PREFACE

A goal of mine ever since becoming an educational researcher has been to help construct a sound theory to guide instructional practice. For far too long, educational practice has suffered because we have lacked firm instructional guidelines, which in my view should be based on sound psychological theory, which in turn should be based on sound neurological theory. In other words, teachers need to know how to teach and that "how-to-teach" should be based solidly on how people learn and how their brains function. As you will see in this book, my answer to the question of how people learn is that we all learn by spontaneously generating and testing ideas. Idea generating involves analogies and testing requires comparing predicted consequences with actual consequences. We learn this way because the brain is essentially an idea generating and testing machine. But there is more to it than this. The very process of generating and testing ideas results not only in the construction of ideas that work (i.e., the *learning* of useful declarative knowledge), but also in improved skill in learning (i.e., the *development* of improved procedural knowledge). Thus, to teach most effectively, teachers should allow their students to participate in the idea generation and testing process because doing so allows them to not only construct "connected" and useful declarative knowledge (where "connected" refers specifically to organized neuron hierarchies called outstars), but also to develop "learning-to-learn" skills (where "learning-to-learn" skills refer to general rules/guidelines that are likely located in the prefrontal cortex).

My interest in the neurological basis of instruction can be traced to a 1967 book written by my biologist father, the late Chester Lawson, titled *Brain Mechanisms and Human Learning* published by Houghton Mifflin. Although the book was written while I was still in high school, in subsequent years my father and I had many long conversations about brain structure and function, learning and development, and what it all meant for education. In fact, in that book, my father briefly outlined a theory of instruction that has subsequently been called the learning cycle. That instructional theory was put into practice by my father, by Robert Karplus and by others who worked on the Science Curriculum Improvement Study during the 1970s. My mathematician brother David Lawson has also boosted my interest in such issues. David worked on NASA's Space Station Program and is an expert in neural modeling. His help has been invaluable in sorting out the nuances of neural models and their educational implications.

Given this background, Chapter 1 begins by briefly exploring empiricism, innatism and constructivism as alternative explanations of learning. Empiricism claims learning results from the internalization of patterns that exist in the external world. Innatism claims that such patterns are internal in origin. Constructivism views learning as a process in which spontaneously generated ideas are tested through the derivation of expectations. The initial ideas are retained or rejected depending upon the extent that their expectations match future observations in an assumed-to-exist external world. Piaget's brand of constructivism with its theory of self-regulation is discussed as an explanation for development and learning. Piaget's self-regulation theory is based on biological analogies, largely on Waddington's theory of genetic assimilation. Genetic assimilation is described and used to explain psychological-level phenomena, specifically the development of proportional reasoning skill during adolescence. In spite of the value of self-regulation theory, an important theoretical weakness exists as the theory is based on biological analogies rather than on brain structure and function. Brain structure and function are discussed in Chapter 2 to hopefully eliminate this weakness.

Chapter 2 explains visual and auditory information processing in terms of basic brain structure and function. In brief, a hypothetico-predictive pattern is identified in both visual and auditory processing. Steven Grossberg's neural modeling principles of learning, perception, cognition, and motor control are presented as the basis for construction of a neurological model of sensory-motor problem solving. The pattern of problem solving is assumed to be universal, thus is sought in the higher-order shift from the child's use of an additive strategy to the adolescent's use of a proportions strategy to solve Suarez and Rhonheimer's Pouring Water Task. Neurological principles involved in this shift and in the psychological process of self-regulation are discussed, as are educational implications. The conclusion is drawn that reasoning is hypothetico-predictive in form because that is the way the brain works.

