-based instruction) and leading proponents of more direct forms of instruction (e.g., formal lectures, explicit instruction, etc.) were given the opportunity to write a chapter defending their positions and then to respond to the comments of two scholars on the other side of the debate (Tobias & Duffy, 2009). Consequently, the Tobias and Duffy text includes both sides of the debate along with the unresolved issues and the projections as to how the field should proceed. Generally, investigators on both sides of the debate feel that there should be more collaboration toward empirically driven educational theory on this matter (e.g., which domains benefit from discovery-based instruction, how much direct instruction or at least guidance should be provided, etc.). However, amidst such professional pleasantries, there is a remarkable amount of incongruity in how each side understands the other's points. For example, Duffy (2009) points out that the entire situation of learning is viewed differently whether one is on the constructivist or direct-instruction side of the debate. Duffy explains that it is a matter of perspective because the direct-instruction advocates seemingly define learning as the process acquiring knowledge whereas constructivism advocates define learning as the process of a learner coming to understand something. Although this difference in perspectives might seem small, it is conflated by issues of learner's motivation and instructor's guidance.

Two major issues were whether learners need to be prepared for discovery-based instruction and the extent, if any, of guidance during discovery-based instruction. Herman and Gomez (2009) suggested that the issue was not whether discovery-based instructional plans should be designed but whether learners were prepared to handle such discovery; consequently, they proposed teaching reading support tools that could prepare learners for such discovery. As mentioned in the preceding discussion of theoretical learning, other investigators (Klahr, 2009; Schwartz, Lindgren, & Lewis, 2009) had similar suggestions of teaching critical thinking and reasoning skills and the control of variables strategy to prepare learners for independent learning. Issues of guidance ranged from the intentions of such guidance (Wise & O'Neill, 2009) to the extent of it (Kintsch, 2009; Wise & O'Neill, 2009) and from the type(s) of guidance (Wise & O'Neill, 2009) to the types of domains suited to having more or less guidance during instructional tasks (e.g., Clark, 2009; Rosenshine, 2009; Spiro & DeSchryver, 2009). In sum, no investigator suggested that completely unassisted discovery-based instruction be employed and all agreed that guidance, in some form and to some extent, could potentially increase learner's success on the learning task.

Theoretical expectations. From a theoretical perspective, discovery learning should be superior to more expository forms of pedagogy if all knowing must be constructed by the learners themselves because discovery learning requires learners to be active and effortful in the process. It does not seem that Piaget or any constructivist theorist suggests that this learner-centered acquisition of knowledge needs to be accomplished in isolation without any assistance at all. On the contrary, Dewey (1910), Piaget (1952, 1962), Vygotsky (Arievitch & Stetsenko, 2000; Karpov & Haywood, 1998), and investigators on both sides of the debate over constructivism (Tobias & Duffy, 2009) all seem to have agreed that assistance in the process is necessary. For Dewey, it is the responsibility of the teacher to take into account the traits and habits of individuals and then to modify how those powers habitually express themselves (1910, p. 46). Piaget and Vygotsky agreed when they both emphasized the importance of the instructor being aware of the learner's spontaneous thoughts and speech (Piaget, 1962). For Piaget, such awareness was thought to facilitate better coordination between the instructor's efforts to guide the activity systematically and with little dictation, and the learner’s efforts to construct an understanding. For Vygotsky, that awareness would help the expert assess the learner’s zone of proximal development and the subsequent scaffolding that was required (Arievitch & Stetsenko, 2000; Vianna & Stetsenko, 2006). Consequently, it would seem reasonable to predict that discovery methods that do not involve any form of assistance or guidance should be the least effective. However, the protocol of psychological science maintains consistency in how each participant is treated and consequently, studies with strict scripts of protocol might negate any benefit of guidance because of the instructor’s insensitivity to what Dewey refers to as the traits and habits of individuals and what Piaget and Vygotsky refer to as the spontaneous thoughts and speech of each learner.

There might also be some issues of previous experience and motivation. Based on the claims of Bruner (1961) and the activity theories (Arievitch & Stetsenko, 2000; Karpov & Haywood, 1998), learners who have had a substantive amount of experience with discovery previously should outperform learners who have not. This claim can be extended to particular types of discovery as well (e.g., scientific methods that require a control of variables strategy) because the learner might need to have had previous experience with that specific type of discovery to employ such a tool within the study in question. Unfortunately, not one article has reported its sample’s experience with the act of discovering. Moreover, if Kendler (1966) is correct, then discovery methods should yield better learner performances than other methods do and the learners’ understandings should be in their own language patterns. Again, it is unfortunate that not one study has asked its participants to write out explanations and then compared the linguistic styles of the learners’ explanations to the linguistic styles of the text(s) provided. It would have also been insightful if studies had asked participants to rate their levels of motivation both before and after the study and to estimate the amount of effort that they felt they had expended to complete the task. Both of these self-ratings might have helped to support the claims of Kagan (1966) and Ausubel (1963). Lastly, proponents of constructivist instruction (e.g., discovery-based) often argue that empirical evidence is difficult because good methods might require lengthy interventions and outcome assessments that are not yet widely accepted (Schwartz, Lindgren, & Lewis, 2009). Schwartz and colleagues argue that the type of outcome assessment necessary to quantify the efficacy of constructivist instruction is *preparation for future learning* (PFL) which unfortunately, is not a dependent measure included in any of the current literature. However, delayed post-tests and transfer tests which are included in the current analyses could potentially demonstrate the benefits of discovery-based instruction.

Cognitive Factors

Memory. When considering the cognitive demands of discovery-based pedagogy, it is difficult to be as optimistic as when considering the theoretical potentials of such pedagogy. At the most basic level, memory is enhanced when learning materials are generated by the learner in some way; this is commonly referred to as the generation effect (Slamecka & Graf, 1978). Experiments investigating the generation effect are commonly carried out within laboratory settings with largely irrelevant materials to control for the participants' past experiences. The robust effect is that materials that were generated or even merely completed by the participants are remembered more often and/or in greater detail than are materials that were provided by the experimenters. The effect can be viewed as evidence that discovery-based pedagogies can be efficacious because if memory for self-generated materials is better even for free-floating context-irrelevant information, it seems reasonable that more meaningful information that is generated by the learner certainly will be remembered. Therefore, the expectation is that discovery-based approaches, because of the requirement that learners construct their own understandings and consequently the content, should at least yield greater retention.

Cognitive load theory and concerns. With regard to the cognitive processes involved in discovery learning, Mayer (2004) emphasized that discovery-based pedagogy works best when the learner strives to make sense of the presented materials by selecting relevant incoming information, organizing it into a coherent structure, and integrating it with other organized knowledge and that of course, instructional methods that foster such processes would be more successful in promoting meaningful learning than would be those that do not. That seems to be the claim of constructivist pedagogies in general, not just of Mayer, but an activity involving such discriminating attention, organization, and integration seems quite demanding of the learner. It also seems that the learner would need to have the ability to monitor these processes of attention to relevant information, organization, and integration (Case, 1998; Kirschner, Sweller, & Clark, 2006). This ability would require that the learner have a reasonable amount of metacognitive skills to monitor himself/herself and his/her use of cognitive strategies and not all learners are prepared with such. If those are the cognitive processes involved, then learning by discovery requires many more mental operations and executive functions to manipulate and maintain all of the relevant information than does learning under a more guided approach. Furthermore, cognitive load theory suggests that the exploration of complex phenomena or learning domains might impose heavy loads on working memory that are detrimental to learning. Sweller (1988) and Rittle-Johnson (2006) have emphasized that because discovery learning relies on an extensive search through the problem-solving space, the process is very taxing on limited working-memory capacities and frequently does not lead to learning.

Predictions. The cognitive demands involved in discovery-based pedagogies make them seem daunting and implicate a number of predictions. It seems reasonable to predict that young learners (i.e., children) would be least likely to benefit from such methods (Case, 1998; Kirshner, Sweller, & Clark, 2006, Mayer, 2004). Younger learners have comparatively limited amounts of organized, preexisting knowledge and schemas to be able to integrate this new potential knowledge. They have limited working memory capacities (Kirschner, Sweller, & Clark, 2006), and have limited - if any - experience in using the cognitive processes outlined by Mayer and others. Furthermore, the metacognitive skills required to monitor their cognitive processes might not develop until adolescence (Flavell, 2000).

It also seems reasonable to predict that learners who are able to manipulate the materials systematically or who are provided with systematic guidance to do so will outperform those who cannot or are not. Support for such an assertion comes from Elshout and Veenman (1992) who found that students of high-intellectual ability worked more systematically to uncover principles of thermodynamics than did a low-intellectual ability group. Consequently, high-ability learners performed better than low-ability learners, regardless of the instructional condition. Such a finding emphasizes not only the importance of learner's systematicity in their efforts but the issues of general ability and the importance of the learner being prepared and equipped with the tools for such pedagogy. Perhaps learners of higher intellectual abilities are prepared better and equipped to orient themselves within the problem-solving space and then carry out organized attempts to accomplish the tasks than are learners of average or lower intellectual abilities.

In sum, the cognitive concerns of discovery-based pedagogies predict the poorest performances amongst the youngest learners. Furthermore, even older learners need to be prepared for the cognitive demands involved and to be able to understand the task well enough to know how to follow the process systematically to its end. Cognitive load theory predicts that unguided or unassisted discovery will not yield maximal learning unless the learner is at a level to handle such a complex task. Although cognitive load theory agrees that there is a great deal more effort involved in discovery-based pedagogies, it seems overly optimistic to think that such an effort will increase learners' senses of motivation. On the contrary, frustrations and a sense of being overwhelmed by the demands of the task might demotivate learners. That said, if the goal of the task is reached in an understandable way, learners might feel it is rewarding to have prevailed over such a daunting task.

Chapter 2: The Literature Review Leading to the Meta-analyses

Methodologies

Defining discovery conditions. Because methods employing discovery learning can involve a wide variety of intended accomplishments during the acquisition of the target content, it seems reasonable to request a definition of just what is meant by *discovery learning*. However, there is a myriad of discovery-based methodologies presented within the literature and it seems that a precise definition has yet to be established (Klahr & Nigam, 2004). Learning tasks considered to be within the realm of discovery learning range from implicit pattern detection (e.g., Destrebecqz, 2004; Jimenez, Mendez, & Cleeremans, 1996) to the elicitation of explanations (e.g., Chi, de Leeuw, Chiu, & La Vancher, 1994; Rittle-Johnson, 2006), and from working with minimal manuals (e.g., Lazonder & VanderMeij, 1993) to manipulating unguided simulations (e.g., Stark, Gruber, Renkl, & Mandl, 1998). What exactly constitutes a discovery learning situation remains seemingly undetermined by the field as a whole. At times, the discovery condition seems to be less determined by the learning task and more determined by the comparison group(s). That is, when the comparison group has received some greater amount of explicit instruction, whatever the type or degree, the investigators consider the other group a discovery group because it has been assisted less during the learning process.

