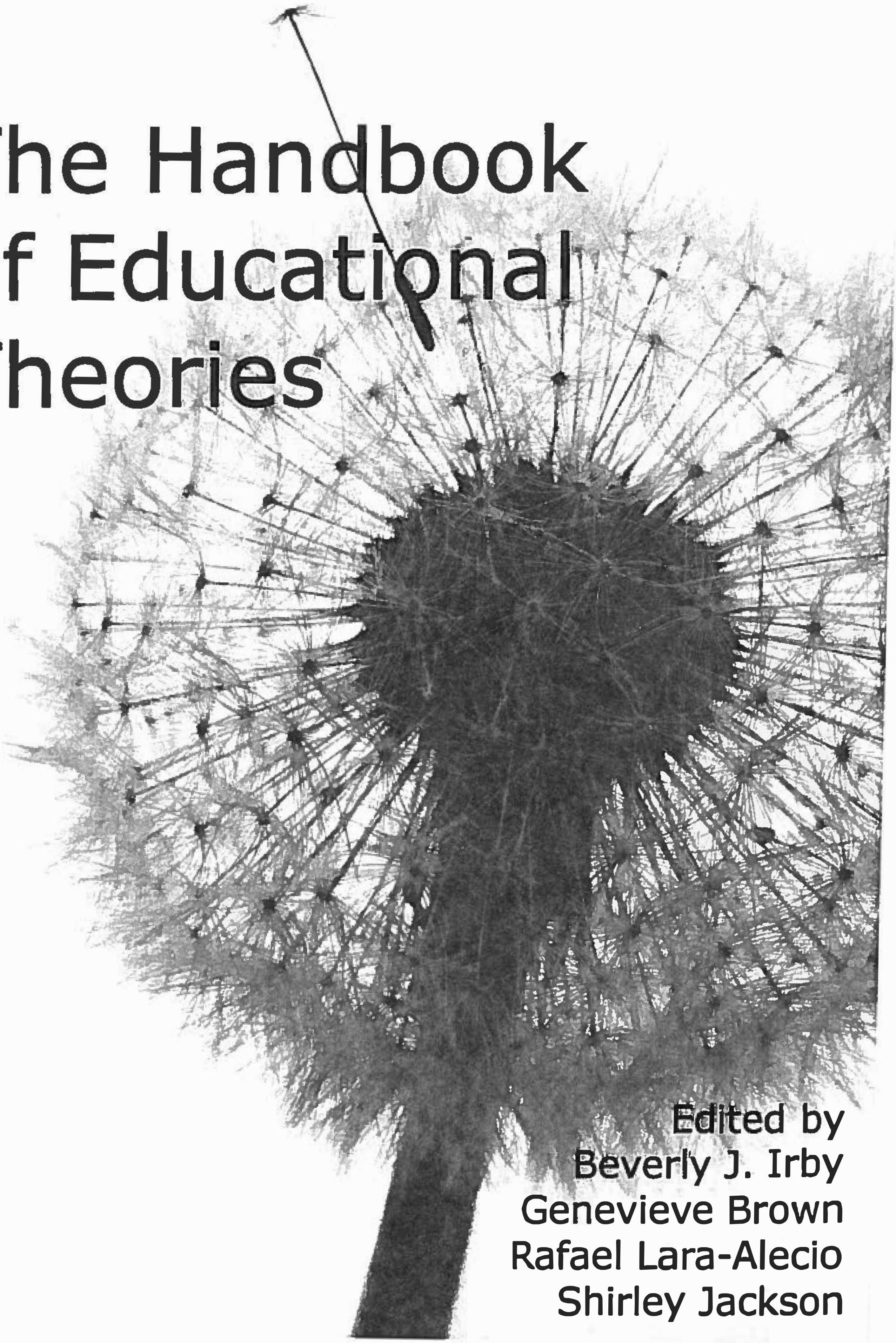
The Handbook of Educational Theories



Edited by
Beverly J. Irby
Genevieve Brown
Rafael Lara-Alecio
Shirley Jackson

CHAPTER 64

Individual Differences in the Ability to Process Information

W. Joel Schneider
Illinois State University

Kevin S. McGrew
The Institute of Applied Psychometrics

Cognitive performance models attempt to integrate the findings of two grand traditions of scientific psychology: the experimental study of information processing and the measurement of individual differences in cognitive abilities. One tradition is concerned with how the mind typically works while the other describes how minds differ. To use a statistical metaphor and only a mild exaggeration, one is about the mean, the other the standard deviation. One tradition draws mostly from experimental findings from academic labs whereas the other draws primarily from population-wide psychometric studies of cognitive abilities thought to be important for success in academic, occupational, and other life settings.