Many adolescents fail when attempting to solve descriptive concept construction tasks that include exemplars and non-exemplars of the concepts to be constructed. Chapter 3 describes an experiment that tested the hypothesis that failure is caused by lack of developmentally derived, hypothetico-predictive reasoning skill. To test this developmental hypothesis, individually administered training sessions presented a series of seven descriptive concept construction tasks to students (ages five to fourteen years). The sessions introduced the hypothetico-predictive reasoning pattern presumably needed to test task features. If the developmental hypothesis is correct, then the brief training should not be successful because developmental deficiencies in reasoning presumably cannot be remedied by brief training. Results revealed that none of the five and six-year-olds, approximately half of the seven-year-olds, and virtually all of the students eight years and older responded successfully to the brief training. Therefore, the results contradicted the developmental hypothesis, at least for students older than seven years. Previous research indicates that the brain's frontal lobes undergo a pronounced growth spurt from about four to seven years of age. In fact, performance of normal six-year-olds and adults with frontal lobe damage on tasks such as the Wisconsin Card Sorting Task, a task similar to the present descriptive concept construction tasks, has been found to be identical. Consequently, the present results support the hypothesis that the striking improvement in task performance found at age seven is linked to maturation of the frontal lobes. A neural network of the role the frontal lobes play in task performance is presented. The advance in reasoning that presumably results from effective operation of the frontal lobes is seen as a fundamental advance in intellectual development because it enables children to employ hypothetico-predictive reasoning to change their "minds" when confronted with contradictory evidence regarding features of perceptible objects, a reasoning pattern necessary for descriptive concept construction. Presumably, a further qualitative advance in intellectual development occurs when some students derive an analogous, but more advanced pattern of reasoning, and apply it to derive an effective problem-solving strategy to solve the descriptive concept construction tasks when training is not provided.

Chapter 4 describes an experiment testing the hypothesis that an early adolescent brain growth plateau and spurt influences the development of higher-level hypothetico-predictive reasoning skill and that the development of such reasoning skill influences one's ability to construct theoretical concepts. In theory, frontal lobe maturation during early adolescence allows for improvements in one's abilities to coordinate task-relevant information and inhibit task-irrelevant information, which along with both physical and social experience, influence the development of reasoning skill and one's ability to reject misconceptions and accept scientific conceptions. A sample of 210 students ages 13 to 16 years enrolled in four Korean secondary schools were administered four measures of frontal lobe activity, a test of reasoning skill, and a test of air-pressure concepts derived from kinetic-molecular theory. Fourteen lessons designed to teach the theoretical concepts were then taught. The concepts test was re-administered following instruction. As predicted, among the 13 and 14-year-olds, performance on the frontal lobe measures remained similar, or decreased. Performance then improved considerably among the 15 and 16-year-olds. Also as predicted, the measures of frontal lobe activity correlated highly with reasoning skill. In turn, prefrontal lobe function and reasoning skill predicted concept gains and posttest concept performance. A principal components analysis found two main components, which were interpreted as representing and inhibiting components. Theoretical concept construction was interpreted as a process involving both the representation of task-relevant information (i.e., constructing mental representations of new scientific concepts) and the inhibition of task-irrelevant information (i.e., the rejection of previously-acquired misconceptions).

Chapter 5 presents a model of creative and critical thinking in which people use analogical reasoning to link planes of thought and generate new ideas that are then tested by employing hypothetico-predictive reasoning. The chapter then extends the basic neural modeling principles introduced in Chapter 2 to provide a neural level explanation of why analogies play such a crucial role in science and why they greatly increase the rate of learning and can, in fact, make classroom learning and retention possible. In terms of memory, the key point is that lasting learning results when a match occurs between sensory input from new objects, events, or situations and past memory records of *similar* objects, events, or situations. When such a match occurs, an adaptive resonance is set up in which the synaptic strengths of neurons increase), thus a record of the new input is formed in longterm memory. Neuron systems called outstars and instars presumably enable this to occur. Analogies greatly facilitate learning and retention because they activate outstars (i.e., the cells that are sampling the to-be-learned pattern) and cause the neural activity to grow exponentially by forming feedback loops. This increased activity boosts synaptic strengths, thus causes storage and retention in long -term memory.

In Chapter 6, two hypotheses about theoretical concept construction, conceptual change and application are tested. College biology students classified at different levels of reasoning skill were first taught two theoretical concepts (molecular polarity and bonding) to explain the mixing of dye with water, but not with oil, when all three were shaken in a container. The students were then tested in a context in which they applied the concepts in an attempt to explain the gradual spread of blue dye in standing water. Next students were taught another theoretical concept (diffusion), with and without the use of physical analogies. They were retested to see which students acquired the concept of diffusion and which students changed from exclusive use of the polarity and bonding concepts (i.e., misconceptions) to the scientifically more appropriate use of the diffusion concept to explain the dye's gradual spread. As predicted, the experimental/analogy group scored significantly higher than the control group on a posttest question that required the definition of diffusion. Also as predicted, reasoning skill level was significantly related to a change from the application of the polarity and bonding concepts to the application of the diffusion concept to explain the dye's gradual spread. Thus, the results support the hypotheses that physical analogies are helpful in theoretical concept construction and that higher-order, hypothetico-predictive reasoning skill facilitates conceptual change and successful concept application.