Consequently, it seems that the literature has used a definition of *discovery learning* that has yet to be set forth explicitly. After reviewing the literature, a general explanation of discovery learning practices seems to be that *the method is one in which a learner is not provided with the target information and must find it independently and with only the provided materials*. Within discovery learning methods, there is the opportunity to provide the learners with intensive, or conversely, minimal guidance and both types can take many forms (e.g., manuals, simulations, feedback, examples, verbal instruction, etc.). The extent to which the learner is provided with assistance seems to be contingent upon the difficulty in discovering the target information with less assistance, and also on the instructional methodologies to which it is being compared. Common to all of the literature, is that the target information must be found by the learner within the confines of the task and its materials and cannot be provided to the learner.

Comparison conditions. It seems reasonable to conclude that the definition of *explicit instruction* might also help to provide a general definition of discovery learning. However, explicit instruction includes somewhat variable conditions as well. These conditions might include the explicit teaching of strategies (e.g., McDaniel & Schlager, 1990), procedures (e.g., Ginns, Chandler, & Sweller, 2003), concepts (e.g., Rieber & Parmley, 1995), and/or rules (e.g., Guthrie, 1967) through the use of formal lectures (e.g., Brant, Hooper, & Sugrue, 1991), demonstrations (e.g., Elias & Allen, 1991), manuals (e.g., van der Meij & Lazonder, 1993), and/or models (e.g., Bobis, Sweller, & Cooper, 1994). Some learners in explicit instruction conditions received explanations (e.g., Crowley & Siegler, 1999) of the materials or procedures to be learned, or of the phenomenon to be understood. The type of explicit instruction employed is seemingly due, at least partly, to the type of information to be learned. However, not all comparison conditions can be considered explicit instruction. Some included reactive feedback during the learning task (e.g., Alibali, 1999) and/or worked examples with solutions provided (e.g., Carroll, 1994). Thus, it becomes apparent that *the condition considered to be discovery learning is not a fundamentally different instructional situation; it might be merely that it is the condition under which learners were provided with the least assistance.*

Domains of subject matter. Are there certain domains in which discovery learning is more appropriate than others and does the domain of the subject matter affect the type of discovery-based approach employed? The literature includes a wide variety of domains from pattern detection (e.g., Destrebecqz, 2004; Jimenez et al., 1996) to social problem solving (e.g., Elias & Allen, 1991; Radziszewska & Rogoff, 1991; Tenenbaum, Alfieri, Brooks, & Dunne, 2007) with mathematics, physics, and computer programming as other examples of more common domains. The domain of the subject matter seemingly influences the type of discovery learning task employed by the respective investigators. For example, a learner might be asked to explain a physical phenomenon after exploring the relevant materials involved in the phenomenon. By trying a number of different manipulations, the learner might discover how the phenomenon in question is produced. Within the domains of physics and other natural sciences, the goal of the learning task may be more obvious to the learner than in other domains. Therefore, purely unassisted discovery learning tasks can be employed (e.g., Hodges & Lee, 1999; Kalyuga, Chandler, & Sweller, 2001; Singer & Gaines, 1975) if the learner is capable of systematically investigating the materials. However, in domains such as math or computer programming, some explanations of the goals of the learning tasks and/or example problems will need to be provided because the learning goals are typically less transparent than in other domains (e.g., Belcastro, 1966; Kersh, 1962; Lazonder & Van Der Meij, 1995; Sweller, Chandler, Tierney, & Cooper, 1990). Guidance, feedback, probes, and/or other structural clues might need to be provided for learners in the discovery condition to grasp the conceptual goal of the task (e.g., Kersh, 1958; Zimmerman & Sassenrath, 1978).

Outcome assessments and theoretical concerns. There is also a great degree of variability regarding the types of outcome variables considered. Some studies report scores from pretests or acquisition trials (e.g., Carroll, 1994; Elshout & Veenman, 1992; Kersh, 1958; Messer, Mohamedali, & Fletcher, 1996) whereas others report the number of errors as a reflection of the learners' understanding or lack thereof (e.g., Hodges & Lee, 1999; Lazonder & Van Der Meij, 1995; Van Der Meij & Lazonder, 1993).

Some studies reporting pretest or acquisition scores include study time (e.g., Carroll, 1994; Lazonder & Van Der Meij, 1993, Lazonder & Van Der Meij, 1995) but this seems to be a less than compelling way to assess the efficacy of discovery learning. It may be that discovery learning requires more of the learner's time, perhaps because of increased cognitive demands (Kalyuga, Chandler, & Sweller, 2001; Nadolski, Kirschner, & Van Merriënboer, 2005), but that this more heavily demanding method could still lead to greater comprehension than the comparison approach.

Moreover, the number of errors that participants make also seems like a problematic outcome assessment to rest a claim on, either for or against discovery learning. Because discovery learning often involves some degree of self-instruction on the part of the learner, the gains in knowledge may be tentative at best. Performance at test, especially a single post-test, might still reflect an amount of uncertainty and consequent errors as the learner continues to refine his/her understanding. If the comparison group has received explicit instruction that included principles or the like, those learners should feel that what they have learned is far less tentative and that it is not necessary to continue to refine their understandings because such refinement could have been accomplished completely at study. If such is the case, the comparison group at post-test may seem to have learned more than the discovery groups. Thus, error rates may reflect uncertainty and further learning to reach clarification more than they reflect true deficits. Again, proponents of discovery learning claim that the approach is more robust and meaningful to the learner, and not merely that it will lead immediately to greater performance. A few studies have included multiple post-tests which may provide supporting evidence for such a claim (e.g., Kersh, 1962; Rittle-Johnson, 2006) because they provide discovery-based learners with ample time and instances to explore the target material and refine their self-generated understandings.

Unusual Designs

Unintentional learning and its implications. Discovery learning is typically considered to be an explicit, conscious search for patterns or principles. However, some studies in the domains of sequence or artificial grammar learning (e.g., Destrebecqz, 2004; Jiménez, Méndez, & Cleeremans, 1996) and second language learning (e.g., Norris & Ortega, 2000) have compared implicit (e.g., incidental) learning to explicit (e.g., intentional) learning. Incidental learning can be considered analogous to unassisted discovery learning because learners in unassisted discovery conditions are often not told what exactly their intentions should be or how to go about attempting the task. Destrebecqz found that explicit knowledge of the presence of a sequence (i.e., intentional learning) led to better sequence learning than did a lack of such knowledge (i.e., incidental learning) as determined by differences in reaction times. However, Jiménez and his colleagues found that incidental learning led to better reaction times than did intentional learning, but that the intentional group performed more accurately than the incidental group. Similarly, in the domain of second language acquisition, Norris and Ortega’s meta-analysis of the efficacy of second language instruction indicated that explicit types of instruction led to far greater target-oriented gains than did implicit types. Unfortunately, reaction times were not the dependent measures included and therefore cannot be compared to the claims of Destrebecqz and Jiménez and his colleagues. However, dependent measures included meta-linguistic judgments, selected responses, constrained constructed responses, and free constructed responses and are therefore comparatively aligned with the claims of Jiménez and his colleagues - that accuracy is improved by intentional learning (i.e., the type elicited by explicit instruction). Such studies are included in the current analyses because their analogous comparisons are interesting ones. If intentional learning is surpassed by incidental learning, such a finding would point to the possibility that the cognitive demands and consequent stresses of unassisted learning, when intentional, might be detrimental to learning and that unassisted learning, when unintentional, might help to facilitate pattern detection because there are less demands and stresses on cognition. Such a finding might illustrate the claims of cognitive load theory.

The Necessity of Two Meta-analyses

Because of the clear ambiguity within the literature as to what constitutes effective discovery learning methods and how and when such methods should be applied, two meta-analyses were conducted. The first meta-analysis compares unassisted discovery learning methods to explicit instruction. The second meta-analysis compares enhanced discovery learning methods to a variety of instructional conditions including unassisted discovery as well as explicit instruction.

Chapter 3: The Meta-Analyses

Literature Search

Articles examining the two different types of discovery learning have been identified through a variety of sources. The majority of the articles thus far were identified using *PsychInfo*, *ERIC,* and *Dissertations Abstracts International* computerized literature searches. Studies were also identified from citations in articles. The selection criterion for the separate meta-analyses were that studies had to test directly for differences between 1) an explicit training or instruction condition (explicit) and a condition in which unassisted discovery learning occurred, which was operationally defined as being provided with no guidance or feedback or 2) a condition in which discovery learning was operationally defined as being provided with guidance to discover the answer and a comparison condition. In other words, the first meta-analysis evaluated the effects of unassisted discovery learning conditions versus explicit instruction, whereas the second meta-analysis evaluated the effects of guided or enhanced discovery learning conditions over other instructional conditions.

Exclusion criteria precluded the use of several potentially relevant studies. First, articles with unclear statistical information or findings based on only qualitative data alone would not be included.[1] However, before discarding any articles, authors were contacted for information that could be included in the meta-analysis.

Variables Coded from Studies as Possible Moderators

Six moderators were used for blocking purposes in both meta-analyses. See Table 1. Of the five, only *publication rank* was tested using studies as the unit of analysis. Studies from top-ranked journals were compared with studies from other sources (lower-ranked journals, book

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[1] Because we did not want to perform simply a sign test, we did not include articles that did not provide useable statistical information.

chapters, and unpublished dissertations). Top-ranked journals included any journal with an impact factor greater than 1.5 based on the 2001 listings of impact factor. Although impact factors have increased in the intervening years, the rank ordering of journals has changed very little. The purpose of this moderator is not to determine strict publication bias because that possibility will be addressed through the calculation of failsafe *N*'s. Instead, this analysis helps to determine whether findings for or against discovery learning are more often found in a particular publication tier.

For the remaining five moderators, analyses were conducted at the level of statistical comparisons. First, the *domains* of the studies were classified as each of the following: math/numbers, computer skills, science, problem solving, physical/motor skills, or verbal/social skills. Next, the *ages* of the participants were classified as children, adolescents, or adults. Participants were considered *children* if they were 12 years-old or younger, *adolescents* if they were between 13 and 17 years-old, and *adults* if they were 18 years-old or older. If the same statistical test included a range of ages, the mean age of the sample was used for coding purposes. If the exact ages were not provided but their grade levels were, participants were coded as children through sixth grade, as adolescents from seventh to twelfth grades, and as adults thereafter.