Information processing theories describe the interplay of perception, attention, memory, and reasoning as people learn information and solve problems. Although information processing theorists do care about the brain, their emphasis is less on brain function location and more how the brain processes information during the learning and problem-solving process. Information processing theorists acknowledge the fact that not all people process information equally well or even in the same way. However, the emphasis is less on understanding the unique challenges of individuals and more on understanding what we have in common, the species-typical functions of the mind.

In contrast, cognitive ability theorists focus on identifying meaningful differences in people's measured discrete abilities. Whereas information processing theorists describe *how* different kinds of cognitive functions work, cognitive ability researchers measure *how well* those functions work in an individual. Cognitive ability researchers focus on establishing empirical relations between specific cognitive abilities and important life outcomes such as academic and occupational success. In general, cognitive ability theorists do not necessarily need to understand how problems are solved as they are mainly concerned about whether a person can solve it, and how individuals differ in their relative proficiency. By analogy, although a racecar driver might be interested how engineer describes how a particular car works, the driver's primary concern is knowing how well the car performs under various conditions during a race.

Cognitive performance models are attempts to integrate findings from both traditions in cognitive psychology. The goal is to assist educators, clinicians, and caregivers in providing their clients with (a) a rich informative understanding of their cognitive strengths and weaknesses and (b) a realistic and practical plan for overcoming their academic and occupational difficulties. This is not always easy as the development of cognitive performance models are still in their infancy. This introduction to cognitive performance models provides a broad overview of the main features of cognitive performance models. Space does not allow a detailed comparison of different models. A more thorough review can be found in Hunt (2011) and Floyd and Kranzler (2012).

The Handbook of Educational Theories, pp 767–782

Information Processing

To process something is to alter it so it becomes more useful. A carrot is not useful until your digestive system breaks it down to usable components and discards what is not useful. Likewise, the raw information your senses gather is not useful to you until your brain breaks it down into elementary parts and then reassembles it in ways that make it understandable and usable. That is, *perception* is when the brain makes sense of sensation. Much of what occurs in perception is automatic and occurs without your conscious knowledge. When you are aware of what your brain is perceiving, it is called *consciousness*. The processes that govern which perceptions arise in consciousness are called *attention*. Sometimes important information comes to our attention but we do not need it immediately. Storing and retrieving information for later use is called *memory*. Combining information in memory in ways that solve new problems is called *reasoning*. Information processing theories attempt to explain how information is perceived, attended to, stored in memory, retrieved from memory, and reasoned with to solve problems.

Sensation and the Problem of Too Much Information

Much of what information processing theories need to explain is the fact that our senses gather much more information than we can perceive at one time. From the myriad of information our brain perceives at any moment, only a fraction can be the focus of attention. That is, at every moment your senses are relaying to your brain an extraordinary amount of information about the external world. Some of this sensory information is selected for processing to see if it might be useful. Most perceived information is not particularly useful and is forgotten almost immediately as it is not attended to consciously. For example, as you read this chapter, you are unlikely to have noticed the sensation of the fabric of your shirt on your shoulder, the sound of your own breathing, the particular shade of white used for the paper in this book, or the smell of the room. Even when you are not eating, messages about the taste of your own saliva are continuously being sent to your brain. Fortunately, we are able to ignore these signals until more interesting and informative events occur.

Your brain, whether you are aware of it or not, is constantly monitoring sensory information for changes that might be important. When a sensation on your brain's watch list is detected (e.g., the smell of toxic fumes, a sharp pain of an injury, the cry of a distressed child, the sight of large objects rushing towards you), the focus of your attention is drawn to it immediately and automatically. When conversing in a crowded room, you typically ignore all other conversations. However, if anyone in the room says your name, even in passing, you often hear it and orient to that person (for obvious reasons, this observation is known as the "Cocktail Party Effect."). Thus, even the sound of your own name is on your brain's watch list.

Perception With Feature Detectors

Your brain adopts a divide-and conquer-strategy as it is bombarded with a constant stream of information. If you ever had an instructor assign more reading than one person could possibly cover in the time provided, you may have deployed a strategy with a group of students in the class. Each group member would read part of the assigned reading and then summarize it for the rest of the group. This works well unless there are weak links in specific group members' summaries. This group strategy can backfire if the exam requires you to integrate information across all readings. The brain has similar integration problems.

