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Plasticity in Learning Pathways: Assessments That Capture and Facilitate Learning

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Schools have huge transformative effects on people and societies, and simultaneously they fail to educate many children effectively. In most environments, wherever schools have been established, they have had transforming effects on the societies that they exist in. At the same time most schools fail with the large majority of children (Suárez-Orozco & Suárez-Orozco, 2010). If schools effectively educate 25% of the children in a developing country, that's a great advance over educating none of them, and it has a huge effect on the developing economy and infrastructure of that country. But it is still only 25%. In the 21st century, we are trying to educate everybody. One of the main problems with schools is easily observed in most classrooms. Simply ask most children to complete this sentence: 'School is what? [Fill in the blank]'. The most common response is, 'School is boring'. This happens even in good schools! In Massachusetts we have some of the best schools in the US, and yet most of our children still say school is boring. School does not have to be boring. Students have a natural curiosity and we owe it to them to try to make schools interesting so that they can learn effectively. A large part of the reason that schools are boring lies in the process of asking students to memorize knowledge without understanding it. A related problem is the failure to show children how what they learn is relevant for their lives. Instead of just memorizing facts, students and teachers in schools can actually think about and analyze tasks, problems, and issues. Also, the focus on standardised tests exacerbates the problems with schools. We will suggest ways around these difficulties so that schools can be more interesting and relevant.

John Dewey (1933, 1963) was a great educational philosopher, with a lot of wise things to say. Dewey said, among other things, that if you want to be a good teacher, you should not teach reading and writing, but teach students. That's a good lesson for us to take, focusing on what students are actually doing in their classrooms and their lives and how they are learning and developing as individuals. We should not treat students as if they are all the same. Students take many different pathways to learning. Most of us that teach in classrooms experience this every time we step into the classroom. Students learn in different ways, they are interested in different things, and it is a major challenge to engage all of the students in any classroom. I like to think of the tower of Babel as a metaphor for these differences. In that Biblical story God made people speak different languages. He likewise made people importantly different from each other in goals, cultures, interests, and talents. Languages and cultures represent important differences among us, but the differences are much more pervasive than language and culture, extending to what we care about and how we learn.

All these differences pose a huge problem for educators, who are stuck with an outdated model of learning in schools. The traditional way of teaching is what I call the 'Holy Book Approach': Here is the sacred text, or the established curriculum, which is what everyone has to learn. There is one way to learn this curriculum well – the traditional way, usually repetition and recitation, which is memorizing the sacred text. Many students are lost to education if they are allowed to learn only according to the Holy Book Approach.

Universal scale for learning and at the same time different ways of learning

People learn differently, but at the same time the processes through which they learn have many similarities. Through extensive research on cognitive development and learning we have discovered a general scale that captures the way learning occurs in any domain or skill, and we can use it to measure learning in classrooms (Fischer, 1980, Fischer & Bidell, 2006; Stein, Dawson, & Fischer, 2010). One of the strengths of this universal scale is that it provides a ruler for analyzing learning differences.

In most of cognitive science (except for psychophysics) measurement scales are treated as arbitrarily created, in the way that the scale for IQ is created by fiat rather than through empirical evidence about the natural scale behind human learning. Psychology and cognitive science have been creating arbitrary scales for a long time, launched by the intelligence testing movement early in the 20th century. Psychometricians create arbitrary scales, forcing distributions based on arbitrary assumptions about scaling. (For an alternative, see van Geert & van Dijk, 2002; van Geert & Steenbeek, 2005). Instead we should be examining the natural scale that children show in learning and development.

Fortunately, the evidence is clear-cut for the existence of this universal scale for learning and development. Children and adults move through a series of reorganizations of their abilities as they learn and develop and even as they perform on standardized tests. This scale provides a powerful rubric for assessing learning in classrooms and other learning environments (Fischer & Bidell, 2006; Stein, Dawson, & Fischer, 2010).

At its simplest, the key criterion for marking the points on the scale is the presence of discontinuities in development and learning along with gaps in test performance. Figure 1 shows an example of one of the discontinuities. We all know about this one – the emergence of language around two years of age. This graph is for one of many children, Tomas, studied by Ruhland and van Geert (1998) in the Netherlands. Tomas showed an abrupt jump in the use of personal pronouns at two years of age. The more specific the skill examined, according to research over the years, the more likely learning will show a rapid jump in performance. Research shows a series of discontinuities or reorganisations throughout childhood and into adulthood, with some of the findings being surprising.

