Section 6

Current conjectures from educational neuroscience

Chapter 16

Bridging between brain science and educational practice with design patterns

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Overview

The current 'neuroscience and education' dialogue seems to centre largely on the question of how (or whether) neuroscience research can inform mainstream educational practice. Building on Dewey's (1929) analysis of educational science in *The Sources of a Science of Education*, we reframe the question to ask: 'How can research in the special sciences (such as neuroscience) and insights from educational practice both inform a science of education?' We point to *explanatory mental models* as the point of overlap between teacher perception, informal expertise, scientific theory and teacher action, and argue that these mental models in the heads of educators are both the site of educational science proper and a leverage point for driving more desirable educational outcomes in a scalable manner. Through our analysis we identify six 'gaps' that must be bridged to catalyse a sustainable science of education. Three of these gaps represent obstacles to collaboration between scientists and educators, and the other three gaps inhibit educators' widespread adoption, application and validation of scientific theories. We propose that design patterns, thoughtfully crafted, can help bridge all six gaps. A design pattern is a description of a recurring problem (such as how to assess specific competencies reliably) plus a description of a general solution that can be applied flexibly to many instances of the problem across diverse contexts. Design patterns have had a tremendous impact on applied domains such as architecture and software engineering. We believe they can play a similarly important role in developing a sustainable interdisciplinary science of education.

16.1 Bridging between brain science and educational practice with design patterns

Psychologists, politicians and educationists have pursued the prospect of a true science of education for over a century. Neuroscientists have joined the conversation in recent decades, giving rise to a movement rooted in efforts to address educational problems using models and methods from the brain sciences. A sizeable and growing literature associated with that movement focuses specifically on the relationship (or lack thereof) between neuroscience and education (Ansari & Coch, 2006; Bruer, 1997, 2002; Byrnes & Fox, 1998; Gabrieli, 2009; Geake & Cooper, 2003; Goswami, 2004; Hall, 2005; Katzir & Pare-Blagoev, 2006; Mayer, 1998; Schunk, 1998; Stanovich, 1998; Willingham, 2008). It appears that in the post-industrial West, questions about the prospects of a science of education are slowly being transformed into questions about how to arrange ways for cognitive science, brain science and genetics to inform—or even to determine—what happens in schools. In the context of these shifting questions and debates about the role of scientific research in educational practice, we offer an analysis and a set of recommendations. We first look back to Dewey to situate the issue of 'neuroscience in education' within the larger context of 'neuroscience, educational practice and educational science', and then we look forward toward a science of education built around a library of design patterns that integrate systematic, interdisciplinary scientific research into flexible and effective educational solutions that educators can readily apply in practice.

In the first section to follow we summarize and elaborate on some of Dewey's central arguments concerning the nature of educational science. Dewey (1929) argues that a science of education must draw on *general descriptions*, such as general scientific models of learning and motivation, to inform *particular prescriptions*, such as specific techniques for helping Johnny manage his math anxiety and ADHD well enough in an overcrowded and noisy classroom that he can come to understand the Pythagorean theorem and its importance. This should be accomplished, suggests Dewey, in a manner that supports the efficient development and effective application of the educator's expert judgement instead of seeking to override that judgement. We should not, in particular, expect neuroscience or any other type of scientific research to provide either a 'stamp of approval' for specific educational practices or detailed 'recipes' for achieving particular educational objectives.

Dewey's (1929) incisive and perspicacious analysis of what educational science should be provides a fresh and relevant perspective on the current conversation about neuroscience and education. In particular, he distinguishes between educational science on the one hand and the *sources* of educational science on the other hand. He classifies the specific sciences (e.g. neuroscience, psychology) as well as educational practice as sources of educational science. This distinction may perhaps seem subtle, but it shifts the terms of the dialogue quite radically. Whereas much of the conversation to date has focused on questions along the lines of 'what is the role of neuroscience *research* in educational *practice*?', Dewey suggests we should instead be asking 'what are the roles of *neuroscience research* and *educational practice* in *educational science*?'. Dewey's educational science resides in the considered judgement of the educator, who draws on the results of relevant sources of scientific research in conjunction with the collective experience of reflective educational practitioners. His analysis thus illuminates a novel way to understand how the dialogue between neuroscientists and educational practitioners can be mediated to move both forward productively.

Dewey's treatment leaves off, however, at quite a conceptual, theoretical and strategic level. He does not, in particular, discuss how his insights can be made useable to practising scientists and educators, either individually or in collaboration. In sections 16.2 ~~and 16.3,~~ therefore, we seek to pick up where Dewey left off, using his analysis as the basis for motivating and describing a very practical framework that we believe can facilitate a robust two-way dialogue between research scientists (including neuroscientists) and educational practitioners. Specifically, we suggest that *design patterns* can catalyse the kind of interdisciplinary dialogue envisioned by Dewey, providing a practical framework supporting the synthesis of insights from basic neuroscience research and educational practice, and fostering the kind of systematic accumulation of valid, useable, public knowledge that is associated with mutually supportive scientific and technological progress in other domains such as medicine, agriculture and engineering.

A design pattern describes a recurring problem in a domain and the core of a solution to that problem in a way that allows the solution to be applied flexibly to a wide range of situations in which the problem occurs. In education, for example, design patterns might address recurring problems such as how to design educational materials that are accessible to all learners, how to build formative assessments of student understanding, or how to engage and motivate students in certain key learning processes. In fields where design patterns are used, the stakeholders agree upon a template, which codifies the basic form of the useable knowledge they collaborate to produce. This is a unique way of representing both what is known scientifically and what has been done in practice; it allows for the cumulative and collaborative construction of useable knowledge at the interface of specific sciences and context sensitive problem-focused domains of application. We introduce a design pattern template that we think could help bring Dewey's ideas about educational science into current practice.

Finally, we illustrate how design patterns can be used to bridge between neuroscience and educational practice. We use one element of the *Universal Design for Learning* framework (Rose & Meyer, 2002) to construct an example of a neuroscience-informed design pattern for addressing the ubiquitous educational problem of accommodating individual learning differences and disabilities. This example is offered as a way of making clear just what design patterns are and how they can be useful in furthering the science of education.