The brain takes raw sensory information and different specialized groups of neurons called *feature detectors* respond to different characteristics of the information (Treisman, 1998). For example, when you see the capital letter "A", one feature detector says, "Somewhere (and I have no idea where, that is another detector's job!) there is a horizontal line." Another detector, the 70° line detector, says, "I detect a line at an orientation of 70°." The 110° line detector also reports that there is a line at a 110° angle. The other line detectors that are responsible for detecting lines at different orientations (e.g., 10°, 20°, 30°, ... 160°, 170°) all say "I have nothing to report." Other detectors are insensitive to the orientation of the lines but instead report when lines are joined at certain angles. In this case, the top of the A makes the 50° angle detector report the presence of a 50° angle. Other detectors that are insensitive to the orientations and angles of the lines specify where the lines are in the visual field. Other detectors report on the presence or absence of other visual features such as curves, colors, textures, and movement.

Much of the perceptual information the brain constantly processes remains unconnected until a stimulus becomes the object of focus in attention (Treisman, 1998). That is, the legions of feature detectors do not talk among themselves much (although some talk to higher-order detectors that detect complex features). However, at the moment of consciousness, the various features of the object are recognized as belonging to the same object. The combination of features is compared with templates stored in long-term memory and if a match is found the object is recognized, in this case as the letter "A."

Feature detectors are not entirely passive. They respond to experience and adapt to frequently encountered patterns. They also can be primed to respond to expected stimuli. That is, the brain is constantly forecasting what is likely to happen in the next few seconds and attempts to match incoming stimuli with expectations (Hawkins, 2004). Information that is very discrepant with expectations tends to capture one's attention.

Attention

Attention is often controlled by automatic processes but it is also deployed flexibly in goal-directed behavior. Much of what is perceived is in line with expectations and triggers well-rehearsed action schemas (Norman & Shallice, 1980). For example, most people can drive to work without thinking very much about what they are doing and few attentional resources are consumed while driving familiar routes. Many of us have had the experience of intending to drive somewhere else on the weekend but find that we have instead driven "on autopilot" and taken a wrong turn or two as if we were driving to work. However, sometimes, in the middle of performing a well-rehearsed action sequence, something unanticipated occurs and we immediately orient to this new event or stimulus. For example, if while driving to work in the usual way, a pedestrian steps into the street heedless of oncoming traffic, we immediately focus and taken action to avoid hitting the person. This orienting response is made possible by the fact that the brain is automatically feeding predictions (typically only milliseconds in the future) to the perceptual systems and "primes" them to perceive particular stimuli. These predictions are typically accurate within a reasonable range. For example, when a friend turns her head towards us, the perceptual system anticipates what her face is going to look like and is typically not surprised. However, if her lips have fluorescent green lipstick (and this friend is not typically adventurous with her makeup), the perception of the color violates our expectations and causes an automatic orienting response. We cannot help but notice the unusual color. However, if the color of her lipstick is within the normal range for that friend, we are unlikely to notice it at all. Although students' attention is naturally captured by innumerable distractions (e.g., the sound of their peers' off-task merriment), good students learn to disengage their attention from task irrelevant distractions and tune them out in order to complete their coursework. Much of what we label "attention" is concerned with the checking our natural impulses to attend to inherently interesting things (competition, social drama, romance, danger, and so forth) and directing our attention toward less interesting things that have a larger long-term payoff (homework, performing the duties of one's job, minding children, and so forth). This function of attention is often called *inhibition*, as the purpose is to inhibit responding to task irrelevant information that may capture or hijack our attention.

The ability to consciously direct the focus of attention in the service of short- and long-term goals has been given many names. We prefer the term *attentional control* but near synonyms include cognitive control, executive control, effortful control, controlled executive attention, executive functions, and central executive functioning, among many others (it seems like almost every combination and permutation of *executive, control, attention,* and *function* has been used by one scholar or another). It is likely that there is not just one attentional control mechanism but several interrelated attentional control mechanisms.

The ability to monitor multiple streams of information simultaneously is typically called *divided attention* (e.g., conversing while driving). The ability to focus attention to one stream of information and ignore competing signals is called *selective attention* (e.g., listening to a teacher while other students are giggling). *Attentional fluency* has to do with the speed, smoothness, and ease with which one is able to engage and disengage the focus of attention without mental lapses while performing a series of simple tasks (e.g., performing a series of easy calculations) or alternating between tasks (e.g., taking notes while listening to a lecture). This is also referred to as task-switching ability, alternating attention, cognitive fluency, mental agility, and a host of other similar terms.