For example, one discovery is that people continue to develop new abilities during the decade of the 20s. One of the domains with the best evidence for new abilities during this age period is what John Dewey (1933) called *reflective judgment*, asking about the basis for knowledge, using evidence and argument to determine what is true. Karen Kitchener and Patricia King

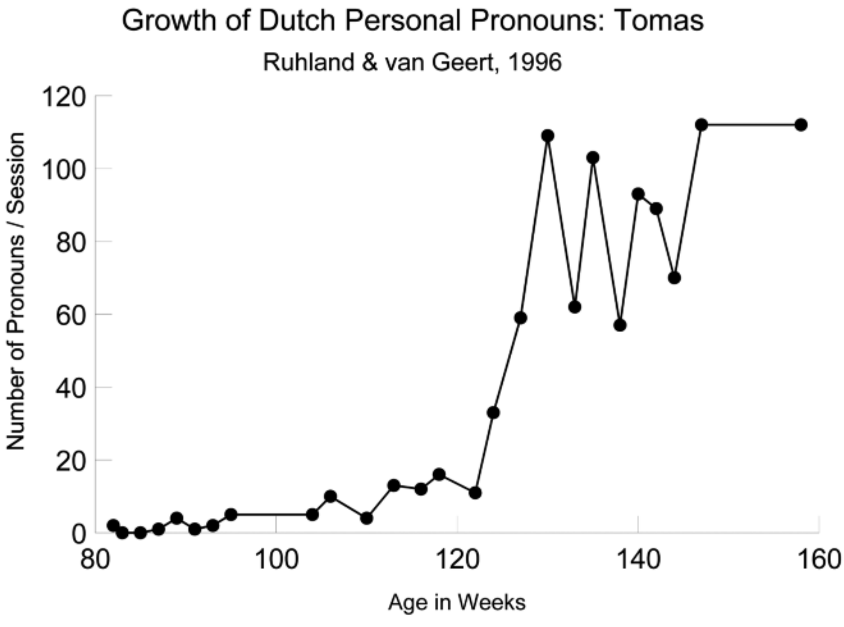

Figure 1. Spurt in vocabulary growth in a Dutch boy.

created a series of dilemmas for measuring reflective judgement based on the Dewey model, including a dilemma about chemical additives to food (Kitchener, King, Wood, & Davison, 1989; Kitchener, Lynch, Fischer, & Wood, 1993). The question is, 'Are chemical additives to food good for you or bad for you?' Chemical additives to bacon, for example, keep it from spoiling, which keeps people from getting sick. On the other hand, there is evidence that the chemical additives can in the long run cause cancer or other illnesses. The question thus becomes 'Are chemical additives to food good because they prevent illness, or are they bad because they cause cancer?' In the reflective judgment coding system the interviewee can take any position – that the additives are good because they prevent illness, that they are bad because they cause cancer, or that both positions can be true. The quality and complexity of the person's argument determine his or her level of reasoning.

In development, the levels of reflective judgment start from a conception of knowledge as absolute – either chemical additives are good for you, or they are bad for you. Then a person's skills move to a kind of relative knowledge, such as an adolescent saying, 'Well, it just depends; it's your bias'. Eventually, in the later stages people come to be able to create complex reasoning where they make specific arguments, talk about evidence, and generally do the kind of reflective judgement reasoning that Dewey was describing. The result is a seven-level learning sequence moving through a series of types of reflective judgment.

Here is an example of a level six argument: Although a person may change what s/he thinks is true, s/he can make strong and justified conclusions based on argument and evidence. Here is an elaborated answer, the gist of which is: 'It can be either way':

There is good evidence to say that some chemical additives help protect us from things like food poisoning. Evidence is open to interpretation and may change with time. Therefore, we can never know for sure. However, just like scientists, we must evaluate the evidence about a given additive. Then we must synthesize the evidence with other things we know about the world into a point of view. The conclusion is a reasonable view of the issue. Differences in point of view about this issue, which come from different ways of evaluating the evidence, can be judged as more or less reasonable.

We interviewed students from local high schools and the University of Denver between 14 and 28 years of age about reflective judgment, matched approximately for intelligence. In one condition (optimal level in Figure 2) we provided contextual support for a more complex response, showing each student a prototype of a good argument (a method called priming). In the