The fourth moderator examined was the *dependent variable*. *Post-tests* were assessments administered after the learning phases. These scores included a variety of assessment types from pure post-test scores to improvement scores with previous assessments used as baseline measures on tasks ranging from error detection/correction to content recall, depending on the domain in question. *Acquisition scores* included measurements of learning, success, or failed attempts/errors during the learning phases. *Reaction time scores* reflect the amount of time to the target answer. *Self-ratings* included ratings by learners of their own motivation levels, competencies, or other aspects of the learning tasks. *Peer-ratings* included ratings by observing peers or other learners in regard to the learners' competencies or other aspects of the learning tasks. *Mental effort* reflected scores determined by the experimenters who calculated mental load reflective of the amount of information being considered, the number of variables to be manipulated, the number of possible solutions, etc. that learners had to manage to complete the task successfully.

The next moderator was the *type of discovery learning* approach employed. See Table 2 for a listing of each type of discovery and each type of comparison condition with examples. For the first meta-analysis (comparing explicit to unassisted discovery learning conditions), the types of discovery learning included the following: unassisted, invention, other, simulation, and work with a naïve peer. The *unassisted* conditions included the learner's investigation or manipulation of relevant materials without guidance, the learners teaching themselves through trial-and-error or some other means, or the learners attempting practice problems. The *invention* conditions included tasks that required learners to invent their own strategies or design their own experiments. The *other* conditions included some guidance, often in the form of probe questions, which were asked of learners in both the unassisted discovery conditions and explicit instruction conditions. The *simulation* conditions included some type of computer-generated simulation that required learners to manipulate components or engage in some type of practice to foster comprehension. The *work with naïve peer* conditions were those that paired learners with novice or equal learning partners.

The types of discovery learning for the second meta-analysis were enhanced forms of discovery learning methods and included generation, elicited explanations, and guided discovery conditions. *Generation* conditions required that learners generate rules, strategies, images, or answers to probe questions. *Elicited explanation* conditions required that learners explain some aspect of the target task or target material, either to themselves or to the experimenters. The *guided discovery* conditions involved either some form of instructional guidance (i.e., scaffolding) or regular feedback to assist the learner at each stage of the learning tasks.

Lastly, the type of *comparison condition* was investigated. *Direct teaching* conditions included the explicit teaching of strategies, procedures, concepts, or rules in the form of formal lectures, models, demonstrations, etc. and/or structured problem solving. *Feedback* conditions took priority over other coding and included any instructional design in which experimenters responded to learners' progress in order to provide hints, cues, or objectives. Conditions of *worked examples* included provided solutions to problems similar to the targets. *Baseline* conditions included designs in which learners were not given the basic instructions available to the discovery group, learners were asked to complete an unrelated task that required as much time as the discovery group's intervention, or learners were asked to complete pre- and post-tests only with a time interval matched to the discovery group's. The *explanations provided* conditions were those in which explanations were provided to learners about the target material or the goal task. *Other* conditions included conditions (i.e., three comparisons in the analysis of unassisted discovery and two comparisons in the analysis of enhanced discovery) that were largely experiment-specific in that the condition could not fairly be categorized as any other code because the instructional change involved only a minimal change in design.

Comparison conditions for the second meta-analysis included all of the above except for *feedback* conditions. Also, the *baseline* conditions for the second meta-analysis differed slightly in that such conditions in the second meta-analysis more often involved designs in which learners were asked to teach themselves either through physical manipulations or through textbook learning (i.e., similar to the unassisted discovery conditions of the first meta-analysis), and designs in which only pre- and post-tests were administered with interceding time intervals matched to the discovery group.

Reliability on Moderators

Coding for moderators was accomplished with recommendations from the four authors who decided on moderator codes to include the range of conditions, completely and yet concisely. Reliability on all moderators for both meta-analyses was found to be consistently high leading to an overall kappa of 0.87. All disagreements were resolved through a discussion of how best to classify the variable in question both within the context of the study and the purposes of analysis.

Computation and Analysis of Effect Sizes

Given the great variety of discovery learning designs and the variety of undetermined factors involved in any potential effects, a random effects model was used in all analyses in the *Comprehensive Meta-analysis, Version 2* (CMA) program (Borenstein, Hedges, Higgins, & Rothstein, 2005). A random effects model is appropriate when participant samples and intervention factors cannot be presumed to be functionally equivalent. Consequently, effect sizes cannot be presumed to share a common effect size because they may differ because of any one or a number of different factors between studies. However, the current meta-analyses report overall results from both fixed and random effects models and then present subsequent results only from the random effects model.

Computation formulae included within the CMA program allowed for direct entry of group statistics in order to calculate effect sizes for each test-by-test comparison. When the only statistics available were *F*-values and group means, DSTAT (Johnson, 1993) allowed us to convert those statistics to a common metric, *g,* which represents the difference in standard deviation units. More specifically, *g* is computed by calculating the difference of the two means divided by the pooled standard deviation of the two samples (e.g., the difference between two groups' mean reaction times, divided by the pooled standard deviation). Those *g* scores and other group statistics were then entered into the CMA program. For analyses at the level of samples, overall *g* statistics were calculated in DSTAT before entry into the CMA program.

Effect sizes. Because *g*-values may "overestimate the population effect size" when samples are small (Johnson, 1993, p. 19), *Cohen's d* values are reported here as calculated by the CMA program. *Cohen's d*s between .20 and .50 indicate a small effect size, *Cohen's d*s between .50 and .80 indicate a medium effect, and *d*s greater than .80 indicate a large effect (Cohen, 1988). However, please note that the size of the effect does not determine whether the effect is statistically significant. Consequently, *p*-values are also presented within all tables.

Post Hoc Tests of Moderators

After grouping the effect sizes by a particular moderator and finding significant heterogeneity among different levels of the same moderator, each level was compared to all others within the CMA program, indicated by *Q*, to determine if the effect sizes between the groups were significantly different from one another. Post hoc *p*-values were adjusted for the number of comparisons conducted. For example, post hoc comparisons of the domain categories required 15 comparisons and consequently led to a set alpha level of 0.003 for levels to be considered significantly different from one another.

Chapter 4: The Results of the Analyses

The effect sizes for comparisons of discovery conditions to other forms of instruction were analyzed in four separate meta-analyses, two at the level of studies and two at the level of comparisons. Table 3 displays the results overall for each of the meta-analyses and includes results for both fixed and random effects models. Effects sizes were coded so that a negative effect size indicates that participants in the compared instructional conditions evidenced greater learning than participants in discovery conditions, whereas a positive effect size indicates that participants in the discovery conditions evidenced greater learning than participants in the compared instructional conditions. Analysis at the level of *studies* includes each experiment that sampled different participants. So, if multiple experiments were included within a single article, each experiment counted as an individual study. Analysis at the level of *comparisons* includes each statistical comparison (i.e., each individual comparison for each dependent measure). That is how the first analysis includes 108 studies with 580 comparisons and the second analysis includes 56 studies with 360 comparisons.

Moderators

An advantage of quantitative meta-analytic techniques is the ability to examine potential moderators of relations with ample statistical power. In the present meta-analyses, the following potential moderators were investigated: publication rank, domain, age of participants, dependent variable, type of discovery condition, and type of compared instructional condition. Whenever heterogeneity of variance was indicated (Johnson, 1989), moderators were tested for each of the meta-analyses. Adjusted post hoc *p* values (i.e., adjustments depended on the number of categories to be compared) were used to determine statistical significance. All moderators for both meta-analyses were examined using statistical tests as the unit of analysis, assuming independence, except for publication rank, which was examined at the level of samples.

Unassisted Discovery

Overall Effects

A total of 580 comparisons from 108 studies compared unassisted discovery learning with more explicit teaching methods. Table 4 lists each sample. With the random effects analysis, the 108 studies had a mean effect size of $d = -.38$ (95% $CI = -.50/-.25$), indicating that explicit teaching was more beneficial to learning than unassisted discovery. This constitutes a small but meaningful effect size ($p < .001$). The effects are highly heterogeneous across the studies, Q (107) = 522.11, $p < .001$. Such heterogeneity is to be expected given the diversity of research methods, participant samples, and learning tasks. To address issues of publication bias, failsafe *N*s were calculated both at the level of comparisons and at the level of studies with alphas set to .05, two-tailed. At the level of comparisons, 3,588 unpublished studies and at the level of studies, 3,551 unpublished studies would be needed to reduce these effects to nonsignificance.

Moderators

First, using studies as the unit of analysis, the type of publication moderated the findings, Q (3) = 10.86, $p < .05$. Articles in first-tier journals ($d = -.67$) evidenced larger effect sizes in favor of explicit instruction than did articles in second-tier publications ($d = -.24$). Post-hoc comparisons revealed that these mean effect sizes were significantly different from one another, Q (1) = 10.20, $p < .008$. Effect sizes from book chapters ($d = -.12$) and unpublished works ($d = -.01$) did not reach significance.

The domain was also found to moderate effect sizes, Q (5) = 91.75, $p < .001$. As Table 5 shows that in the domains of math ($d = -.16$), science ($d = -.39$), problem solving ($d = -.48$), and verbal and social skills, ($d = -.95$) participants evidenced less learning in the unassisted-discovery conditions than in the explicit conditions. Post-hoc comparisons indicated that the mean effect size favoring explicit conditions within the verbal/social skills domain was significantly greater than within the domains of math, Q (1) = 50.03, $p < .001$, computer skills, Q (1) = 58.17, $p < .001$, science, Q (1) = 22.65, $p < .001$, problem solving, Q (1) = 18.35, $p < .001$, and physical/motor skills, Q (1) = 14.87, $p < .001$. The mean effect size favoring explicit conditions within the domain of problem solving was also significantly greater than within the domains of math, Q (1) = 13.65, $p < .001$, and computer skills Q (1) = 28.29, $p < .001$. Lastly, the mean effect size favoring explicit conditions in the domain of science was significantly greater than within the domain of computer skills, Q (1) = 16.64, $p < .001$.

The next moderator investigated was participant age, which also moderated the findings, Q (2) = 12.29, $p < .01$. Table 6 displays the effect sizes by the age group of the participants. As can be seen, effect sizes for all age groups showed significant advantages for more explicit instruction over unassisted discovery. Post-hoc comparisons revealed that the mean effect size for adolescents (d = -.53) was significantly greater than the mean effect size for adults (d = -.26), Q (1) = 10.41, $p = .001$. The type of dependent variable was also found to moderate the findings, Q (5) = 37.38, $p < .001$. Measures of post-test scores (d = -.35), acquisition scores (d = -.95), and time to solution (d = -.21) favored participants in explicit conditions, as can be seen in Table 7. Post-hoc comparisons indicated that the measure of acquisition scores led to significantly greater effect sizes in favor of explicit conditions than did the measures of post-test scores, Q (1) = 31.41, $p < .001$, time to solution, Q (1) = 23.84, $p < .001$, and self-ratings Q (1) = 15.89, $p < .001$.