Sustained attention is a kind of mental stamina, the ability to control and focus attention over long periods of time. One kind of sustained attention, *vigilance*, is the ability to monitor an uninteresting stimulus over long periods of time without lapses (e.g., watching the output of a factor assembly line to detect quality control problems). A vigilant person can resist boredom and stay alert. *Concentration* typically refers to a different kind of sustained attention, the ability to engage in difficult, attention-demanding tasks for a long time without lapses (e.g., playing in chess tournaments).

It is likely that some people are better at these various types of kinds of attention than others. However, it is also clear that most complex activities (such as reading Shakespeare and writing geometry proofs) require that attentional control processes act in concert with each other. A person's excellent selective attention abilities are of little help if the person cannot sustain attention long enough to master a new skill. Thus, it is typically a person's overall synchronized attentional abilities that determine success in complex domains.

The Limits of Attention

It is impossible to attend to many things simultaneously. Attention can be compared to a zoom lens or an adjustable spotlight (Eriksen & St James, 1986). When the light is narrowly focused, a small area is brightly illuminated. When the light is dispersed, a wide area is illuminated but not as brightly. Most spotlights can provide a compromise between these extremes by illuminating a moderately sized area but the center is more brightly illuminated than the periphery. If we wish to simultaneously illuminate two areas brightly, we can move the spotlight back and forth quickly. So it is with attention.

Consider the task demands air traffic controllers face as they guide airplanes safely to their destinations. They can focus their attention very narrowly on a single plane to insure accurate awareness of the position of the specific plane. This accuracy, of course, comes at the expense of awareness of other planes in the immediate vicinity. Air traffic controllers can attempt to be aware of all of the planes concurrently but this grand view comes at the expense of accurate awareness for any particular plane. What they cannot do is be fully aware of all planes concurrently and be completely accurate with regard to any individual plane. Therefore, they compromise by quickly switching their awareness back and forth between planes. They can also quickly zoom their attention in and out between a narrow focus on one plane and a broader view of all the planes.

Our ability to focus attention is extremely fragile. Almost any brain injury affects attention. Although Attention-Deficit/Hyperactivity Disorder is the only mental disorder to have the word "attention" in its name, almost all of the major mental disorders (e.g., mood disorders, anxiety disorders, psychotic disorders, dissociative disorders) involve attention deficits of one kind or another. Even moment to moment, our ability to pay attention fluctuates considerably. Contrast this with the ability to hear. Tired or energized, sick or healthy, hungry or well fed, distressed or content, intoxicated or sober, our ability to hear remains fairly consistent. On the other hand, when we are even a little bit tired, sick, hungry, distressed, or intoxicated, our ability to concentrate is much reduced.

MEMORY

The process of storing and retrieving information is not the same for all types of information (e.g., visual/spatial versus acoustic/verbal). Cognitive psychologists have developed numerous fine-grained distinctions when discussing the various types of memory. In this discussion we will highlight the distinction between short-term memory and long-term memory. Because short-term memory has a special relationship with the active processes of attention, it is often referred to as *working memory* (Baddeley, 1986).

Working Memory

Descriptions of working memory often invoke a metaphor of a temporary storage space for information. Although no metaphor is perfect, this one is misleading because it suggests that the information just sits there, inert. A more helpful comparison is that working memory is similar to the RAM in your computer (in that it is a form of memory that is held temporarily in a state that can be manipulated very quickly). However, if you are not a computer geek, that metaphor might be confusing. In many ways, a more illuminating (if likely less accurate) comparison is that working memory is like the screen on your computer. It displays a very limited amount of information at a time, and counter-intuitively, this is what makes it so useful. If all the gigabytes of data on your computer could be displayed simultaneously on the screen, it would be impossible to sort through it all to select the specific bits of information relevant to your current task. What makes the screen so useful is that it is updated constantly to display relevant information only. However, it is not just a dumb display. The screen is a point of contact between you and the computer. Via the graphical user interface, you manipulate images on the screen to control the computer to do what you want to accomplish your task. On the screen you combine and manipulate information.

Working memory is like an active updatable screen for your conscious awareness. By controlling the focus of your attention, you can activate relevant long-term memories, compare them to incoming sensory perceptions, and manipulate information internally to make it more useful. A classic example of this is performing arithmetic in your head, such as multiplying 9 by 14. You probably do not have the product of 9 and 14 stored in long-term memory. However, you most likely do have basic math facts stored in memory and the procedure of multiplying large numbers in memory. If you were to solve this problem in your head, it might go like this:

Activate (i.e., retrieve) memory of the procedure for multiplying large numbers

Recall the first step: Multiply the units digits

Implement: 9 Ĭ 4 = 36

Recall the next step: Multiply the bottom number's units by the top number's tens digit

Implement: 9 Ĭ 1 = 9

Recall the next step: Place the results of the second step under the results of the first step and shift the result one digit to the left.