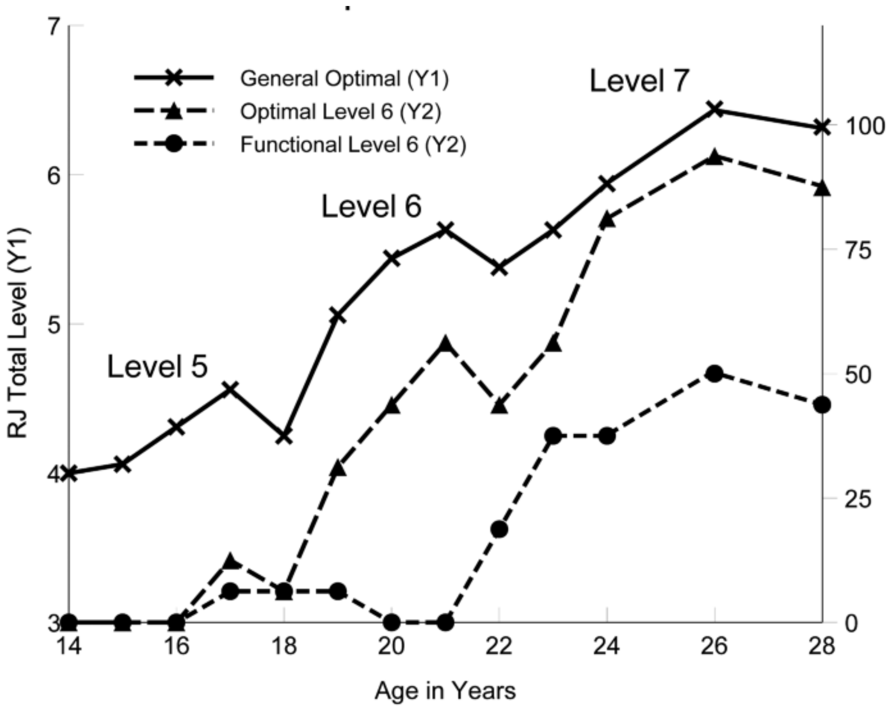

Figure 2. Development of reflective judgment: level 6 explanations.

other condition (functional level in Figure 2) we presented the dilemma without any contextual support. Prior research shows that people can often function at a higher level for several minutes when such contextual support is provided, but the higher level response falls back to baseline after several minutes (Fischer & Bidell, 2006). Thus support produces a higher level response, but the effect is transient.

This is an example from our study of what happens with no support. A student is asked about the chemicals dilemma, and s/he gives an answer and explanation. With age students show slow improvement over many years, and most of them do not understand the complex stage six argument until they are into their 20s. Even then most of them do not score above 50% at stage six, as shown in Figure 2.

When we offer support (by priming a more complex response) we see a different pattern, as shown in the higher dotted line: Students show a series of jumps in performance across the age range of the experiment, as evident in Figure 2. Typically, assessments of supported performance show such discontinuities, such as the jump to near perfect performance for stage six at age 26. An earlier jump is also evident at age 20, but the level reached is only 50% correct. Students required about five more years after their initial creation of stage six answers to reach nearly 100%. In other words, for complex reasoning, learning takes a while. It is a slow process, requiring a long time to come together consistently. In schools we should know that learning of complex material is often slow, but we do often do not act that way.

In Figure 2 the overall score for the whole assessment shows a jump for stage five, a jump for stage six, and a jump for stage seven. Note that these performances are not fixed at a 'stage' but instead vary across 'levels'. One of the characteristics of learning and performance is that skills move around. People do not operate at one level consistently. A given person in a matter of minutes can move up and down on the developmental scale in a dynamic process. Our research is intended to articulate principles for this variation.

Relations of Cognitive and Brain Development

The focus of this paper is primarily on learning environments, but also relevant is the model we have built of how brain activity patterns change systematically with cognitive development. Most of the relevant research assesses the electroencephalogram (EEG) although studies of other brain imaging tools often suggest similar cycles (Fischer & Rose, 1994; Fischer, 2006; Fischer, 2008). In the EEG one can look, among other things, at the energy in the waves. Figure 3 shows growth curves for the alpha band of the EEG for relative energy in the occipital area of the cortex (Matousek & Petersén, 1973). The similarity with the growth patterns for reflective judgment are striking, with spurts and plateaux correlating well with the ages of spurts and plateaus in cognitive developmental research. Here I've transformed the data into change scores (differences from one year to the next) to highlight the spurts.

These are the kinds of growth curves that we see repeatedly, marked by spurts and plateaus, which correlate with the emergence of new cognitive capacities. Michelle Lampl and her colleagues have shown that spurts and plateaus are the normal pattern even for physical growth (Lampl, Beldhuis, & Johnson, 1992; Lampl & Jeanty, 2003). The straight-line growth curves that paediatricians display to show children's growth do not capture the way individual growth actually occurs, but instead are normative patterns that result from averaging over many children.