The type of unassisted-discovery condition moderated the findings, Q (4) = 10.02, $p < .05$, but post-hoc comparisons failed to reveal any reliable differences. Table 8 displays that all levels of unassisted-discovery conditions except for matched probes somewhat favored participants in the explicit conditions. Next, we investigated the explicit conditions to which unassisted-discovery conditions were compared. The type of explicit condition moderated the findings, Q (5) = 32.31, $p < .001$. Participants in unassisted discovery fared worse than participants in comparison conditions of direct teaching (d = -.29), feedback (d = -.46), worked examples (d = -.63), and explanations provided (d = -.28). Table 9 provides more information regarding these comparisons. Post-hoc comparisons revealed that effect sizes for direct teaching and worked examples were significantly different from one another, Q (1) = 18.98, $p < .001$, and indicated that participants learning with worked examples outperformed participants learning through unassisted discovery to a greater extent than did participants learning from direct teaching outperform participants learning from unassisted discovery. Post-hoc comparisons also revealed that feedback, Q (1) = 9.15, $p < .003$, and worked examples, Q (1) = 13.70, $p < .001$, benefited learners more than having no exposure with pre- and post-tests only.

Overall, the findings indicate that explicit instructional conditions lead to greater learning than do unassisted-discovery conditions. The lack of significant differences between the mean effect sizes of the unassisted-discovery conditions helps to illustrate that claim.

Enhanced Discovery

Overall Effects

A total of 360 comparisons from 56 studies compared enhanced discovery learning (i.e., generation, elicited explanation, or guided discovery) with other types of instructional methods. Table 10 lists each sample. With the random effects analysis, the 56 studies had a mean effect size of d = .30 (95% CI = .15/.44), indicating that enhanced-discovery methods led to greater learning than did comparison methods of instruction. This constitutes a small but meaningful effect size ($p < .001$). The effects are highly heterogeneous across the studies, Q (55) = 260.14, $p < .001$. Again, such heterogeneity is to be expected given the diversity of research methods, participant samples, and learning tasks. To address issues of publication bias, failsafe *N*s were calculated both at the level of comparisons and at the level of studies with alphas set to .05, two-tailed. At the level of comparisons, 4,138 unpublished studies and at the level of studies, 960 unpublished studies would be needed to reduce effects to nonsignificance.

Moderators

First, using studies as the unit of analysis, the type of publication moderated the findings, Q (2) = 18.66, $p = .001$. Articles in first-tier journals ($d = .35$) and second-tier journals ($d = .40$) generally favored enhanced-discovery conditions, whereas datasets from unpublished studies and dissertations did not ($d = -.54$). Post-hoc comparisons revealed that although the effect sizes derived from first-tier and second-tier journal articles were not significantly different, Q (1) = .10, *ns*, the mean effect size from unpublished works and dissertations differed from both the mean effect size from first-tier journals, Q (1) = 9.65, $p < .003$, and the mean effect size from second-tier journals, Q (1) = 21.59, $p < .001$.

Domain was also found to moderate the findings, Q (5) = 65.53, $p < .001$. As can be seen in Table 11, in the domains of math ($d = .29$), computer skills ($d = .64$), science ($d = .11$), physical/motor ($d = 1.05$), and verbal and social skills ($d = .58$), participants evidenced more learning in the enhanced-discovery conditions than in the comparison conditions. Post-hoc comparisons indicated that the mean effect size in the physical/motor domain was significantly greater than the effect sizes in the domains of math, Q (1) = 34.59, $p < .001$, science, Q (1) = 41.67, $p < .001$, and problem solving, Q (1) = 15.73, $p < .001$. Also, the mean effect size for the domain of computer skills was significantly greater than the effect sizes in the domains of math, *Q* (1) = 12.14, *p* < .001 and science, *Q* (1) = 18.65, *p* < .001.

The next moderator, participant age, also influenced the findings, *Q* (2) = 10.68, *p* < .01. Table 12 displays the effect sizes by the age group of the participants. Post-hoc comparisons revealed that the mean effect size for adults was significantly greater than the effect size for children, *Q* (1) = 7.64, *p* < .01. Although superficially there was a greater difference between the mean effect sizes of adults and adolescents, that difference was not found to be significant due to the larger variance within the adolescents (95% CI = .04/.33). Next, the type of dependent variable was found to moderate the findings, *Q* (4) = 64.60, *p* < .001. Measures of post-test scores (*d* = .28), acquisition scores (*d* = .54), and self-ratings (*d* = 1.25) favored participants in enhanced-discovery conditions over participants in comparison conditions, whereas measures of reaction times (*d* = -.72) favored participants in comparison conditions over participants in enhanced-discovery conditions. See Table 13. Post-hoc comparisons indicated that the measure of post-test scores led to significantly greater effect sizes in favor of participants in enhanced-discovery conditions than did the measure of self-ratings, *Q* (1) = 29.68, *p* < .001. Comparisons also indicated that the mean effect size derived from reaction time measures was significantly different (i.e., significantly opposite in effect size direction) from both the mean effect size derived from acquisition scores, *Q* (1) = 10.19, *p* = .001, and the mean effect size derived from post-tests, *Q* (1) = 31.61, *p* < .001. Lastly, the mean effect size for self-ratings which favored enhanced discovery was found to be significantly different (i.e., opposite to) the mean effect size for mental effort/load which showed trends favoring other forms of instruction.

The type of enhanced-discovery condition used also moderated the findings, *Q* (2) = 65.00, *p* < .001. Table 14 shows that elicited explanation (*d* = .36) and guided discovery (*d* = .50) favored enhanced discovery whereas generation (*d* = -.15) favored other instructional methods. Post-hoc comparisons indicated that indeed, generation conditions were significantly different in their effect sizes to both elicited explanation, *Q* (1) = 33.20, *p* < .001, and guided discovery, *Q* (1) = 57.43, *p* < .001, but the effect sizes for elicited explanation and guided discovery did not differ from one another. Next, we investigated the instructional conditions to which enhanced-discovery conditions were compared but the type of comparison condition failed to moderate the findings, *Q* (4) = 9.12, *p* = .06, *n.s.* As shown in Table 15, with the exception of worked examples (*d* = .06, *n.s.*), all other comparisons conditions indicated significantly superior performances in the enhanced-discovery conditions.

Overall, results seemed to favor enhanced-discovery methods over other forms of instruction. However, the dependent measure and the type of enhanced discovery employed affected the outcome assessments.

Chapter 5: Discussion of Results and Implications

The first meta-analysis was intended to investigate under which conditions unassisted discovery learning might lead to better learning outcomes than explicit-instructional tasks. However, more explicit-instructional tasks were found to be superior to unassisted-discovery tasks. Moreover the type of publication, the domain of study, the age of participants, the dependent measure, the type of unassisted-discovery task, and the comparison condition all moderated outcomes. Post-hoc comparisons revealed that on average, publications in first-tier journals showed greater benefits for explicit-instructional tasks than did publications in second-tier journals. Among the variety of different domains in which more explicit instruction was found to benefit learners, verbal and social learning tasks seemed to favor explicit instruction most, followed by problem solving and science. Adolescents were found to benefit significantly more from explicit instruction than did adults. Analysis of dependent measures indicated that learners' acquisition scores showed a greater detriment under discovery conditions than did post-test scores, time to solution, and self-ratings. Although the type of unassisted-discovery task moderated trends favoring explicit instruction, unassisted tasks, tasks requiring invention, and tasks involving collaboration with a naïve peer were all found to be equally detrimental to learning. Analyses of the types of explicit instruction in the comparison conditions indicated that worked examples benefited learners more than direct teaching and also indicated that feedback and providing explanations are useful aids to learning. The finding that worked examples evidenced greater learning than did unassisted discovery is expected given the worked-example effect (Sweller, Kirschner, & Clark, 2007). However, the finding that worked examples benefited learners to a greater extent than did direct teaching was unexpected.

The second meta-analysis investigated under which conditions enhanced forms of discovery-learning tasks might be beneficial. This meta-analysis showed better learning for enhanced-discovery instructional methods, with the type of publication, the domain, the age of participants, the dependent measure, and the type of enhanced-discovery task moderating the findings. Unpublished studies and dissertations were found to show disadvantages for enhanced-discovery conditions whereas first and second-tier journal articles favored enhanced discovery. Of the different task domains, physical/motor[2], computer skills, and verbal and social skills benefited most from enhanced discovery. Also, analyses revealed that adult participants benefit more from enhanced discovery than children. Of the three types of enhanced discovery, the generation method of enhanced discovery failed to produce learning benefits over other instructional methods, which was unexpected given the typical benefits reported as the generation effect (Bertsch, Pesta, Wiscott, & McDaniel, 2007; Slamecka & Graf, 1978). It should be noted that the advantage of other forms of instruction over generation also led to the finding that unpublished studies and dissertations showed an advantage for other forms of instruction over enhanced discovery. This was due to the fact that four out of the five studies sampled from unpublished works or dissertations employed generation conditions. Although the meta-analysis indicated that the type of comparison condition did not moderate the results, note that enhanced discovery was generally better than both direct teaching and explanations provided. Thus, the construction of explanations or participation in guided discovery is better for learners than being provided with an explanation or explicitly taught how to succeed on a task, in

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[2] Because of concerns that the domain category of physical/motor skills might be dominating the overall analysis of enhanced discovery, those 24 comparisons were removed and analyses were run again. The removal of physical/motor skills from the overall analyses under the random effects model only reduced the mean effect size slightly [i.e., from (*d* = .30) to (*d* = .25)]. Consequently, we retained the category of physical/motor skills within our analyses.

support of constructivist claims. In regard to the large mean effect size for the category of comparison conditions labeled *other*, it should be noted that this category included only two comparisons; these two comparisons[3] were included to ensure a complete inclusion of comparison conditions, despite the fact that they did not fit into the other categories. Lastly, analysis of the dependent measure indicated that although learners' post-test and acquisition scores benefited from enhanced-discovery tasks, reaction times did not. This suggests that learners may take more time to find problem solutions or perform target responses when engaged in enhanced-discovery tasks.

The moderating effect of age across the two meta-analyses did not follow the expected pattern of results. First, the adolescent age group was shown to benefit least from unassisted-discovery conditions, as opposed to the children, as had been predicted. Although enhanced-discovery conditions led to better learning outcomes for all age groups, adults seemed to benefit from enhanced-discovery tasks more so than children. Interestingly, the adolescents tended to benefit least and the adults tended to benefit most from both unassisted-discovery tasks and enhanced-discovery tasks. One might speculate that the negative trend among adolescents could reflect a general lack of motivation or lack of domain-relevant knowledge (Mayer, 2009). However, if the trend was the result of a lack of domain-relevant knowledge, one might expect to see even larger deficits in children. With regards to the adults, perhaps their greater domain-relevant knowledge helped them to succeed on unassisted-discovery tasks to a greater extent than

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[3] The participants in the first *other* comparison condition were asked the same questions that were asked of the elicited explanations group but the elicited explanations condition required participants to provide a specific target answer before proceeding to the next question, and the comparison condition did not. The participants in the second *other* comparison condition were asked to discuss how/why things balance on a beam within a group without input from the experimenter, and were compared to participants who were asked to explain to the experimenter who guided the learner with subsequent questions toward the target explanation.

the adolescents. It is also possible that the tasks used in the enhanced-discovery studies were more appropriate for adult learners (e.g., having participants explain the strategies they were using to solve problems) than for young learners. Organizing guidance to facilitate discovery requires sensitivity to the learner's zone of proximal development (Vygotsky, 1962; Pea, 2004) if it is to be maximally useful.