16.2 **The virtuous cycle of educational science**

Dewey (1929) defines educational science in terms of two central elements: *explanatory models*[1] that educators use to guide their practice and *systematic methods of inquiry* that they use to improve those models. One can glean from Dewey's writings a vision of educational science as a kind of progressive, self-correcting system constructed around these two central elements that provides educators with immediately useable knowledge while also driving a virtuous cycle in which the cumulative store of educational expertise is systematically expanded and progressively refined over time.

Building on Dewey's philosophical analysis in an effort to make his ideas more practically accessible, we find it useful to identify explanatory models as the central organizing structures in educational science. These structures can be seen as the point of overlap between two distinct processes or loops (see Figure 16.1). The *application loop* corresponds to educational practice, in which educators apply explanatory models to make sense of their observations about students and to make informed decisions about what educative actions to take next. The *adaptation loop* corresponds to scientific inquiry, wherein the stock of explanatory models is adapted (that is, expanded and refined) through an ongoing systematic process of problem identification, solution generation and solution validation. Note that the adaptation loop involves a dialogue between educators and scientists in the specific sciences, such as neuroscience. In this dialogue, educators are responsible for identifying worthwhile problems and testing the validity of proposed solutions. Neuroscientists and other scientists outside of education, in contrast, are responsible for generating explanatory models of phenomena associated with the patterns and problems identified by educators.

[1] Dewey ~~(1929)~~ actually calls them 'explanatory laws', but we prefer the term 'explanatory models' because it seems to have less of a normative connotation, especially given the association with fundamentally normative civil and criminal laws.

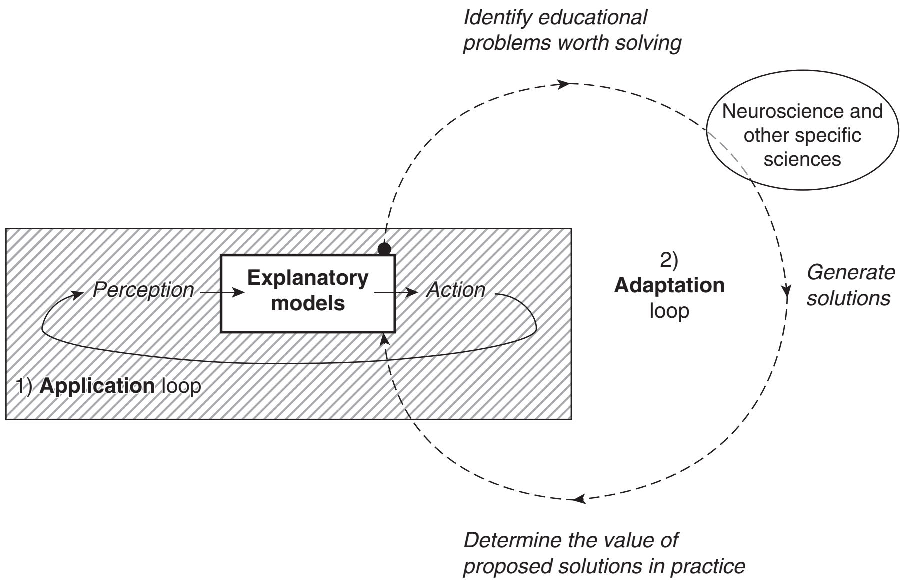

Fig. 16.1 Educational science as a system of two feedback loops (application and adaptation) organized around explanatory models. The *application loop* (1) corresponds to the process of applying the explanatory models in educational practice, and the *adaptation loop* (2) corresponds to the process of expanding and refining the stock of practically useful explanatory models through systematic scientific inquiry.

The system of educational science depicted in Figure 16.1 draws heavily on Dewey's (1929) philosophical analysis. The motivation for this proposal derives, in part, from analogies to other domains such as engineering and medicine, where this kind of progressive system linking theory and application has to date been realized more fully and successfully than in education. Our proposal, simply put, is that the kind of progressive, self-correcting science of education envisioned by Dewey is feasible, and that closing the application and adaptation loops depicted in Figure 16.1 is certainly necessary—and may be sufficient—to establish it.

Closing the adaptation loop means facilitating the dialogue between educators, neuroscientists and others that could generate relevant scientific explanatory models and integrate them into effective educational solutions. Closing the application loop means supporting teachers in integrating these solutions (and the explanatory models embedded within them) into their regular practice. But the work of educational practitioners and research scientists differs in a number of fundamental ways. These differences can be thought of as 'gaps' that make it challenging to close the two loops. In the following sections, we identify key gaps that need to be bridged to close the loops, and then we argue that design patterns—when organized specifically to address these gaps—can be used to bridge virtually all of them.

16.3 **Obstacles to establishing a sustainable science of education**

The adaptation and application loops depicted in Figure 16.1 represent the two fundamental processes involving explanatory models—that is, systematically changing (generating and refining) the models over time, and systematically applying them to guide educational practice, respectively. In this section, we elaborate the idealized system of Figure 16.1 to identify some of the practical obstacles that must be overcome to close these loops.

Adaptation loop: systematically generating and refining explanatory models

The adaptation loop involves a complex collaborative dialogue between educators and researchers in the specific sciences, such as neuroscience, cognitive psychology and economics. These researchers operate outside of education, but nonetheless have insights that can help educators solve practical problems and achieve educational objectives.

An educational practitioner's role in closing the adaptation loop differs from that of neuroscientists and other special scientists (see Chapter 3, this volume). Specifically, educators, in the course of their classroom practice, should simultaneously be carrying out two functions of systematic inquiry, namely:

1. Problem identification: systematically identifying recurring practical problems worthy of solution.
2. Solution validation: systematically testing the value of proposed solutions in improving practice.

Researchers in the special sciences, in contrast, are responsible for systematically generating *explanatory models* of phenomena relevant to the educational problems identified by educational practitioners.