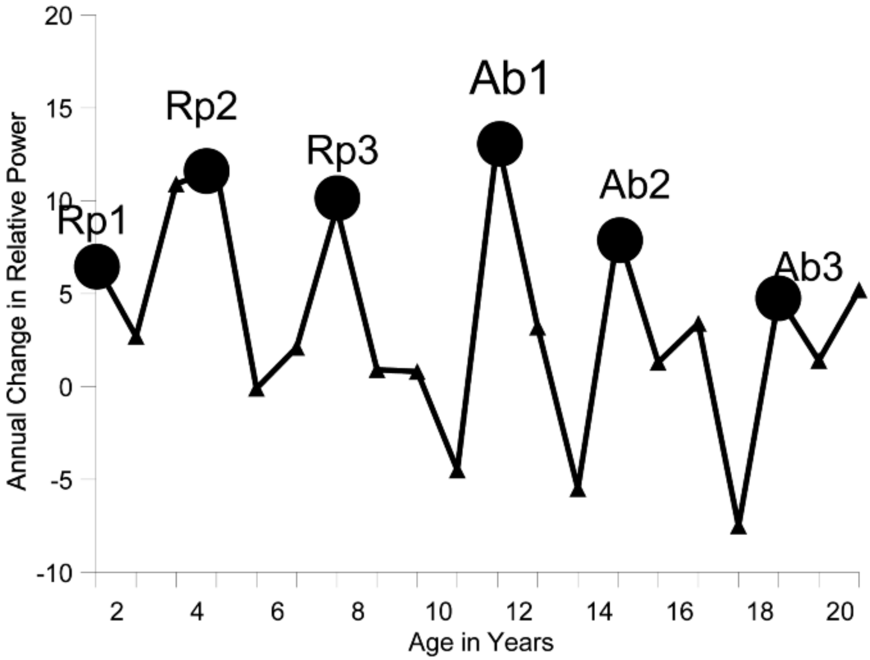

Figure 3. Growth of relative energy in the EEG.

Combining content and complexity in developmental analysis

In cognitive development and learning, people move through different learning sequences as they master thinking about a specific content or topic. Different people learn along different pathways, based on their goals, interests, and experience. That is why schools and teachers need to deal with the large differences in how students learn. With the methods that we have devised we first analyze content and complexity separately, and then we combine them to characterize different learning sequences.

Content themes are combined with complexity to produce learning sequences. For example, categories of arguments from students' interviews include the following examples: truth is uncertain, proof is required, or people can show bias. Often these categories are connected with specific levels of complexity. Sometimes the same categories occur across multiple levels. Sometimes they are specific to one or two levels.

The complexity scale consists of ten levels of complexity, with four levels in each of a series of three cycles (actions, representations, and abstractions) as shown in Figure 4. The scale is built strongly on prior work by Piaget (1983), James Mark Baldwin (1894), Vygotsky (1978), and Werner (1957), as well as other developmental scholars. Note that in the complexity scale, 3 x 4 = 10. The final level of each cycle – actions, for example – leads to the emergence of representations, so there is an overlap of one level from one cycle to the next.

Figure 5 (see p. 252) gives an example of how these cycles appear not only in development but also in test performance. A sample of 747 cases of moral reasoning was analyzed according to a system related to Kohlberg's analysis of moral judgment based on his standard moral dilemmas (Colby & Kohlberg, 1987). The Kohlberg system had some inaccuracies in it, especially for the levels of moral reasoning in young children (not surprising because his focus was on adolescents and adults). We have been able to correct these errors and improve the scale based on empirical evidence for moral development at early ages (Dawson & Gabrielian, 2003; Dawson-Tunik, Commons, Wilson, & Fischer, 2005).

The graph is based on Rasch (1980) analysis of the scaling of performances about moral reasoning. Note what look like jumps in performance – showing a clustering of scores at points that represent the core developmental score for each level on the Rasch scale. These findings illustrate that there is a common scale underlying learning and development, even while different children often learn in distinct ways, moving along different learning pathways.

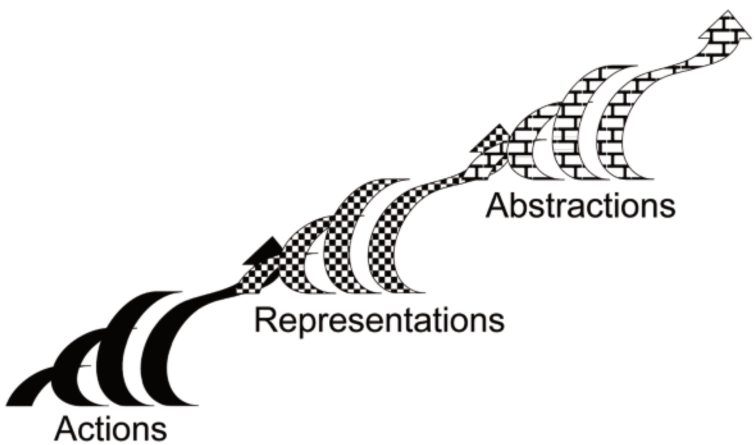

Figure 4. A scale of 10 levels of skill complexity marked by reorganization of behavior & neural networks.