Implications for Teaching

The results of the first meta-analysis indicate that unassisted discovery generally does not benefit learning. Although direct teaching is better than unassisted discovery, providing learners with timely feedback and/or worked examples might be optimal. Whereas providing well-timed, individualized feedback to all learners might be impossible (e.g., in a classroom setting), providing such feedback on homework assignments seems possible and worthwhile. Students might also benefit from having worked examples provided on those homework assignments when the content allows for it. Furthermore, the second meta-analysis suggests that teaching practices should employ scaffolded tasks that have support in place as learners attempt to reach some objective, and/or activities that require learners to explain their own ideas. The benefits of feedback, worked examples, scaffolding, and elicited explanation can be understood to be part of a more general need for learners to be redirected, to some extent, when they are mis-constructing. Feedback, scaffolding, and elicited explanations do so in more obvious ways through an interaction with the instructor, but worked examples help lead learners through problem sets in their entireties and perhaps help to promote accurate constructions as a result. Although our suggestions are conservative as to how to apply the current findings, we suspect and hope that these analyses will be influential in subsequent designs, both instructional and empirical.

Implications for Theory

Perhaps the inferior outcomes of unassisted discovery should not be surprising. Hake (2004) referred to such methods as *extreme* modes of discovery and pointed out that methods with almost no teacher guidance will, of course, be inferior to more guided methods. It does not seem that many researchers on either side of the argument would disagree with such a claim (Tobias & Duffy, 2009). Nonetheless, it seems that many of Mayer's (2004) concerns are justified. Unassisted discovery tasks appear inferior to more instructionally guided tasks, whether explicit instruction or enhanced discovery. Mayer's concern that unassisted discovery tasks do not lead learners to construct accurate understandings of the problem sets illustrates the potential disconnect between activity and constructivist learning. As Mayer points out, it has been the accepted practice to consider hands-on activities as equivalent to constructivism but active instructional methods do not always lead to active learning, nor do passive methods always lead to passive learning (Mayer, 2009).

Recently, Chi (2009) outlined the theoretical and behavioral differences between learning tasks that require the learner to be active and learning tasks that require the learner to be constructive, and emphasized that the two are certainly not one in the same. Although a meta-analysis of Chi's claims would be optimal to support her outline, she nonetheless has provided tentative explanations that are useful fodder and seemingly in agreement to some extent with the points of Mayer (2004). She explained that although activities requiring hands-on active participation from learners guarantee a level of engagement greater than passive reception of information, these activities do not guarantee that learners will understand enough of the subject matter or that they will be engaged to the extent necessary to make sense of the materials for themselves. From Chi's perspective, learning activities entailing true constructivism should require learners not only to engage in the learning task (e.g., manipulate objects or paraphrase) but also to construct ideas that surpass the presented information (e.g., to elaborate, predict, reflect). Chi's emphasis that constructivism should require learners to achieve those *higher-order objectives* - similar to those outlined by Fletcher (2009) that include analysis, evaluative abilities, and creativity - illustrates that the objectives of constructivism are at least in part, present within the learning activity itself.

Perhaps the completely unguided discovery activities objected to by Mayer (2004) were too ambiguous to allow learners to transcend the mere activity and reach the level of constructivism intended. Through more guided tasks, the learner is liberated potentially from high demands on working memory and executive functioning abilities (Chi, 2009; Kirschner, Sweller, & Clark, 2006; Mayer, 2003; Rittle-Johnson, 2006; Sweller, 1988) and can therefore direct his/her efforts toward more creative processes (e.g., inference, integration, and reorganization) as outlined by both Chi (2009) and Fletcher (2009). Our finding that generation is not an optimal form of enhanced discovery may illustrate this claim. The generation conditions required learners to generate rules, strategies, or images, or to answer questions about the information but there was little consistency as to the extent that learners had to go beyond the presented information to do so. Of the three types of enhanced discovery, generation required the least engagement of learners with respect to the types of activities that Chi identified as constructive.

The finding that enhanced forms of discovery are superior to unassisted forms also calls into question ecological perspectives of learning inherent within discovery pedagogy and perhaps constructivism more generally. Although it seems reasonable to expect learners to be able to construct their own understandings with minimal assistance because they do so on a daily basis in the context of everyday activities, perhaps the content and context of formal education are extraordinary (Geary, 2008) and consequently require more assistance to arrive at accurate constructions, understandings, and solutions (Sweller, Kirschner, & Clark, 2007). It is also possible that people often learn what they do within daily life activities through forms of guided participation (Rogoff, 1990).

The Potential of Teaching Discovery

In light of the previous discussion of Mayer (2004) and Chi (2009), we should return to the possibility that it might serve educators and students alike to spend time learning the procedures of discovery (Ausubel, 1964; Bielaczyc, Pirolli, & Brown, 1995; Bruer, 1993; Dewey, 1910; Karpov & Haywood, 1998; King, 1991; Kozulin, 1995; Kuhn, Black, Keselman, & Kaplan, 2000). Teaching learners first to be discoverers (e.g., how to navigate the problem solving space, use limited working memory capacities efficiently, and attend to relevant information) could *prepare* them (Bruner, 1961) for those active learning demands as outlined by Chi (2009), and perhaps provide some of the needed curricular focus and necessary structure to discovery tasks as emphasized by Mayer (2004). Furthermore, by having learners better familiarized with the processes of discovery, the cognitive load demands (Kirschner, Sweller, & Clark, 2006; Rittle-Johnson, 2006; Sweller, 1988) might be reduced and consequently allow learners to engage with the learning tasks not only in active ways, but also constructively (i.e., in the ways outlined by Chi, 2009) to allow them to go beyond the presented information. Bruner (1961, pp. 26) emphasized that discovery encourages learners to be constructivists and that practice in discovering teaches the learner how best to acquire information to make it more readily available. Again, he implied that the act of discovering is one that requires practice to be of value.

Bruner also warned that the learner’s mind has to be prepared for discovery. The preparation that Bruner emphasized was not merely an existing knowledge base regarding the domain of study; he also emphasized that learning by discovery does not necessarily involve the acquisition of new information. Bruner claimed that discovery was more often the result of a learner gaining insights that transform their knowledge base through new ways of organizing the previously learned information. Furthermore, the prepared mind for Bruner was one with experience in discovery itself.

> It goes without saying that, left to himself, the child will go about discovering things for himself within limits. It also goes without saying that there are certain forms of child rearing, certain home atmospheres that lead some children to be their own discoverers more than other children (pp. 22).

Although Bruner referred to a child, the same might be said of all learners: an intuitive ability to discover is profoundly limited. Bruner (1961) continued by explaining Vygotsky’s (1962) emphasis that the narrative of teaching is a conversation that is internalized by the learner who can subsequently use that narrative to teach himself/herself. Bruner emphasized that opportunities for discovery might facilitate this process. Consequently, it seems reasonable to conclude that discovery might be itself, a scripted tool (i.e., a narrative) for making sense of materials on one’s own (Arievitch & Stetsenko, 2000; Kozulin, 1995; Stetsenko & Arievitch, 2002; Wertsch, 1981). The steps and procedures of that script are not intuitive to the learner but need to be presented by teachers, or parents as emphasized by Bruner, because they are part of a culture (e.g., the culture of formal education). Thus, if learning through discovery is superior to other forms of instruction, then it might serve educators and students alike to spend time learning the procedures of discovery (Ausubel, 1964; Bielaczyc, Pirolli, & Brown, 1995; Bruer, 1993;

Dewey, 1910; Karpov & Haywood, 1998; King, 1991; Kozulin, 1995; Kuhn, Black, Keselman, & Kaplan, 2000). Generally, teaching the procedures of discovery to learners might provide some of the needed curricular focus and necessary structure to discovery instructional methods (concerns raised by Mayer, 2004). It might also reduce the cognitive demands of discovery learning tasks and make such methods more easily employed (a concern raised by Kirschner et al., 2006).

Although the suggestion is to teach learners how to discover, that is not to imply that these analyses have led to some oversimplified strategy for discovery that can bridge all domains or learning tasks. On the contrary, as pointed out by both Klahr (2009) and Wise and O'Neill (2009), directly instructing learners on problem solving skills, analogies, and other cognitive processes should not be expected to lead learners to generalize those skills to all other areas of learning. However, providing ample opportunities for learners to discover when and where those processes are appropriate, could lead learners to such discovery-based constructivism only after those processes have been directly taught within the contexts of their appropriate domains.

More generally, teaching students how to discover or how to be constructive might begin with more basic preparation. Perhaps many learners are not prepared for such activities and that instruction needs to be focused first at the level of reading comprehension, to teach students how to make sense of new information (Herman & Gomez, 2009) because domain-relevant information might be essential for successful construction of novel understandings during instruction, particularly in ill-structured domains (Rosenshine, 2009; Spiro & DeSchryver, 2009). Herman and Gomez have outlined several *reading support tools* (p. 70) that are designed to help students understand science texts in meaningful and useful ways. Although these tools need first to be taught explicitly, they could provide self-guidance while reading science texts thereafter.

Perhaps similar reading support tools need to be developed for other texts as well so that students can come to view textbooks as helpful resources within their environments that they are able to interact with in meaningful ways to reach objectives, the definition of learning as proposed by Gresalfi and Lester (2009). These tools could establish foundations for learning that might not be readily generalizable from the moment that they are mastered but can be after practice, experience in different contexts, and in the presence of scaffolding and feedback (Wise & O'Neill, 2009).

Conclusion

Overall, the effects of unassisted discovery tasks seem limited, whereas enhanced discovery tasks requiring learners to be actively engaged and constructive seem optimal. Based on the current analyses, optimal approaches should include at least one of the following: 1) guided tasks that have scaffolding in place to assist learners toward the target, 2) tasks that require learners to explain their own ideas and that ensure that those ideas are accurate by providing timely feedback, or 3) tasks that provide worked examples of how to succeed in the task. Opportunities for construction might not present themselves when learners are unassisted and perhaps spending their efforts on making sense of the task alone. Perhaps these findings can help to move the debate away from issues of unassisted forms of discovery and towards a fruitful discussion and consequent empirical investigations to decide at which point during the learning task direct forms of instruction are optimal, how scaffolding is best implemented, how to provide feedback in classroom settings, how to create worked examples for varieties of content, etc.