For example, imagine a language arts teacher who notices that over the years a few students seem to have persistent and profound difficulties with reading compared to their age mates. This individual teacher might learn to recognize the signs of this language difficulty and develop ad hoc strategies for responding to it—by coordinating one-on-one tutoring services for such students, or arranging for them to participate in a less advanced reading group, perhaps in a lower grade. Having taken such 'common sense' actions in response to these particular students' needs, the teacher might consider her responsibility fulfilled to the best of her ability and available resources. This is an example of educational practice that does *not* meet the criteria of educational science, which specifically entails applying explanatory models in practice and employing systematic methods of inquiry.

The teaching scenario described falls short of educational science in the first respect because the educator lacks any explanatory model she can use to reason about the observed pattern of struggling readers—that is, her response does not derive from an understanding of *why* the children might be having extra difficulties. Often, such explanatory models can be found outside of education proper. For example, neuroscientists and cognitive psychologists have developed models of memory (Anderson, 1983; Atkinson & Shiffrin, 1968; Baddeley, 1976; Eichenbaum, 1997; Eichenbaum, Otto & Cohen, 1994; Miller, 1956), attention (Pashler, 1997; Posner & Peterson, 1990) and visual processing (Frost & Katz, 1992; Seidenberg, 1995; Seidenberg & McClelland, 1989) that might be relevant to the pattern the teacher observes. Poor reading has been associated with disorders in a wide range of cognitive and neural systems, including impaired working memory that inhibits a student's ability to hold the words online long enough to extract their meaning, attentional problems, and problems recognizing or decoding the written language symbols (Grigorenko, 2001; Paloyelis, Rijsdijk, Wood, Asherson & Kuntsi, 2010; Rose & Meyer, 2002). Each explanatory model would lead the educator to seek additional data further afield than she might otherwise consider relevant—such as in the student's performance in math or science classes, or related to the student's comprehension of stories during 'circle time' where the teacher does the reading compared to comprehension during independent reading time. Applying such explanatory models would thus lead the educator to *perceive* the situation in a more systematic, comprehensive and generally intelligent way, and would guide her to *respond* or *act* in a more nuanced, individualized and generally more effective manner than the general 'common sense' response that might otherwise be applied across the board. This example illustrates how explanatory models provide 'a light to the eyes and a lamp to the feet' (Dewey, 1929), simultaneously engaging and supporting processes of careful observation, systematic reasoning and thoughtful judgement on the part of the educator as opposed to triggering rigid educational scripts or 'recipes'.

The teacher in this hypothetical scenario also fails to fulfil the second criterion of educational science, which requires her to employ systematic methods of inquiry. Having identified a recurring problem in the classroom—in this case a small subset of students who exhibit unusual difficulties with reading, as an educational scientist she would endeavour to isolate or even formalize this as a problem requiring solution, and then seek solutions, and then test the validity of those solutions in practice. Solutions to such problems may already exist, or explanatory models may exist elsewhere that can be integrated into useable educational solutions, or basic research may need to be initiated in other domains to generate explanatory models of the phenomenon of interest. Regardless of the current state of scientific understanding, the practicing educator is in the best position to identify important problems of practice and to test the value of available or proposed solutions (Dewey, 1929).

This example surfaces some of the practical obstacles to closing the adaptation loop of educational science, especially given that educators need explanatory models, most of which will come from scientific domains outside of educational practice (see Figure 16.2). In particular, in addition to the physical separation between groups of people (especially educators and scientists), there are also fundamental differences in the nature of each group's work. We highlight three

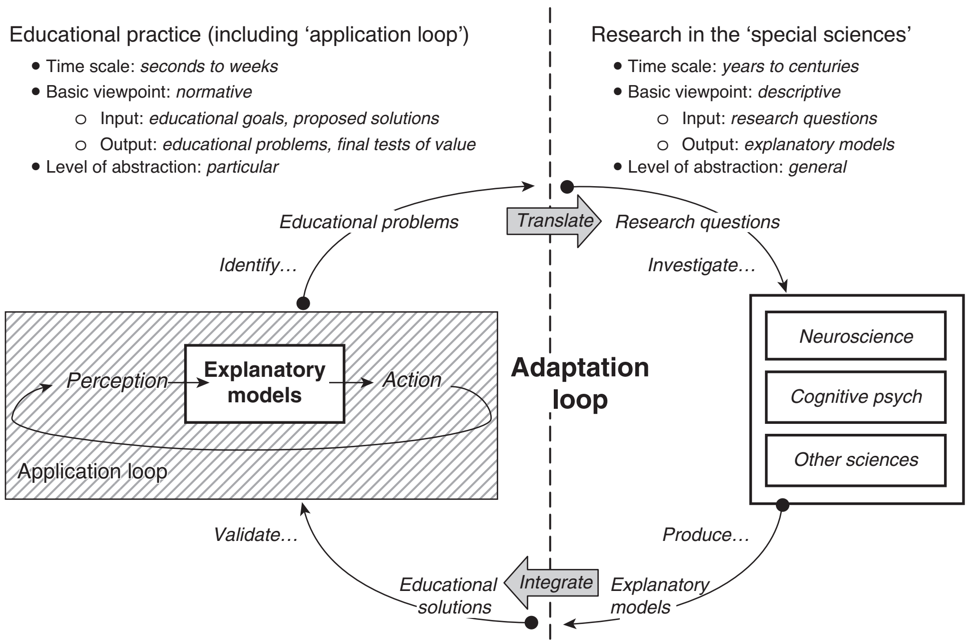

Fig. 16.2 Closing the 'adaptation loop'. With respect to the adaptation loop of educational science, classroom practice is a source of educational *problems* worth solving, and of the final *test of value* of proposed solutions. The special sciences are sources of *explanatory models* that can inform practice when integrated into comprehensive solutions, strategies and techniques. To close the adaptation loop of educational science, it is necessary to bridge across the distinct *time scales*, *basic viewpoints* and *levels of abstraction* that distinguish educational practice from research in the special sciences.

dimensions along which domain differences create practical obstacles to productive dialogue and collaboration:

- Time scales: scientific research follows its own course, typically over *years*, *decades* or even *centuries*, whereas educators need immediate solutions to guide their practice from *moment-to-moment*, *day-to-day* and *week-to-week.*
- Levels of abstraction: scientific explanatory models are by definition general in scope (tying together and explaining many particular data points) and therefore tend to be relatively *abstract* and *context-free*, whereas classroom practice typically requires educators to respond to very *particular* and *context-specific* situations.
- Basic viewpoints: scientific research is a fundamentally *descriptive* enterprise, whereas education is fundamentally *normative*—that is, goal-oriented, value-laden and ethically and morally charged (see Stein, Connell & Gardner, 2008 for a discussion of basic viewpoints in the context of interdisciplinary educational research and practice).