Different pathways for learning to read and for dyslexics

Research on learning to read shows that young children learning English learn along three distinct pathways. They do not all develop along one common pathway! In addition, research with dyslexics (who have difficulties learning to read English) demonstrates that their visual systems have different properties from 'normal' readers, apparently indicating that the eye and the visual field for dyslexics are structured differently from the standard analysis of fovea and periphery.

The standard model of early reading development, especially for English, starts with the concept that a young reader needs to coordinate three domains: the meaning of words, the sounds of words, and the visual representation of letters. In the standard model of reading the child has to integrate these three domains. In general, developmental sequences take the form of a web, with different strands of the web marking different domains that can be integrated. Children are not at the same level in each domain but instead they show much variability, which can be captured by the model of a web of skills moving along independent strands (Fischer & Bidell, 2006).

The standard model for early reading posits full integration across domains early in the reading process, shown in Figure 6a (LaBerge & Samuels, 1974). In the model the three domains of letter identification, word defi-

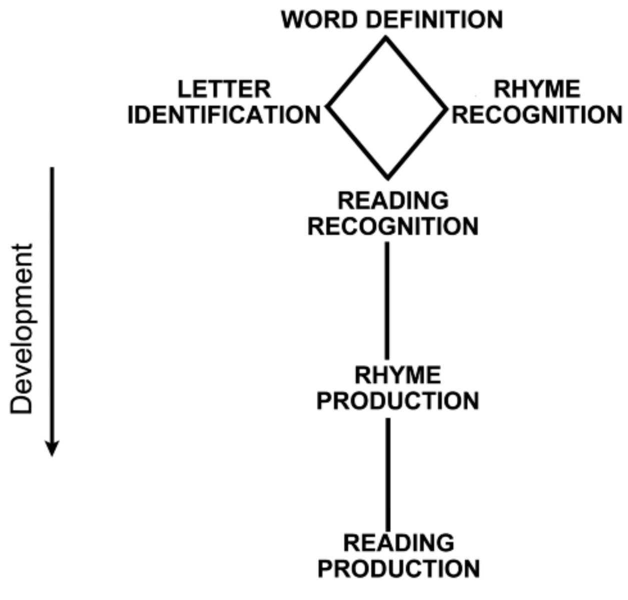

Figure 6a. Modal developmental pathway for learning to read: integration of read & rhyme.

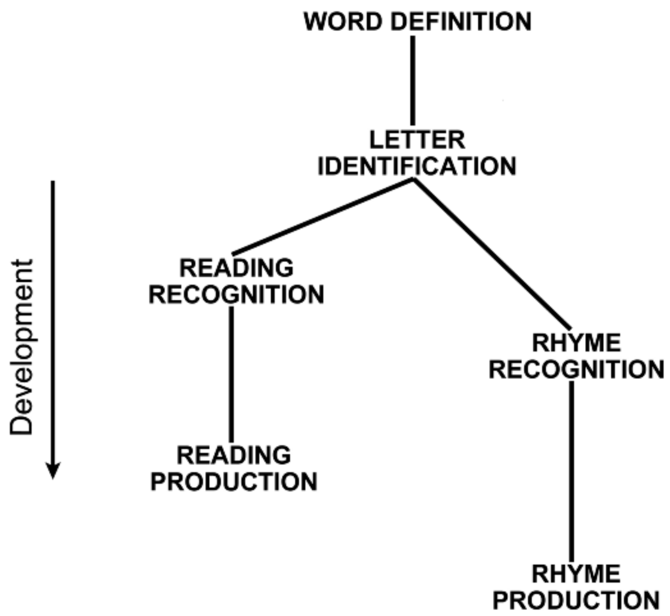

Figure 6b. Second developmental pathway: read & rhyme independent.

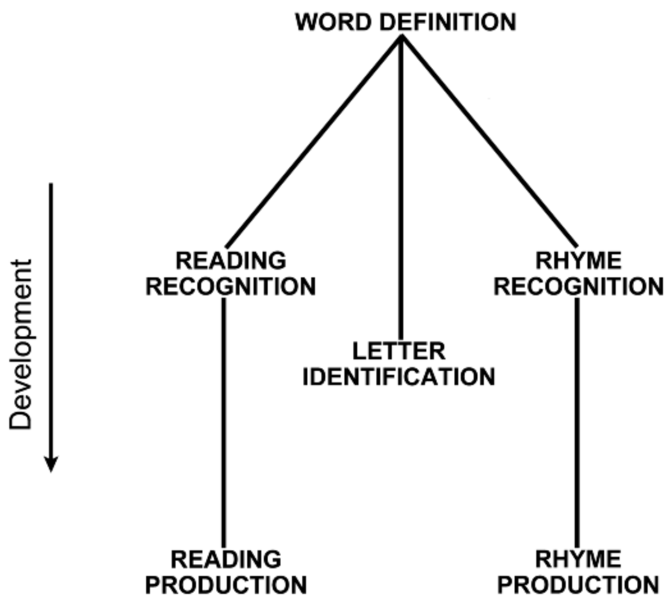

Figure 6c. Third developmental pathway: read, rhyme, and letter identification independent.