Table 1

Categories of Each Moderator

Moderator	*Categories*
Publication rank	Journal impact factor of 1.5 +
	Journal impact factor below 1.5
	Book chapters
	Unpublished/dissertations
Domain	Math/numbers
	Computer skills
	Science
	Problem solving
	Physical/motor skills
	Verbal/social skills
Age	Children: under 12 y/o
	Adolescents: between 12 and 18 y/o
	Adults: 18 y/o +
Dependent measure	All post-tests scores, error rates, rates of error detection
	Acquisition scores
	Reaction time scores
	Self-ratings
	Peer ratings
	Mental effort/load ratings

Moderator	Categories
Unassisted discovery	Unassisted, teaching oneself, practice problems
	Invention
	Other: matched guidance/probes in both discovery and comparison conditions
	Simulation
	Work with a naïve peer
Enhanced discovery	Generation
	Elicited explanation
	Guided discovery
Comparison condition	Direct teaching
	Feedback
	Worked examples with solutions provided
	Baseline
	unassisted: no exposure nor explanation
	enhanced: unassisted discovery or textbook only
	Explanations provided
	Other: study-specific condition

Table 2

Descriptions of Discovery Conditions and Comparison Conditions

Unassisted Discovery	Moderator	Categorical definition: Learners…	Specific example
Type of discovery	Unassisted	taught themselves or completed practice problems.	Kalyuga, Chandler, & Sweller E2: To learn about Boolean switching equations for relay circuits, learners were asked to explore the circuitry without worked examples.
	Invention	invented their own strategies or design their own experiments.	Charney, Reder, & Kusbit: To learn about data entry, learners were asked to invent their own problems to solve.
	Other: matched probes	in both conditions were provided with probe questions or a minimal form of guidance.	Kersh, article 2: To learn about addition rules, learners were asked to complete practice problems and were told whether correct or incorrect.
	Simulation	manipulated components or engaged in some type of practice within a computer-generated simulation.	Rieber & Parmley: To learn about Newtonian mechanics through inductive reasoning, learners were asked to manipulate a simulation in order to discover and apply Newtonian principles.
	Work with naïve peer	worked with equally novice partners.	O'Brien & Shapiro: To learn about mathematical patterns, learners were asked to work in groups of three to find and list patterns.
Type of explicit instruction	Direct teaching	received explicit instruction.	Kersh, article 2: To learn about addition rules, learners were first trained and then asked to complete practice problems and were told whether correct or incorrect.
	Feedback	received hints, cues, or objectives during the task.	Charney, Reder, & Kusbit: To learn about data entry, learners were asked to solve problems within a manual and were provided with feedback during that task.
	Worked examples	received completely worked examples to study.	Kalyuga, Chandler, & Sweller E2: To learn about Boolean switching equations for relay circuits, learners were asked to study worked examples.
	Baseline: no exposure	did not have an opportunity to discover nor receive explicit instruction.	Peters: To succeed on a Piagetian conservation task, learners were asked to complete pre- and post-tests without an intervention.
	Explanations provided	were provided with explanations of how to succeed or what to understand.	Kelemen E2: To learn about scientific explanations of the natural world, learners were provided with scientific explanations by the instructor.
	Other	studied under conditions that only differed slightly from the discovery condition	Quilici & Mayer E1: To learn about similarities between statistical word problems, learners were provided with only one example of each type instead of three (i.e., as in the discovery condition).

Enhanced Discovery	Moderator	Categorical definition	Specific example
Type of discovery	Generation	were required to generate rules, strategies, images, or answers to general questions.	Ginns, Chandler, & Sweller E2: To learn geometric rules for calculations, learners were asked to generate images of the steps required to solve the problem.
	Elicited explanation	were required to explain some aspect of the task or concepts.	Mwangi & Sweller E3: To learn 2-step mathematical word problems, learners were required to answer open-ended questions that prompted them to explain while studying worked examples.
	Guided discovery	received regular feedback or scaffolding during the task.	Anastasiow et al.: To learn about geometric shapes, learners were provided with cuing, guidance, and direct connections between target shapes and the instructional examples.
Type of other instructional condition	Direct teaching	received explicit instruction.	Anastasiow et al.: To learn about geometric shapes, learners were provided with an explanation of the concepts, cues during the task, explicit references to the rules, and the rules were explicitly verbalized.
	Worked examples	received completely worked examples to study.	Mwangi & Sweller E3: To learn 2-step mathematical word problems, learners were required to study worked examples.
	Baseline: unassisted discovery	had to teach themselves or study from the textbook.	Anastasiow et al.: To learn about geometric shapes, learners were asked to explore the shapes but were only provided with minimal assistance and only when necessary to keep the learner on task.
	Explanations provided	were provided with explanations of how to succeed or what to understand.	Crowley & Siegler: To learn how to play tic-tac-toe, learners watched a demonstration of the game and the instructor explained the move strategies.
	Other	studied under conditions that only differed slightly from the discovery condition.	Amsterlaw & Wellman: To learn about false beliefs, learners were questioned about protagonists' false beliefs but were not corrected or reasked if incorrect (as in the elicited explanation condition).

Table 3

Summary of Effect Sizes

Unassisted Discovery	Level of Analysis	Cohen's *d*	95% CI	Z	*p*-value (Z)	N	*Q*	*df* (*Q*)	*p*-value (*Q*)
	Studies								
	Fixed	-.30	[-.36, -.25]	-10.62	0.00	5,226	522.11	107	0.00
	Random	-.38	[-.50, -.25]	-5.69	0.00	5,226			
	Comparisons								
	Fixed	-.30	[-.32, -.27]	-23.08	0.00	25,986	3,490.42	579	0.00
	Random	-.38	[-.44, -.31]	-11.40	0.00	25,986			
Enhanced Discovery	Level of Analysis	Cohen's *d*	95% CI	Z	*p*-value (Z)	N	*Q*	*df* (*Q*)	*p*-value (*Q*)
	Studies								
	Fixed	.26	[.20, .32]	8.39	0.00	4,243	260.14	55	0.00
	Random	.30	[.15, .44]	4.10	0.00	4,243			
	Comparisons								
	Fixed	.24	[.21, .26]	18.61	0.00	25,925	2,037.19	359	0.00
	Random	.30	[.23, .36]	9.12	0.00	25,925			

Table 4

Samples Included in the Unassisted Discovery Meta-analysis

Author(s)	Year	Discovery *n*	Comparison *n*	*Cohen's d*	Domain	Age	Journal rank
Alibali	1999	26	29.25	-0.89	math/numbers	children	journal ≥ 1.5
Anastasiow, Sibley, Leonhardt, & Borich	1970	6	6	-0.06	math/numbers	children	journal < 1.5
Bannert	2000	37	35	0.74	computer skills	adults	journal < 1.5
Belcastro	1966	189	189	-0.26	math/numbers	adolescents	journal < 1.5
Bobis, Sweller, & Cooper E1	1994	15	15	1.07	math/numbers	children	journal < 1.5
Bobis, Sweller, & Cooper E2	1994	10	10	1.11	math/numbers	children	journal < 1.5
Bransford & Johnson E1	1972	10	10	-0.63	verbal/social	adolescents	journal ≥ 1.5
Bransford & Johnson E2	1972	17	17.5	-0.60	verbal/social	adults	journal ≥ 1.5
Bransford & Johnson E4	1972	9	11	-0.50	verbal/social	adolescents	journal ≥ 1.5
Brant, Hooper, & Sugrue	1991	33	35	0.55	science	adults	journal < 1.5
Brown, Kane, & Long E3	1989	21	16	-0.17	problem solving	children	journal < 1.5
Butler, Pine, & Messer	2006	34	28	-0.01	math/numbers	children	unpub/diss
Cantor, Dunlap, & Rettie	1982	24	24	-0.46	math/numbers	children	journal < 1.5
Carroll E1	1994	16.8	16.8	-0.89	math/numbers	adolescents	journal ≥ 1.5
Carroll E2	1994	12	12	-2.05	math/numbers	adolescents	journal ≥ 1.5
Charney, Reder, & Kusbit	1990	20	45	-0.33	computer skills	adults	journal < 1.5
Craig	1965	30	30	-0.11	math/numbers	adults	journal < 1.5
Danner & Day	1977	20	20	-0.86	science	adolescents	journal ≥ 1.5
Destrebecqz E1	2004	20	20	-0.56	problem solving	adults	journal < 1.5
Destrebecqz E2	2004	12	12	-2.36	problem solving	adults	journal < 1.5
Elias & Allen	1991	37.86	34.43	-0.01	problem solving	children	journal < 1.5
Elshout & Veenman E1	1992	4.5	4.25	-0.19	science	adults	journal < 1.5
Elshout & Veenman E2	1992	4.4	5	-0.24	science	adults	journal < 1.5

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen's *d*	Domain	Age	Journal rank
Fender & Crowley E2	1992	12	12	-1.04	science	children	journal < 1.5
Guthrie	1967	18	18	-0.64	problem solving	adults	journal ≥ 1.5
Hendrickson & Schroeder	1941	30	30	-0.32	physical/motor	adolescents	journal ≥ 1.5
Hendrix	1947	13	13.5	0.51	math/numbers	adults	journal < 1.5
Hodges & Lee	1999	8	8.5	0.39	physical/motor	adults	journal < 1.5
Howe, McWilliam, & Cross E2	2005	36	36	0.43	science	children	journal < 1.5
Howe, McWilliam, & Cross E3	2005	36	36	0.29	science	children	journal < 1.5
Jackson, Fletcher, & Messer	1992	36	24	-0.23	math/numbers	children	journal < 1.5
Jimenez, Mendez, & Cleeremans	1996	6	6	0.00	verbal/social	adults	journal ≥ 1.5
Kalyuga, Chandler, & Sweller E1	2001	9	8	-0.78	math/numbers	adults	journal < 1.5
Kalyuga, Chandler, & Sweller E2	2001	9	8	-0.28	math/numbers	adults	journal < 1.5
Kalyuga, Chandler, Tuovinen...E1	2001	12	12	-0.53	computer skill	adults	journal ≥ 1.5
Kalyuga, Chandler, Tuovinen...E2	2001	12	12	0.70	computer skill	adults	journal ≥ 1.5
Kamii & Dominick	1997	16.29	16.71	0.21	math/numbers	children	journal < 1.5
Kelemen	2003	12	11	-0.82	science	children	journal ≥ 1.5
Kersh	1958	16	16	-0.18	math/numbers	adults	journal ≥ 1.5
Kersh: Article 2	1962	10	10	0.50	math/numbers	adolescents	journal ≥ 1.5
King	1991	8	7.5	-0.58	problem solving	children	journal ≥ 1.5
Kittell	1957	45	43.5	-0.78	verbal/social	children	journal ≥ 1.5
Klahr & Nigam	2004	52	52	-1.14	science	children	journal ≥ 1.5
Kuhn & Dean	2005	12	12	-1.18	science	children	journal ≥ 1.5
Lawson & Wollman	1976	16	16	-0.82	science	adolescents	journal < 1.5
Lazonder & van der Meij	1993	30	34	0.67	computer skill	adults	journal < 1.5
Lazonder & van der Meij: Article 2	1994	21	21	0.05	computer skill	adults	journal < 1.5