We must bridge the gaps along these three dimensions (time scales, levels of abstraction and basic viewpoints) in order to close the adaptation loop and catalyse a self-sustaining science of education in which important educational problems are identified, systematic scientific research produces robust explanatory models that can be incorporated into useable educational strategies and solutions, and the value of those strategies and solutions is evaluated through application in actual practice so that the solutions (and the explanatory models embedded within them) can be further refined. Before discussing a constructive proposal for bridging the gaps we have identified, we first discuss another set of challenges related to educators' application of explanatory models—namely, how explanatory models become integrated into educators' repertoire of practical strategies and tactics to influence actual practice.

Application loop: how explanatory models influence educational practice

On the surface, the application loop of educational science corresponds to educational practice as people generally conceive it (that is, teachers educating students). In terms of educational science, we define the application loop more specifically as an iterative process in which educators observe students (gauging student motivation and understanding from one moment to the next, for example) and act responsively in light of their own understanding (or 'mental model') of the situation as they perceive it (Figure 16.3). In general, we assume that teachers act in ways that they believe will help students achieve specific educational goals. Teacher actions change the classroom situation, which leads to new observations, which in turn drive decisions about new actions, and so on. As already suggested, this iterative process—and in particular the educator's decision-making about what actions to take—occurs against a normative backdrop that includes educational goals, moral and ethical concerns, cultural values, social norms and the like.

Although educational practice always involves some kind of mental model linking perception to action, not all such mental models are *explanatory* models. The application loop of educational science (as defined in this essay and following Dewey, 1929) depends specifically upon *explanatory* mental models.

What are mental models?

Mental models are representations in people's minds of some part of the world 'out there'. More specifically, mental models function as simplified simulations of some small aspect of reality, thereby supporting understanding, reasoning and decision-making (Craik, 1943; Johnson-Laird, 1983).

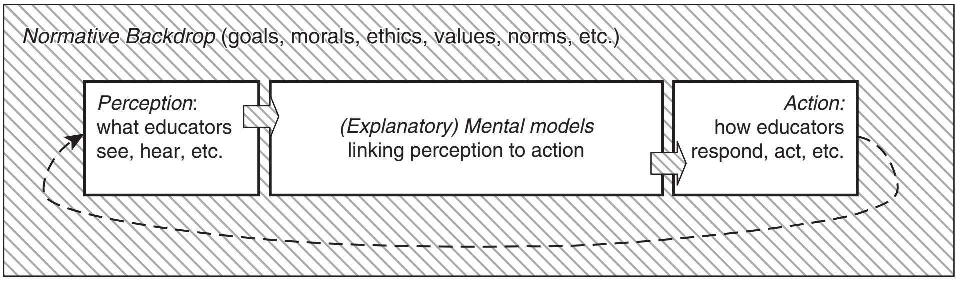

Fig. 16.3 The 'application loop' of educational science is an iterative process in which educators respond to what they *perceive* in the classroom, in light of the *mental models* they use to make sense of their perceptions and decide which *actions* will be most effective given the *normative backdrop* of educational goals, moral and ethical concerns, cultural values, social norms, etc. Although educational practice always involves some kind of mental model linking perception to action, not all such mental models are *explanatory models*. The application loop of educational science depends specifically upon *explanatory* mental models.

Educators, in particular, use these mental models to make sense of their observations about student behaviour and performance, to predict what will happen in response to possible actions they might take, and therefore to decide what educative actions are appropriate in a particular situation in light of their immediate and long-term educational objectives.

For example, imagine a language arts teacher has just assigned an essay for a group of students to read. He then hands out a comprehension test. One student answers all of the questions correctly, another answers half correctly, a third produces all incorrect answers and a fourth doodles on the worksheet without writing any answers at all.

Different teachers placed in this situation would behave differently. One teacher might infer that the student who produced all correct answers has mastered the strategies for reading comprehension covered in class and that the other three students have not. Based on that interpretation of the situation, one teacher might decide to have the first student work independently while he repeats the prior instruction more slowly and in greater detail with the other three. Another teacher making the same interpretation might decide on a different strategy, having the first student explain the strategies to the other three. A third teacher might draw the same conclusion about the first student, but infer that the other three students have distinct challenges with reading comprehension that need to be diagnosed and remediated individually, and proceed accordingly. A fourth teacher might interpret the doodling behaviour not as a problem primarily of understanding but as a problem with lack of engagement or motivation, and respond very differently to address that student's need. And so on.

The point is that even though the objective classroom situation is identical in all the cases just described, there are myriad ways teachers might *interpret* this situation, and for each interpretation, there are myriad ways teachers might *respond* to it. These manifest differences in teacher behaviour can be explained by differences in their underlying mental models, which determine how they make sense of the students' behaviour and decide what actions to take next. As Dewey (1929) observes '. . . the final reality of educational science is not found in books, nor in experimental laboratories, nor in the classrooms where it is taught, but in the minds of those engaged in directing educational activities' (p. 32).