Chapter 7 describes research aimed at testing the hypothesis that two general developmentally based levels of causal hypothesis-testing skill exist. The first hypothesized level (i.e., Level 4, which corresponds generally to Piaget's formal operational stage) presumably involves skill associated with testing causal hypotheses involving observable causal agents, while the second level (i.e., Level 5, which corresponds to a fifth, post-formal stage) presumably involves skill associated with testing causal hypotheses involving unobservable entities. To test this fifth-stage hypothesis, a hypothesis-testing skill test was developed and administered to a large sample of college students both at the start and at the end of a biology course in which several hypotheses at both causal levels were generated and tested. The predicted positive relationship between causal hypothesis-testing skill and performance on a transfer problem involving the test of a causal hypothesis involving unobservable entities was found. The predicted positive relationship between causal hypothesis-testing skill and course performance was also found.

Scientific concepts can be classified as descriptive (e.g., concepts such as predator and organism with directly observable exemplars) or theoretical (e.g., concepts such as atom and gene without directly observable exemplars). Understanding descriptive and theoretical concepts has been linked to students' developmental stages, presumably because the procedural knowledge structures (i.e., reasoning patterns) that define developmental stages are needed for concept construction. Chapter 8 describes research that extends prior theory and research by postulating the existence of an intermediate class of concepts called hypothetical (e.g., concepts such as subduction and evolution with exemplars that can not in practice be observed due to limits on the normal observational time frame). To test the hypothesis that three kinds of scientific concepts exist, we constructed and administered a test of the concepts introduced in a college biology course. As predicted, descriptive concept questions were significantly easier than hypothetical concept questions, than were theoretical concept questions. Further, because concept construction presumably depends in part on reasoning skill, students at differing reasoning skill levels (Levels 3, 4 and 5, where Level 5 is conceptualized as 'post-formal' in which hypotheses involving unseen entities can be tested) were predicted to vary in the extent to which they succeeded on the concepts test. As predicted, a significant relationship ($p < 0.001$) was found between conceptual knowledge and reasoning skill level. This result replicates previous research, therefore provides additional support for the hypothesis that procedural knowledge skills associated with intellectual development play an important role in declarative knowledge acquisition, i.e., in concept construction. The result also supports the hypothesis that intellectual development continues beyond the 'formal' stage during the college years, at least for some students.

Chapter 9 considers the nature of scientific discovery. In 1610, Galileo Galilei discovered Jupiter's moons with the aid of a new more powerful telescope of his invention. Analysis of his report reveals that his discovery involved the use of at least three cycles of hypothetico-predictive reasoning. Galileo first used hypothetico-predictive reasoning to generate and reject a fixed-star hypothesis. He then generated and rejected an *ad hoc* astronomers-made-a-mistake hypothesis. Finally, he generated, tested, and accepted a moon hypothesis. Galileo's reasoning is modeled in terms of Piaget's self-regulation theory, Grossberg's theory of neurological activity, Levine & Prueitt's neural network model and Kosslyn & Koenig's model of visual processing. Given that hypothetico-predictive reasoning has played a role in other important scientific discoveries, the question is asked whether it plays a role in *all* scientific discoveries. In other words, is hypothetico-predictive reasoning the essence of *the* scientific method? Possible alternative scientific methods, such as Baconian induction and combinatorial analysis, are explored and rejected as viable alternatives. The "logic" of scientific discovery and educational implications are discussed.

Instructional attempts to provoke preservice science teachers to reject nature-of-science (NOS) misconceptions and construct more appropriate NOS conceptions have been successful only for some. Chapter 10 describes a study that asked, why do some preservice teachers make substantial NOS gains, while others do not? Support was found for the hypothesis that making NOS gains as a consequence of instruction requires prior development of Stage 5 reasoning skill, which some preservice teachers lack. In theory, science is an enterprise in which scientists often use Stage 5 reasoning to test alternative hypotheses regarding unobservable theoretical entities. Thus, anyone lacking Stage 5 reasoning skill should be unable to assimilate this aspect of the nature of science and should be unable to reject previously constructed NOS misconceptions as a consequence of relatively brief instruction. As predicted, the study found the predicted positive relationship between reasoning skill (Levels 3, 4 and 5) and NOS

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