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen’s *d*	Domain	Age	Journal rank
Lazonder & van der Meij: Article 3	1995	25	25	-0.44	computer skill	adults	journal < 1.5
Lee & Thompson	1997	66	64	-0.92	computer skill	adults	journal < 1.5
Leutner E1	1993	16	16	-0.09	problem solving	adolescents	journal < 1.5
Leutner E2	1993	19	19	-0.36	problem solving	adults	journal < 1.5
Leutner E3	1993	20	20	-0.38	problem solving	adolescents	journal < 1.5
McDaniel & Pressley E1	1984	16.6	17.6	-1.21	verbal/social	adults	journal ≥ 1.5
McDaniel & Pressley E2	1984	21	21	-1.06	verbal/social	adults	journal ≥ 1.5
McDaniel & Schlager E1	1990	31	29.5	0.00	problem solving	adults	journal < 1.5
McDaniel & Schlager E2	1990	60	60	0.42	problem solving	adults	journal < 1.5
Messer, Joiner, Loveridge, Light… E1	1993	14	13	0.32	science	children	journal < 1.5
Messer, Joiner, Loveridge, Light,… E2	1993	18	20	-1.14	science	children	journal < 1.5
Messer, Mohamedali, & Fletcher	1996	21	20	0.34	problem solving	children	journal < 1.5
Messer, Norgate, Joiner, Littleton…E1	1996	11.75	10.5	-0.89	science	children	journal < 1.5
Messer, Norgate, Joiner, Littleton…E2	1996	16	15	0.43	science	children	journal < 1.5
Morton, Trehub, & Zelazo E2	2003	15.29	16.14	-2.19	verbal/social	children	journal ≥ 1.5
Mwangi & Sweller E1	1998	9	9	-0.46	math/numbers	children	journal < 1.5
Nadolski, Kirschner, & Van Merriënboer	2005	11	12	0.09	problem solving	adults	journal < 1.5
O'Brien & Shapiro	1977	15	15	-0.15	math/numbers	adults	journal < 1.5
Paas	1992	13	15	-2.25	math/numbers	adolescents	journal ≥ 1.5
Paas & Van Merriënboer	1994	30	30	-0.77	problem solving	adults	journal ≥ 1.5
Pany & Jenkins	1978	6	6	-1.93	verbal/social	children	journal < 1.5
Peters	1970	30	30	0.25	math/numbers	children	journal < 1.5
Pillay E1	1994	10	20	-1.09	problem solving	adolescents	journal < 1.5
Pillay E2	1994	10	20	-0.78	problem solving	adolescents	journal < 1.5
Pine, Messer, & Godfrey	1999	14	14	-0.74	science	children	journal < 1.5

Author(s)	Year	Discovery n	Comparison n	Cohen’s d	Domain	Age	Journal rank
Quilici & Mayer E1	1996	27	54	0.92	math/numbers	adults	journal ≥ 1.5
Quilici & Mayer E2	1996	18	18	-1.69	math/numbers	adults	journal ≥ 1.5
Radziszewska & Rogoff	1991	20	20	-1.25	problem solving	children	journal ≥ 1.5
Rappolt-Schlichtmann, Tenenbaum…	2007	27	37	-0.61	science	children	journal < 1.5
Reinking & Rickman	1990	45	15	-1.09	verbal/social	children	journal < 1.5
Rieber & Parmley	1995	25	27.5	-0.65	science	adults	journal < 1.5
Rittle-Johnson	2006	21	21.5	-0.23	math/numbers	children	journal ≥ 1.5
Salmon, Yao, Berntsen, & Pipe	2007	16	16	-1.66	verbal/social	children	journal < 1.5
Scandura E2	1964	23	23	0.00	math/numbers	children	journal < 1.5
Shore & Durso	1990	60	60	-0.14	verbal/social	adults	journal ≥ 1.5
Shute, Glaser, & Raghavan	1989	10	10	0.42	math/numbers	adults	bookchapter
Siegel & Corsini	1969	12	12	-0.90	problem solving	children	journal ≥ 1.5
Singer & Gaines	1975	19	18	-0.27	physical/motor	adults	journal < 1.5
Stark, Gruber, Renkl, & Mandl	1998	15	15	-0.54	math/numbers	adults	journal < 1.5
Strand-Cary & Klahr	2008	29	32	-0.85	science	children	journal < 1.5
Sutherland, Pipe, Schick, Murray…	2003	12	11.5	-0.10	verbal/social	children	journal < 1.5
Swaak, deJong, & van Joolingen	2004	67	55	-0.56	science	adolescents	journal < 1.5
Swaak, van Joolingen, & de Jong	1998	21	21	-0.44	science	adults	journal < 1.5
Sweller, Chandler, Tierney, & Cooper E1	1990	16	16	0.20	math/numbers	adolescents	journal ≥ 1.5
Sweller, Chandler, Tierney, & Cooper E3	1990	12	12	-1.78	math/numbers	adolescents	journal ≥ 1.5
Tarmizi & Sweller E3	1988	10	10	0.20	math/numbers	adolescents	journal ≥ 1.5
Tarmizi & Sweller E4	1988	10	10	0.28	math/numbers	adolescents	journal ≥ 1.5
Tarmizi & Sweller E5	1988	10	10	-0.71	math/numbers	adolescents	journal ≥ 1.5

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen's *d*	Domain	Age	Journal rank
Trafton & Reiser	1993	20	20	0.39	computer skills	adults	journal < 1.5
Tunteler & Resing	2002	18	18	-2.19	problem solving	children	journal < 1.5
van der Meij & Lazonder	1993	13	12	1.03	computer skills	adults	journal < 1.5
van hout Wolters	1990	24	24	-0.54	science	adolescents	book chapter
Veenman, Elshout, & Busato	1994	15	14	-0.49	science	adults	journal < 1.5
Ward & Sweller E1	1990	21	21	-1.07	science	adolescents	journal < 1.5
Ward & Sweller E2	1990	16	16	-1.52	science	adolescents	journal < 1.5
Ward & Sweller E3	1990	17	17	0.25	science	adolescents	journal < 1.5
Ward & Sweller E4	1990	15	15	-0.42	science	adolescents	journal < 1.5
Ward & Sweller E5	1990	15.5	15.5	-0.47	science	adolescents	journal < 1.5
Wittrock	1963	67	75	-0.84	verbal/social	adults	journal ≥ 1.5
Worthen	1968	216	216	0.08	math/numbers	children	journal < 1.5
Zacharia & Anderson	2003	13	13	4.62	science	adults	journal < 1.5

Effect Sizes by Domain for Unassisted Discovery

Domain	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Math/numbers	-.16	[-.30, -.03]	-2.38*	129	6,639	
Computer skills	.07	[-.11, .23]	0.75	72	3,627	
Science	-.39	[-.53, -.24]	-5.27**	117	4,399	
Problem solving	-.48	[-.60, -.36]	-7.73**	154	5,637	
Physical/motor skills	-.01	[-.39, .38]	-0.02	15	520	
Verbal/social skills	-.95	[-1.11, -.79]	-11.66**	87	5,164	
Between-classes effect				5	25,986	91.75**

*$p < .05$, **$p < .01$

Post-hoc comparisons (*Q)*

Domain	Math/numbers	Computer skills	Science	Problem solving	Physical/motor skills
Math/numbers					
Computer skills	4.72				
Science	6.09	16.64***			
Problem solving	13.65***	28.29***	0.88		
Physical/motor skills	0.63	0.11	3.67	5.95	
Verbal/social skills	50.03***	58.17***	22.65***	18.35***	14.87***

***$p < .003$ (adjusted for post-hoc comparisons)

Table 6

Effect Sizes by Age for Unassisted Discovery

Age	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Children	-.44	[-.56, -.32]	-7.11**	163	8,784	
Adolescents	-.53	[-.66, -.40]	-8.01**	148	5,556	
Adults	-.26	[-.35, -.16]	-5.28**	266	11,646	
Between-classes effect				2	25,986	12.29*

**p* < .05, ***p* < .01

Post-hoc comparisons (*Q*)

Age	Children	Adolescents
Children		
Adolescents	1.51	
Adults	5.00	10.41***

****p* < .017 (adjusted)

Table 7

Effect Sizes by Dependent Measure for Unassisted Discovery

Dependent measure	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Post-test scores	-.35	[-.42, -.28]	-9.30**	430	20,070	
Acquisition scores	-.95	[-1.16, -.74]	-8.93**	54	2,059	
Reaction times	-.21	[-.39, -.02]	-2.20*	69	2,632	
Self-ratings	.07	[-.39, .54]	0.31	9	668	
Peer ratings	-.32	[-1.12, .49]	-0.77	2	306	
Mental effort/load	-.16	[-.64, .32]	-0.66	10	251	
Between-classes effect				5	25,986	37.38**

**p* < .05, ***p* < .001

Post-hoc comparisons (*Q*)

Dependent measure	Post-test scores	Acquisition scores	Reaction times	Self-ratings	Peer ratings
Post-test scores					
Acquisition scores	28.14***				
Reaction times	1.98	23.84***			
Self-ratings	3.30	15.89***	1.28		
Peer ratings	0.01	1.88	0.06	2.70	
Mental effort/load	0.60	7.82	0.04	1.99	0.14

****p* < .003 (adjusted)

Table 8

Effect Sizes by Type of Unassisted Discovery

Type of Discovery	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Unassisted	-.41	[-.48, -.34]	-11.15**	476	21,832	
Invention	-.34	[-.60, -.08]	-2.52*	38	1,191	
Matched probes	.19	[-.26, .64]	0.84	13	303	
Simulation	-.13	[-.42, .15]	-0.92	29	1,652	
Work with a naïve peer	-.47	[-.81, -.13]	-2.72**	19	1,008	
Between-classes effect				4	25,986	10.02*

*$p < .05$, **$p < .01$

Post-hoc comparisons (*Q*)

Type of Discovery	Unassisted	Invention	Matched probes	Simulation
Unassisted				
Invention	0.23			
Matched probes	6.57	7.06		
Simulation	3.35	0.95	1.56	
Work with a naïve peer	0.13	0.35	4.37	2.23