We argue that the form educational science takes in the minds of educators can be productively conceived in terms of mental models—and more specifically, *explanatory* mental models. Moreover, we submit that such explanatory mental models are a natural point of convergence where teacher perception, teacher action, informal teacher expertise and formal scientific theory come together, which makes them a potentially powerful leverage point for driving improved educational outcomes in a scalable manner—if we can figure out how to close the application loop of educational science by bridging between explanatory models as they are represented in the textbooks, literature, laboratories, etc. of the special sciences and the useable explanatory mental models of educators. Closing the application loop requires closing at least three gaps:

- Educators must *internalize* explanatory scientific models as useable mental models.
- Educators must develop *conditional expertise* in selecting an appropriate mental model and adapting it to the particulars of a situation encountered in practice.
- Any new mental models must *displace* less effective ones that educators are currently using to inform their practice.

16.4 **Proposal for supporting a sustainable science of education**

Through the preceding analysis we have identified several tactical requirements that must be implemented to close the two loops of educational science and make explanatory models both useable by and progressively more useful to educators in practice. These requirements can be organized into two groups: process and infrastructure.

Process requirements

To support a sustainable science of education, educators need to be supported in:

- Identifying recurring educational problems requiring solutions, and, if necessary, communicating these to the people who can conduct relevant scientific investigations.
- Accessing and learning how to use available educational solutions embodying explanatory models.
- Testing the utility of proposed educational solutions and providing feedback in some systematic, cumulative form.

In order to bridge between the different basic viewpoints of educational practice and the special sciences (normative and descriptive, respectively), some group of people[2] needs to be supported in:

- Translating normative educational problems into descriptive scientific research questions.
- Integrating descriptive/explanatory scientific models into normative educational solutions that educators find accessible, learnable, useable and useful.

Scientists in the special sciences need to be supported in:

- Becoming aware of the set of research questions derived from educational problems so they can initiate scientific investigations based on those questions.
- Making relevant explanatory models accessible to the people who can integrate them into educational solutions.

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[2] This role is analogous to the M.D.-Ph.D. in the medical domain, who is trained in both theory and practice and helps facilitate bi-directional transfer between them. It seems like an excellent role for graduates of interdisciplinary graduate programs in education emerging around the globe, such as the Master's programme in Mind, Brain and Education at the Harvard Graduate School of Education (Blake & Gardner, 2007). Note also that some teams of people conducting design experiments in education also seem to be performing this kind of role (Brown, 1992; Cobb, Confrey, diSessa, Lehrer & Schauble, 2003).

Infrastructure requirements

Given the highly interdisciplinary and distributed nature of the sources of educational science that need to be coordinated in the minds of educators at the point of application, a supportive infrastructure is absolutely critical to bridging many of the gaps and overcoming the obstacles described in previous sections (recall Figure 16.2, in particular). Many of these challenges arise because the different groups of contributors work in fundamentally distinct ways (on different time scales, with different goals, etc.) and make qualitatively different kinds of contributions to educational science. Conferences and other socially-based venues are useful for connecting members of the different groups together to promote dialogue and collaboration, but such events are based on a fundamentally 'synchronous' model of interaction where all parties must bring their contributions to the table simultaneously. The probability that just the right people will come together at just the right time around just the right problem and everyone will be willing and able to follow through immediately with a collaborative project is quite low if everything depends on this kind of synchronous collaboration model.

Progress would be greatly facilitated if different parties could make their contributions asynchronously, largely independently of one another—for example, if educators could generate a running 'wish list' of recurring problems they would like solved, the appropriate people could, at their convenience, translate these into a running list of scientific research questions that are linked to the original problems, scientists could access the list of research questions and investigate them as they have interest and resources and later contribute their explanatory models as they develop and validate them, the appropriate people could integrate those explanatory models into educational solutions, educators could access the relevant solutions when they encounter a specific problem in practice and come back later to annotate the solution with application examples and data on their experience of the solution's usability and effectiveness, etc.—all independently of each other.

The basic infrastructure that would be required to support asynchronous collaboration and communication between disparate contributors includes the following two components:

- A database or library of problem specifications and associated solutions (or solution fragments) asynchronously accessible to and independently updateable by all parties.
- A standard format or template for entries in the library.

In the next section, we describe *design patterns*, which have been used to achieve similar ends in other applied domains such as architecture and software engineering. We argue that design patterns could be used to bridge many of the gaps and overcome many of the obstacles to establishing a sustainable educational science as depicted in Figures 16.1–16.3.

16.5 Design patterns as a medium for coordinating the diverse sources of educational science and making them useable by practitioners

The system of relationships between educational science and educational practice laid out in Figure 16.2 has analogues in other practical domains, such as engineering, architecture and software design. In all these professions, there are explanatory laws from various scientific domains that inform better practice without over-specifying tactics for the practitioner in the form of 'recipes' or scripts. In some domains, such as chemical and electrical engineering, there is a fairly tight coupling between one or more scientific disciplines (chemistry and physics, respectively) and the practical applications that are typically developed. In other domains, the relationship between explanatory science and practical application is looser. In some of these latter domains, most notably architecture and software engineering, people have introduced the idea of 'design patterns' to facilitate the process of integrating the kinds of theoretical and practical elements shown in Figure 16.2 and making them useable by practitioners to support systematic perception and better decision-making. In what follows, we explain what design patterns are and illustrate through a detailed example how they might be used to support the development, acquisition, and application of educational science by teachers.

Overview of design patterns

Alexander and colleagues (Alexander, Ishikawa & Silverstein, 1977) are credited with originating the idea of design patterns in the domain of architecture. They describe the basic idea thus:

> Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice (p. x).

An architectural example of a recurring problem is the outdoor porch. Porches serve a variety of purposes—for example, some porches are small and meant to shade entryways from the rain and snow, while others are large covered areas where people can sit outside shaded from the sun, and still others connect the interior of the building to a specific exterior space such as a courtyard. In addition, every porch design is unique. In terms of design patterns, what porches have in common is that they provide a transitional space that is neither inside nor outside, and these transitional spaces are important both practically (for example, to shelter people from the elements while waiting at the door) and psychologically (for instance, the transition from inside to outside or vice versa is less jarring if it is mediated by a space that has elements of interior spaces—like a roof—and exterior spaces—like open walls). Viewed in this way, the *Porch* design pattern provides much more useful information to support an architect than would a series of examples alone, because it specifies the criteria of a good porch design without constraining the specific implementation details unnecessarily. The design pattern also formalizes and subjects to public scrutiny and negotiation a set of well-defined and revisable criteria for distinguishing between better and worse designs, which would otherwise only be implicitly defined in the heads of experts. Finally, by creating meaningful categories applicable to diverse exemplars to which simple names can be attached, design patterns support the development of a common vocabulary to facilitate communication among members of the field.