nition, and rhyme recognition are coordinated with each other in reading early words. Each item in the graph represents a test of a domain of reading skill, with a total of six tests: word definition, letter identification, rhyme recognition, reading recognition, rhyme production, and reading production. The names of the tasks capture well what each child was asked to perform. Each student needed to know what a word means, how to identify the letters, how to relate the letters to sounds, and how to match sounds with rhyme. According to the model in Figure 6a, a young reader integrates the three domains (top of sequence), which creates a simple linear sequence from reading recognition to rhyme production to reading production. Based on a statistical analysis of these six tests with 16 different words, the model was strongly confirmed.

However, we were not happy with the model or the statistical results. Of the 80 children we tested, about 20 of them did not fit the model well based on the patterns that they showed across words. We performed a pattern analysis for each of those children and found powerful support for two additional patterns of learning to read. Because we had 16 words for the six tests we could perform profile analysis for each individual child. The evidence was clear: There were two other pathways, with every child showing one of three pathways for the sixteen words.

Figure 6b shows the second pathway, in which reading and rhyming were independent of each other. Still more complex was the third pathway, where reading, rhyming, and letter identification developed independently of each other, forming separate strands in the learning web for early reading (Figure 6c). It is no surprise that these children read least skilfully.

The conclusion is that children learning to read English words develop along three different pathways. This is but one example of how different children develop in different ways, even when they are all being taught based on the standard model of learning to read. Educators need to attend to these differences. Children show many differences in the ways they learn and in the ways they are motivated to learn.

Different visual systems in dyslexic readers

Dyslexia is often conceived as a simple defect in brain organization. However, research with dyslexics suggests that their brains are not defective but instead are organized differently from ‘normal’ readers – in particular, their visual systems are biased toward integrating information across wide areas of the visual field. This organization is distinct from the normative description given routinely about the nature of the eye, the retina, and the neural organization of vision.

Our dyslexia research project is led by Matthew Schneps, co-director of the Harvard Smithsonian Center for Astrophysics group on Science Education. One part of the project focused on dyslexic astrophysicists. The National Science Foundation in the US has recently realized not only that learning disabilities are important but that a large number of scientists have been characterized as having disabilities such as dyslexia, attention deficit disorder, and Asperger's syndrome. More generally for science education, educators and researchers are coming to realize that children learn in different ways and that different models are needed to capture the variations in how people learn.

Our research project demonstrates a different visual system in dyslexics and establishes that many visually talented astrophysicists have dyslexia and apparently have a different visual system from the 'normal' one. For example, research has shown that dyslexics commonly have a visual talent for quickly detecting visual contradictions in graphic art, such as Escher diagrams. They detect the contradictions 50% faster than normal readers. The very beginning of this research actually started with Geiger and Lettvin (1987) and was replicated by von Károlyi, Winner, Gray, & Sherman (2003). Dyslexics are also overrepresented in art schools, which enrol twice as many dyslexics as the normal population.

An important skill in astrophysics is integrating information across wide areas of the visual field, as in star fields. We tested the astrophysicists on tasks based on real skills that are important in astrophysics. A key skill is detecting black holes by using wave patterns. Figure 7a shows a prototype for detecting a black hole, but detection with real waves is much harder because actual wave patterns are more likely to look like Figure 7b. Our testing showed that the dyslexic astrophysicists were much better at detecting black holes than the non-dyslexic ones. In fact, the best astrophysicist at detecting them has sensitivity in her periphery that is close to what we expect in the fovea for most people.

This unusual visual skill has an advantage for detecting black holes in these kinds of waveforms but it has a disadvantage for reading, because a reader needs to focus text in the fovea, mostly, and make fine discriminations (such as p versus d versus q versus b). Also when a person is highly sensitive in the periphery of the visual field, s/he is distractible – frequently distracted by events in the periphery. Peripheral events demand an obligatory eye movement toward the event. As a result, dyslexic children and dyslexic scientists are presumably much more distractible.