***$p < .005$ (adjusted)

Table 9

Effect Sizes by Comparison Condition for Unassisted Discovery

Comparison condition	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Direct teaching	-.29	[-.38, -.20]	-6.10**	272	14,145	
Feedback	-.46	[-.64, -.29]	-5.11**	74	2,578	
Worked examples	-.63	[-.76, -.50]	-9.70**	150	5,319	
No exposure / pre + post	.21	[-.14, .56]	1.18	17	881	
Explanations provided	-.28	[-.47, -.08]	-2.77*	59	2,927	
Other	.02	[-.84, .87]	0.04	2	136	
Between-classes effect				5	25,986	32.31**

**p* < .05, ***p* < .001

Post-hoc comparisons (*Q*)

Comparison condition	Direct teaching	Feedback	Worked examples	No exposure / pre + post	Explanations provided
Direct teaching					
Feedback	3.27				
Worked examples	18.98***	1.57			
No exposure / pre+post	8.70	9.15***	13.70***		
Explanations provided	0.01	1.80	6.99	5.00	
Other	0.62	1.05	1.56	0.13	0.44

****p* < .003 (adjusted)

Table 10

Studies Included in the Enhanced Discovery Meta-analysis

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen’s *d*	Domain	Age	Journal rank
Amsterlaw & Wellman	2006	12	12	1.11	verbal/social skills	children	journal < 1.5
Anastasiow, Sibley, Leonhardt, & Borich	1970	6	6	-0.08	math/numbers	children	journal < 1.5
Andrews	1984	25	28	1.27	science	adults	journal < 1.5
Bielaczyc, Pirolli, & Brown	1995	11	13	0.95	computer skills	adults	journal < 1.5
Bluhm	1979	20	17	1.44	science	adults	journal < 1.5
Bowyer & Linn	1978	312	219	0.20	science	children	journal < 1.5
Butler, Pine, & Messer	2006	32	31	-0.02	math/numbers	children	unpub/diss
Chen & Klahr	1999	30	30	-0.07	science	children	journal ≥ 1.5
Chi, de Leeuw, Chiu, & LaVancher	1994	14	10	0.94	science	adolescents	journal ≥ 1.5
Coleman, Brown, & Rivkin	1997	14	14	0.61	science	adults	journal < 1.5
Crowley & Siegler	1999	57	57	-0.25	problem solving	children	journal ≥ 1.5
Debowski, Wood, & Bandura	2001	24	24	1.07	computer skills	adults	journal ≥ 1.5
Denson	1986	45	34	0.10	science	adults	unpub/diss
Foos, Mora, & Tkacz E1	1994	78	90	0.53	science	adults	journal ≥ 1.5

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen's *d*	Domain	Age	Journal rank
Foos, Mora, & Tkacz E2	1994	25	25	0.71	science	adults	journal ≥ 1.5
Gagne & Brown	1961	11	11	1.41	math/numbers	adolescents	journal ≥ 1.5
Ginns, Chandler, & Sweller E1	2003	10	10	-0.67	computer skills	adults	journal < 1.5
Ginns, Chandler, & Sweller E2	2003	13	13	0.67	math/numbers	adolescents	journal < 1.5
Grandgenett & Thompson	1991	72	71	0.05	computer skills	adults	journal < 1.5
Greenockle & Lee	1991	20	20	0.48	physical/motor skills	adults	journal < 1.5
Hiebert & Wearne	1993	24	21.25	0.70	math/numbers	children	journal < 1.5
Hirsch	1977	61	76	0.56	math/numbers	adolescents	journal < 1.5
Howe, McWilliam, & Cross E1	2005	31	30	0.15	science	children	journal < 1.5
Howe, McWilliam, & Cross E2	2005	35	36	0.15	science	children	journal < 1.5
Howe, McWilliam, & Cross E3	2005	35.5	36	0.34	science	children	journal < 1.5
Jackson, Fletcher, & Messer	1992	12	24	0.01	math/numbers	children	journal < 1.5
Kasten & Liben	2007	34	99	0.42	problem solving	children	journal ≥ 1.5
Kersh	1958	16	16	0.12	math/numbers	adults	journal ≥ 1.5
Kersh: Article 2	1962	10	10	-0.10	math/numbers	adolescents	journal ≥ 1.5

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen's *d*	Domain	Age	Journal rank
Kuhn, Black, Keselman, & Kaplan	2000	21	21	0.29	science	adolescents	journal < 1.5
Lamborn, Fischer, & Pipp	1994	113	113	1.06	verbal/social skills	adolescents	journal ≥ 1.5
Murphy & Messer	2000	41	40.5	0.46	science	children	journal < 1.5
Mwangi & Sweller E3	1998	12	12	-0.04	math/numbers	children	journal < 1.5
Ohrn, van Oostrom, & van Meurs	1997	11	12	0.99	science	adults	journal ≥ 1.5
Olander & Robertson	1973	190	184	-0.02	math/numbers	children	journal < 1.5
Peters	1970	30	30	-0.09	math/numbers	children	journal < 1.5
Pillow, Mash, Aloian, & Hill	2002	15	15	0.44	verbal/social skills	children	journal < 1.5
Pine & Messer	2000	40	44	0.55	science	children	journal < 1.5
Pine, Messer, & Godfrey	1999	14	14	-0.35	science	children	journal < 1.5
Ray	1961	45	45	0.44	math/numbers	adolescents	journal < 1.5
Reid, Zhang, & Chen	2003	20	18	0.16	science	adolescents	journal < 1.5
Rittle-Johnson	2006	22	21	0.19	math/numbers	children	journal ≥ 1.5
Rittle-Johnson, Saylor, & Swygert	2007	36	18	0.81	problem solving	children	journal < 1.5
Scandura E1	1964	23	23	0.00	math/numbers	children	journal < 1.5

Author(s)	Year	Discovery *n*	Comparison *n*	Cohen’s *d*	Domain	Age	Journal rank
Singer & Pease	1978	16	16	2.62	physical/motor skills	adults	journal < 1.5
Stark, Mandl, Gruber, & Renkl	2002	27	27	0.94	math/numbers	adults	journal < 1.5
Stull & Mayer E1	2006	51	52.5	-0.60	science	adults	unpub/diss
Stull & Mayer E2	2006	38	39	-1.14	science	adults	unpub/diss
Stull & Mayer E3	2006	33	32.5	-1.10	science	adults	unpub/diss
Tarmizi & Sweller E2	1988	12	12	-0.08	math/numbers	adolescents	journal ≥ 1.5
Tenenbaum, Alfieri, Brooks, & Dunne	2008	32	30.5	0.20	verbal/social skills	children	journal < 1.5
Tuovinen & Sweller	1999	16	16	-0.67	computer skills	adults	journal ≥ 1.5
Vichitvejpaisal et al.	2001	40	40	-0.28	science	adults	journal ≥ 1.5
Zhang, Chen, Sun, & Reid E1	2004	13	13.67	-0.16	computer skills	adolescents	journal < 1.5
Zhang, Chen, Sun, & Reid E2	2004	14	16	0.36	computer skills	adolescents	journal < 1.5
Zimmerman & Sassenrath	1978	119.67	119.67	0.51	math/numbers	children	journal < 1.5

Table 11

Effect Sizes by Domain for Enhanced Discovery

Domain	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Math/numbers	.29	[.18, .40]	5.24**	116	9,100	
Computer skills	.64	[.44, .84]	6.26**	36	1,379	
Science	.11	[.02, .20]	2.30*	152	12,164	
Problem solving	.20	[-.08, .47]	1.40	14	1,723	
Physical/motor skills	1.05	[.80, 1.30]	8.25**	23	896	
Verbal/social skills	.58	[.26, .90]	3.51**	13	663	
Between-classes effect				5	25,925	65.53**

**p* < .05, ***p* < .001

Post-hoc comparisons (*Q*)

Domain	Math/ numbers	Computer skills	Science	Problem solving	Physical/motor skills
Math/numbers					
Computer skills	12.14***				
Science	6.69	18.65***			
Problem solving	0.84	5.55	0.31		
Physical/motor skills	34.59***	4.96	41.67***	15.73***	
Verbal/social skills	3.59	0.04	6.67	3.51	3.48

****p* < .003 (adjusted)

Table 12

Effect Sizes by Age for Enhanced Discovery

Age	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Children	.24	[.14, .33]	4.94**	157	16,556	
Adolescents	.19	[.04, .33]	2.50*	71	3,420	
Adults	.44	[.33, .55]	7.97**	129	5,949	
Between-classes effect				2	25,925	10.68*

**p* < .05, ***p* < .001

Post-hoc comparisons (*Q*)

Age	Children	Adolescents
Children		
Adolescents	0.02	
Adults	7.64***	5.37

****p* < .017 (adjusted)

Table 13

Effect Sizes by Dependent Measure for Enhanced Discovery

Dependent measure	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Post-test scores	.28	[.22, .33]	8.38**	303	22,636	
Acquisition scores	.54	[.35, .74]	5.50**	34	2,205	
Reaction times	-.72	[-1.07, -.37]	-4.04**	11	668	
Self-ratings	1.25	[.84, 1.65]	6.02**	7	384	
Mental effort/load	-1.01	[-2.22, .19]	-1.65	0	32	
Between-classes effect				4	25,925	64.60**

***p* < .001

Post-hoc comparisons (*Q*)

Dependent measure	Post-test scores	Acquisition scores	Reaction times	Self-ratings
Post-test scores				
Acquisition scores	6.73			
Reaction times	31.61***	10.19***		
Self-ratings	29.68***	6.66	5.18	
Mental effort/load	5.94	4.68	0.03	21.33***

****p* < .005 (adjusted)

Table 14

Effect Sizes by Type of Enhanced Discovery

Discovery	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Generation	-.15	[-.28, -.02]	-2.32*	87	3,905	
Elicited explanation	.36	[.26, .47]	6.93**	128	7,037	
Guided discovery	.50	[.40, .59]	9.96**	142	14,983	
Between-classes effect				2	25,925	65.00**

**p* < .05, ***p* < .001

Post-hoc comparisons (*Q*)

Discovery	Generation	Elicited explanation
Generation		
Elicited explanation	33.20***	
Guided discovery	57.43***	3.86

****p* < .017 (adjusted)

Table 15

Effect Sizes by Comparison Condition for Enhanced Discovery

Comparison condition	Cohen's *d*	95% CI	*Z*	*k*	*N*	*Q*
Direct teaching	.26	[.15, .37]	4.74**	123	13,668	
Worked examples	.06	[-.21, .32]	0.41	22	634	
Unassisted / pre + post	.33	[.25, .42]	7.48**	190	10,280	
Explanations provided	.33	[.06, .60]	2.39*	19	1,238	
Other	1.30	[.40, 2.20]	2.82*	1	105	
Between-classes effect				4	25,925	9.12

**p* < .05, ***p* < .001

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References marked with an asterisk indicate studies included in the meta-analysis.

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