Design patterns have had an even more dramatic impact in computer science than in architecture where they originated, facilitated greatly by the publication of a now classic book compiling many common and useful software design patterns in one comprehensive reference, all organized around a standard pattern template (Gamma, Helm, Johnson & Vlissides, 1994). The demonstrated utility of design patterns in domains such as architecture and software engineering provides a proof-of-concept that they could also add significant value in education.

Design pattern specifications

Other people have started working to apply the idea of design patterns to education (Anthony, 1996; Bergin et al., n.d.; Mislevy et al., 2003). In general, design patterns are specified using a standardized template. Various standards have been proposed by different camps within and across domains. There is variation in these proposed standards, but there is also significant overlap. Standard elements include, for example, a short descriptive name, to facilitate learning of the patterns and efficient communication among practitioners; a description of the recurring problem that the pattern helps to address; a description of the general solution; information on when and how to apply the pattern; and examples of applications.

Our analysis has generated additional constraints and design goals for a design pattern framework, above and beyond the elements common to many existing frameworks. Specifically, we propose that design patterns in educational science should:

- Help close the adaptation loop of educational science by supporting coordination across the characteristic time scales, basic viewpoints and levels of abstraction that distinguish the world of educational practice from the world of scientific research—by allowing, for example, educators and scientists to make their contributions independently and asynchronously; and
- Facilitate the integration of explanatory models into educator practice by providing representations that educators find accessible, learnable, useable and useful.

The tactical role of design patterns in closing the two loops of educational science is illustrated in Figure 16.4.

Design pattern template

Combining the key common elements of other design pattern templates with the design considerations summarized at the end of the previous section leads us to propose the following design pattern template for educational science:

- Name: a short, descriptive name for the pattern.
- Intent: a succinct description of what applying the pattern is intended to accomplish.
- Motivation: a description of the educational problem or opportunity the pattern is meant to address, illustrated with a representative example scenario.
- Explanatory model(s): brief description of the scientific explanatory models that support good reasoning and decision making with respect to the problem or opportunity specified in the Motivation section, plus references to relevant scientific literature describing and substantiating the models.
- Applicability: conditions under which this pattern might be applicable.
- Validation: criteria for testing the value of the pattern in practice, plus cumulative data on its value in practice:
  - How to test the value of the pattern.
  - Informal feedback on its utility and/or effectiveness.
  - Formal research on educational outcomes resulting from application of the pattern.
- Research questions: a list of open research questions that follow from the educational problem statement or that have been generated in the course of applying it.
- Additional resources: examples, supporting materials, techniques, tactics, technologies, standards, guidelines, etc. on applying the pattern in general or specific cases.
- Related patterns: other design patterns that are complementary to or need to be differentiated from this one.

Example of a design pattern in educational science

In this section, we illustrate what a design pattern in educational science looks like using one of the three foundational principles of Universal Design for Learning (UDL)—the principle of representing information using multiple formats and media to make it accessible to all learners (Rose & Meyer, 2002). We selected this principle because UDL is a research-based framework grounded