Our goal is to move towards an education system that honors not only people who see the trees in the forest but also people who see the forest in

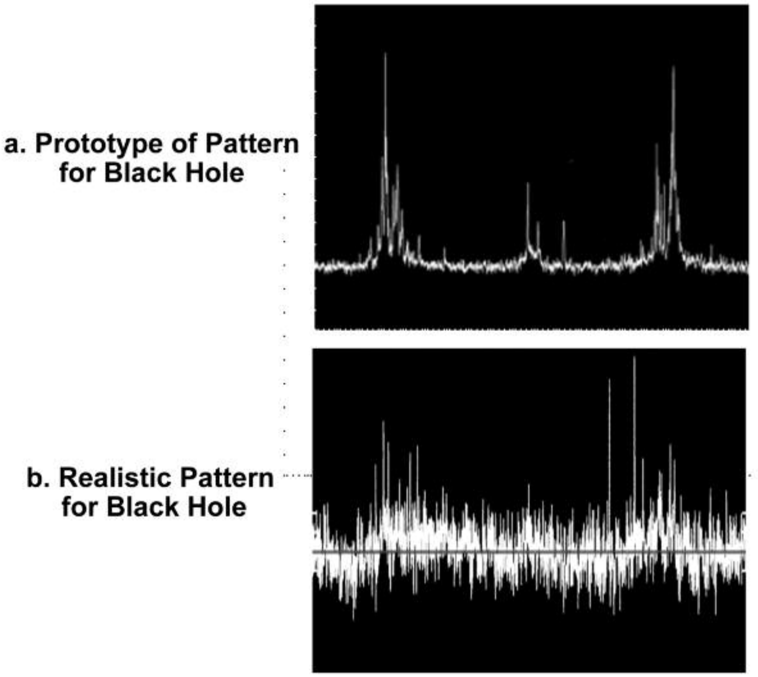

Figure 7a-b. Prototype for black hole versus realistic pattern.

the black hole wave patterns. We need education that honors these differences instead of stigmatizing dyslexics as disabled. We need to stop talking about disabilities and instead talk about differences in patterns of abilities, including strengths as well as weaknesses.

Tools for assessing learning in educational settings (not with high-stakes tests)

We now have the tools to create assessments for learning that make it possible to examine how it happens in the classroom – using, for example, dialogue among students and arguments or essays that students produce. In this way we can use actual learning activities to assess how students learn in environments such as classrooms or videogames.

Today tests are used mostly for sorting students, not improving their learning. A college or university can decide who they will accept based on standardized tests. With the new tools based on the skill scale, we can examine learning in the actual learning environments. For these assessments, we need five to seven items to produce reliable results comparable to the current high-stakes standardized tests. However, the new assessments add the feature that they examine learning as it occurs in the classroom or other learning environment – where the action is.

In this paper we will focus on computer-based assessment because it makes assessment inexpensive. We are creating a series of assessments that we call DiscoTests™, as in discourse tests. With the first versions of these tests students can enter text into a computer or speak to a computer. For example, here is a standard test item that a lot of science educators use. Figure 8 shows a balance beam with vinegar and baking soda on both sides. On one side they are separated, while on the other they are combined so that they produce a gas inside the container. The question then is, when that gas is produced, will the balance stay balanced or will one side move up or down?

Students give many answers, which we can code rigorously to analyse learning sequences. We can then use the sequences to create tools to help students move more effectively through their learning pathways. The figure

Multiple Choice Options

What will happen to the pan with the fizzing baking soda?

a. It will move up.
b. It will not move.
c. It will move down.
d. It will first move up and then down.
e. There is not enough information to answer the question.

Student's Spontaneous Answer.

What will happen to the pan with the fizzing baking soda?

"The pan with the baking soda inside the jar will move up because when vinegar and baking soda are mixed together they make a gas that is lighter than air. So it goes up like a birthday balloon."

Figure 8. Vinegar and baking soda task.

shows both traditional multiple-choice items and a format where the student can produce his or her own answer. For example, one student said, 'The pan with the baking soda inside the jar will move up because when vinegar and baking soda are mixed together they make a gas that's lighter than air, so it goes up like a birthday balloon'. That answer is incorrect, but it shows lots of reasoning, interesting reasoning, reasoning that can be used to assess how students are thinking about the task and moving through a learning sequence.

With this kind of assessment we can address many questions. What concepts are the students working with? How do they understand the concepts? What are their lines of reasoning? How well do they explain their thinking? In addition, we can use the tests to guide the student's learning. For example, a student can answer a number of items, and then we can show them what kind of learning pattern they are showing, based on the analysis we have of learning sequences in this domain, and we can suggest to them activities that will move their learning forward.

With our methods, the first phase of research in any domain is to collect a large quantity of data from a wide range of students, first to get a description of what the common learning sequences are and then to guide students to improve their learning. For example, from the data base we can provide students with feedback into the learning process. With these kinds of assessments it is easy to provide this feedback, based on the data base in the content domain and the rubrics and learning sequences that come from those data. This is a major advantage of working with assessments based on what students actually do in the classroom.