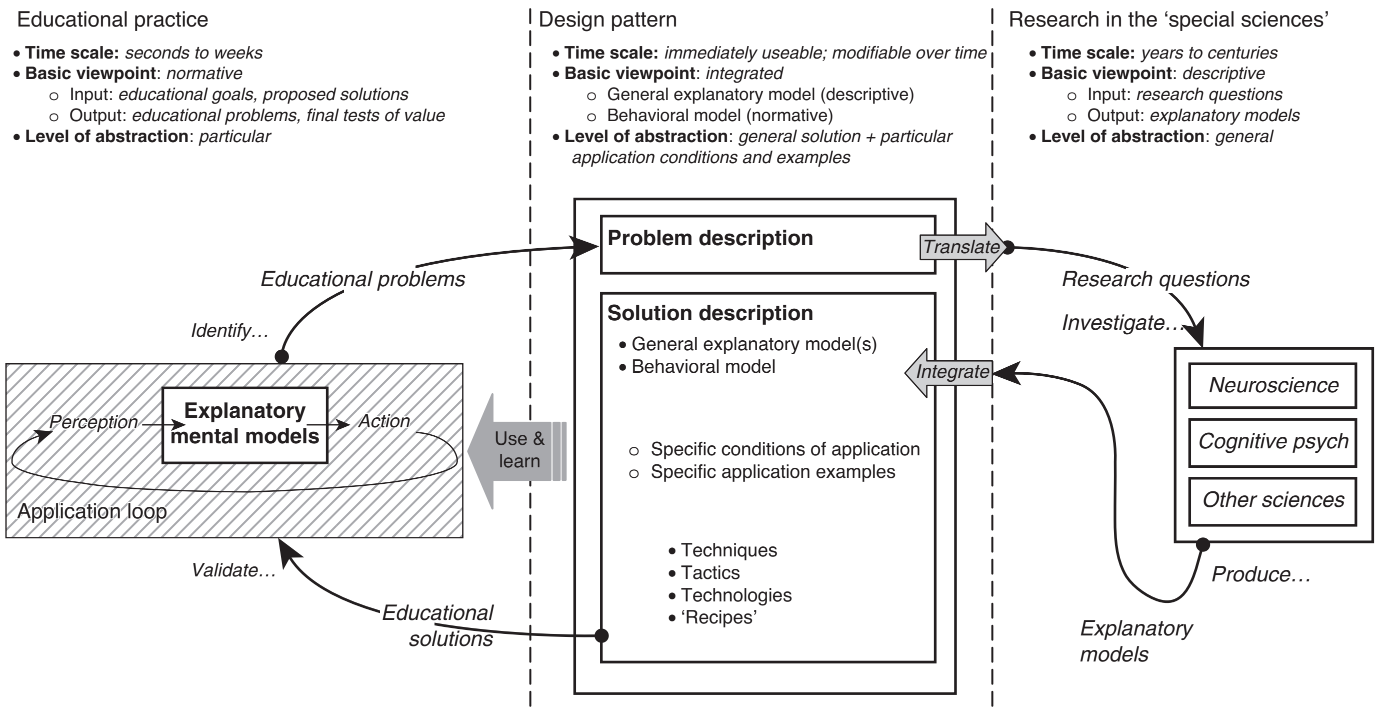

Fig. 16.4 Closing the 'adaptation loop' and 'application loop' of educational science with design patterns. Design patterns describe recurring problems plus the core of a general solution that can be applied repeatedly across a wide range of contexts and situations. They provide a persistent medium that can bridge across the time scales, basic viewpoints and levels of abstraction that distinguish educational practice from research in the special sciences. They also provide a standard format for representing and accessing immediately useable solutions to recurring educational problems that facilitates educator learning of the embedded explanatory models over time.

in multiple scientific sources—including neuroscience—that supports the development of practical tools for use by educators. We call this design pattern 'Perceptual Accessibility' for short.

Name: Perceptual Accessibility

Intent: separate the storage medium of educational content from its delivery mode (including perceptual modality, communication medium and content format) so that the content and its delivery mode can be changed independently of each other.

Motivation: historically, much educational content has been bound inflexibly to a particular delivery mode (including perceptual modality, medium and format) at the time it is first generated. For example, the content of a classic printed textbook is inextricably bound to the visual modality, in the medium of fixed text supplemented with static images, and in a particular format (such as 12-point Times New Roman font).

Binding the storage medium in this way to the specific delivery mode selected by the producer limits access by some groups of learners (those with specific sensory impairments, for example) and to all learners under some learning conditions (where lighting is poor, movement is constricted, etc.). This binding of storage medium to delivery mode makes it difficult to accommodate the full range of learner needs, preferences, and study environments and limits the ability of educators to re-use content and presentation components independently of each other.

Educational content designers should be able to create and store educational content without committing to a concrete set of fixed decisions about delivery modality, media and format. Only the delivery configuration in a particular learning *instance* should depend on these specific decisions. Therefore, educational content specifications should define content without mentioning particular delivery characteristics.

The Perceptual Accessibility pattern addresses these concerns by separating the specification of the content storage medium from the specification of delivery parameters. A textbook might be *stored* on a computer server in one format (as digitized text, for example), and *delivered* (or *accessed*) in a variety of perceptual *modalities*, including visual (for example, printed text), auditory (for example, using text-to-speech), or tactile (translated into Braille, for instance). Within a single modality, such as visual, the stored content might be rendered in a variety of *media*, such as animations, static images, or text. Finally, within any medium, the *format* of the content can be varied (rate of speech slowed, size of text increased, contrast of images enhanced, colour palette customized, etc.).

Explanatory model(s): learning depends upon the coordination of parallel streams or 'channels' of perceptual information coming in from the senses, such as sight and hearing. Each channel comprises a sequence of processing stages. Cognitive psychologists, neuroscientists and researchers in other domains have characterized some of the processes and systems involved in the perceptual processing and maintenance of incoming information that is necessary for effective learning, particularly in the visual and auditory channels (and to a lesser extent the tactile systems involved in reading Braille, for example). Key systems include:

- Physical sensory systems (eyes, ears etc.).
- Perceptual buffers (large-capacity, very short-duration memory systems not accessible to conscious control).
- Attention.
- Working memory (limited-capacity, short-duration memory systems that can be consciously manipulated and maintained).
- Executive function (necessary, for example, for allocating limited attention efficiently and effectively and for actively managing working memory).
- Long-term memory (large capacity, durable memory systems, of which there are several subtypes).

Although gross sensory impairments such as profound blindness or deafness are generally self-evident, problems with any other processing subsystem in this list can be much less obvious, but can nonetheless inhibit learning within a specific modality or modalities. By enabling access to content through a variety of modalities, media, and formats, the Perceptual Accessibility pattern enables educators and learners to switch the mode of instruction flexibly between different perceptual modalities or 'channels' to support cognitively diverse learners, and can also support informal diagnosis on the educator's part so she can take appropriate next actions (such as making referrals to appropriate specialists).

Applicability: use the Perceptual Accessibility pattern when. . .

- The learning infrastructure supports it—for example, when a digital delivery medium is reliably available in all instances where the content will be delivered.
- There are individual students who have profound limitations in one or more perceptual modalities, or in any modality-specific supporting systems including attention, working memory, executive function or long-term memory; these might be identifiable by formal assessments and clinical diagnoses, and in some cases may be initially identified through informal observations by educators.
- The learner population is or may be diverse with respect to perceptual strengths, limitations and/or preferences.
- The same content will be delivered across a variety of delivery platforms with different learning affordances and limitations, such as PCs, e-books, smartphones, iPods and on-demand hard-copy printouts.
- Students appear disengaged or frustrated, or are having trouble comprehending the educational content, and there is reason to believe that the delivery mode, medium or format is contributing to the problem (this is an especially good time to give the learners some control over how the content is delivered so they can match the delivery to their preferences).

Validation:

- See Rose and Meyer (2002) for a review of some of the formal research demonstrating that applying the Perceptual Accessibility pattern can produce significant educational benefits compared to control conditions where modality, medium and/or format of the educational materials are inflexible.