Here is another example of a DiscoTest. We ask students questions about the energy in a bouncing ball. There are many difficulties for students in thinking about the nature of energy. For example, most physics curricula actually expect students to understand, around 9th grade, conservation of energy. From talking to physics teachers and looking at students' answers to questions about conservation of energy, it is clear that there is a mismatch. Learning sequences indicate that most 9th graders are not capable of using concepts of conservation of energy. The complex understanding requires a more sophisticated kind of thinking that they will not develop for several years.

Still we can ask questions about energy and characterize learning sequences and the effectiveness of one kind of learning support versus another. What is happening to the energy of a ball as it falls to the floor? One of the answers was: 'As it falls, some of the energy is released'. A next question is 'What is happening to the energy of a ball as it hits the floor?' A student says, 'Some of the energy is transferred to the floor and the other energy is staying with the ball as it rebounds upwards'. Next question: 'What's happening to the energy of the ball right after it hits the floor?' Answer: 'Good question! Some of the energy remains with the ball. Does it move the ball? I don't know'. So these are the kinds of answers we can get from talking to students or from asking them to answer questions on the computer. And they are the same kinds of questions that teachers and students talk about as they are seeking to understand energy in a bouncing ball.

Conclusion: a new kind of assessment based on cognitive science

In conclusion we have discovered a common scale for development and learning that makes it possible to assess students in their actual learning environments, such as classrooms. It is particularly easy and inexpensive if students can answer questions on a computer (writing or speaking). The scale was originally based on analyses of discontinuities in learning patterns with age, and eventually research showed that the same discontinuities appear as clusters and gaps in Rasch analysis of test performance.

With this set of tools based on a common scale and coding of content categories, we analyse diverse learning sequences, uncovering common sequences in school domains, such as learning to read and learning about energy concepts in physics. This toolkit can be used in any domain that students learn about. For example, we are working now with a school that teaches students about cultural history, and we are able to analyse learning sequences in understanding cultural differences and commonalities. Eventually we aim to create DiscoTests for at least a dozen common learning domains, making tools for teachers and students to create a feedback process where with computer facilitation they can receive feedback on what they are saying and understanding and how their arguments and explanations connect to their goals for their own learning. With these new assessment tools we will help students and teachers go shape their own learning.

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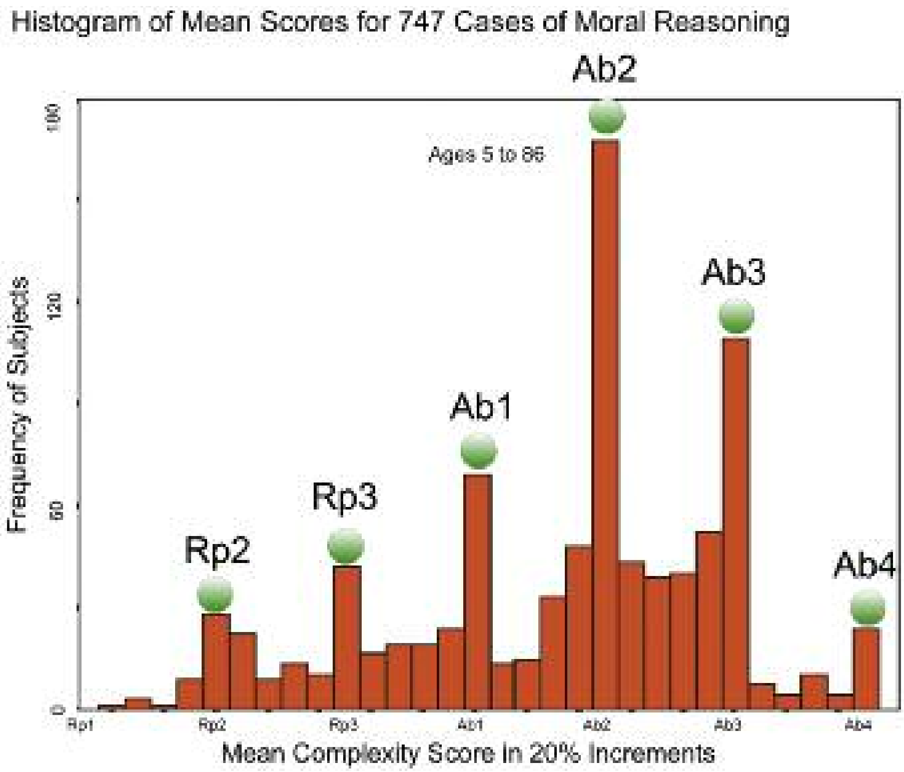

Figure 5. Distribution of levels of moral arguments based on Rasch analysis.