Research questions:

- *Computer science*: are there more effective and universal formats we could use to store the abstract educational content than digital text, images, etc.? For example, instead of converting an image to text via a pre-stored caption for auditory delivery, would it be possible to provide an abstract conceptual description in place of a string of text or a particular image, and then based on the delivery parameters set for a given learning session, to search the web at the time of delivery for the best possible instance of the specified content in the desired delivery mode (image, explanation, model, etc.) that is available at that time?
- *Cognitive psychology, neuroscience, cognitive science*: are certain kinds of content more easily or effectively learned via certain cognitive/neural pathways? What kinds of delivery configurations most effectively support certain learner profiles?
- *Computational neuroscience:* given that the different perceptual modalities have very different 'bandwidth' or information capacities, are there general models to understand tradeoffs when switching between them and strategies for doing so most effectively?

Additional resources: see CAST's web site at http://www.cast.org for a list of relevant research and resources.

Related patterns: if we had a database of design patterns in educational science, we would refer in this section, for example, to more specific patterns in the database related to each processing component mentioned earlier (attention, working memory etc.). Such references would provide more specific diagnostic criteria educators could use to isolate specific problems and/or refer learners to appropriate specialists for follow-up diagnosis and support.

16.6 **Discussion**

How design patterns close the two loops of educational science

Design patterns help close the *adaptation loop* of educational science by bridging gaps in time scales, basic viewpoints and levels of abstraction that distinguish educational practice from research in the special sciences.

- Time scales: design patterns are immediately useable, supported by guidelines on when to apply them and what to look for to assess effectiveness, application examples etc. Specific subcomponents of design patterns provide connections for scientific researchers in other domains to draw from (e.g. research questions) in their research and to update with relevant information as it becomes available (e.g. explanatory models).
- Basic viewpoints: the translation from educational problem (described in the 'intent' and 'motivation' sections of the pattern) to scientific research question (listed in the 'research questions' section of the pattern) is made explicit to facilitate the transition from the normative basic viewpoint of education to the descriptive basic viewpoint of scientific research. Going the other way, the explanatory models can be contributed by research scientists and the integration into educational solutions is at least in part accomplished by supplementing the descriptive explanatory models with information on when to apply the model, examples of application, suggestions and data on evaluating the utility of the model, etc.
- Levels of abstraction: research questions and explanatory models are general and relatively context-free, while the other components of the pattern provide more particular context (when to apply, particular examples of application, etc.), making it easier for educators to know when and how to apply, and how to know if the pattern is adding value in practice.

Design patterns help close the *application loop* of educational science by making scientific explanatory models accessible, learnable, useable and useful to educators.

A design pattern can be thought of as an externalized mental model, or a 'tool to think with'. The intent is that through the process of applying a design pattern, educators will over time internalize the explanatory models at the heart of the pattern and be able to apply them flexibly. The techniques, tactics, examples and other supporting materials provide initial scaffolds (Fischer & Bidell, 1998; Vygotsky, 1978) that can be dispensed with as the explanatory models become integrated into educators' repertoires and conditionalized on appropriate application conditions.

16.7 **Conclusion**

We began by describing a vision of educational science as a system organized around scientifically rigorous *explanatory models* that are *applied* by educators in their moment-to-moment practice and progressively *adapted* (that is, broadened in scope and refined in terms of usefulness) through a systematic process of scientific inquiry involving a collaboration between educators and scientists in other domains, such as neuroscience. We argued that supporting such a system of educational science could catalyse a virtuous cycle of progress in educational practice grounded in a cumulative store of transparent, high-quality domain knowledge of the sort available to experts in other complex applied domains, such as medicine and engineering.

Following Dewey (1929), our analysis distinguishes *educational science* proper from its *sources*, which include both educational practice and the special sciences such as neuroscience and cognitive psychology. In addition, we argue that educational science is located in the brains and minds of educators, whereas its sources can be found in various forms, represented in various media, and distributed across a wide range of domains. This key distinction between educational science and its sources helps clarify a number of important but otherwise potentially confusing issues. For example:

- What is educational science? Educational science is practical educational expertise grounded in explanatory mental models derived from systematic scientific research, plus systematic methods of inquiry used by educators to identify educational problems worth solving and to test the practical value of proposed solutions.
- What is the role of neuroscience in education? In our analysis, neuroscience is one of many scientific sources of educational science which can make quite specific contributions to it, in the form of explanatory models that can be integrated into solutions to recurring educational problems. Neither neuroscience nor any other scientific source of educational science should be confused with educational science proper, which exists in the brains and minds of educators.
- What is the role of 'recipes' in educational science? Detailed educational scripts or 'recipes' for action that are meant to be followed by educators without judgement or reflection—even if generated through scientific means—do not constitute educational science. They can, however, serve as useful examples (as in the Perceptual Accessibility design pattern specification) that help educators know how to apply explanatory models in particular cases, thereby helping them to internalize and become fluent with applying the explanatory models in more general and nuanced ways with experience over time.
- Why does Dewey (1929) state that science cannot provide 'stamps of approval' for particular educational practices? As illustrated in Figure 16.2, educational practice and scientific research embody different basic viewpoints—normative and descriptive, respectively. Stated another way, scientific research can help us understand how the world is and why it is that way, but we cannot discover through research how the world should be—including what educational ends to pursue, or even in the final analysis how we should behave—that is, what means we should pursue to achieve specific educational objectives. We do of course recognize that scientific research can answer questions such as whether flash cards or constructivist activities are more efficient at teaching children their maths facts according to some strict operational criterion. Our point is that this kind of scientific evidence is always an insufficient basis upon which to choose an educational intervention, because—just as an example—we are also choosing to subject the student to a certain kind of experience. And that choice necessarily has moral implications—whether we are talking about subjecting them to flash cards or pharmaceuticals.

Note that even as we package up some of the explanatory models into technologies such as automated assessments or computer tutoring systems, we do not decrease the need for or the status of teachers, any more than we decrease the need for or status of engineers or architects as we understand more about physics. On the contrary, the net effect of such technological advances in other scientific domains tends to be to expand the available toolkit, the leverage of the individual practitioner, and the range of goals, challenges and opportunities that are within their professional reach (see Chapter 19, this volume). Given the inherent challenges of education compared even to other very complex domains such as medicine and engineering, there is every reason to believe that moving toward a bona fide science of education would have an expansive—not a diminishing—effect on the professional status and capabilities of educators.

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