Implement: $\begin{array}{r}36\\9\end{array}$

Recall the next step: Add the columns of numbers, starting at the right.

Implement: $\begin{array}{r}36\\+9\\\hline 126\end{array}$

Notice that once the answer of 126 is found, you no longer need to remember the intermediate steps (e.g., 9 × 4 = 36). Once it is deemed unnecessary, this information can be forgotten or dumped from your memory. Information in working memory is very vulnerable to interference. Unless constantly maintained via conscious rehearsal, the information is likely to be forgotten with 10 to 30 seconds. If new information captures attention, the previous contents of working memory are likely to be forgotten much more quickly. If the memory is kept active long enough or if it is processed deeply or vividly, it is possible that it will stored in more robust coding system. That is, it will enter long-term memory.

Long-Term Memory

Whereas working memory holds recently activated information for a matter of mere seconds, long-term memory lasts for minutes, hours, days, weeks, years, or even a lifetime. There are many different kinds of long-term memory. *Explicit memory* (or *declarative memory*) can be articulated verbally. Two types are explicit memory are *episodic memory*, the memory of particular events (e.g., your first kiss) and *semantic memory*, the memory of particular facts (e.g., that Antarctica is an icy continent that surrounds the South Pole). Implicit memory is difficult to articulate verbally but is expressed indirectly via behavior. Two types of implicit memory are conditioned responses (e.g., after recently being bitten by a dog, you feel jumpy at the sight of any dog, even one that is calm, far away, and on a leash) and *procedural memory*, the memory of how to implement a sequence of motor actions skillfully (e.g., riding a bicycle). *Retrospective memory* is about past events whereas *prospective memory* is about remembering to implement plans in the future (e.g., go to the dentist at 2 P.M. today).

Information in long-term memory is processed in various stages. Information is encoded by perceptual functions of the brain. Different aspects of an object are bound together and elaborated upon when attended to in consciousness. The object is compared and contrasted with previously encountered objects stored in memory. The memory of the object is abstracted and consolidated (the essential features are analyzed and stored in a durable code that can be retrieved later). When needed, the memory of the object can be retrieved. This process is not like the playback of a video. Rather, the various features of the object have been stored separately and must be reassembled in working memory. Thus, remembering is an act of reconstruction rather than an act of reproduction. Of course, memory errors can occur at any of these stages.

Individual Differences in Cognitive Abilities

People have always known that not everyone has the same level or pattern of cognitive abilities. When psychologists conducted the first scientific studies of cognitive abilities, one of the first nonobvious findings to emerge was that all cognitive abilities were positively correlated. That is, if we know some of an individual's cognitive abilities, we can forecast the unmeasured abilities with better-than-chance accuracy. If a person has an excellent vocabulary and good logical reasoning, it is likely that the person also has above average spatial reasoning, is more creative than average, and has a faster reaction time than average. Some of these predictions might turn out to be false but such predictions will turn out to be correct more often than not. Some interpret the finding that cognitive abilities are positively correlated as evidence that there is something called *general intelligence*.

IQ tests are designed to measure general intelligence. They test a wide variety of cognitive abilities and then average the scores to estimate what the tests measure in common (i.e., general intelligence). A person with high general intelligence is likely to perform above average on most cognitively demanding activities. A person with low general intelligence is likely to have difficulty in general in almost any domain requiring learning, judgment, or reasoning.

Not all researchers believe that general intelligence is a helpful explanation for the positive correlations in ability. The issue is hotly debated and the evidence for either side of the debate is less than compelling. The point of agreement, however, is that general intelligence is not the only ability that exists and it is not the only ability that matters.

All researchers accept that cognitive abilities tend to be positively correlated. They also know that some cognitive abilities are more correlated than others. That is, certain cognitive abilities tend to cluster together in meaningful ways. For example, if a person has difficulty with language comprehension, a prediction that the person also has deficits in general knowledge (i.e., knows few facts that his or her culture deems important) is more likely to be accurate than the prediction that the person has difficulty concentrating. Clusters of highly similarly and correlated specific abilities are often called *broad abilities*.

Many lists of broad abilities have been proposed by psychologists over the last century. In the last 20 years, researchers have come to a tentative consensus about the broad abilities that must be included in any successful theory of cognitive abilities. The field is not unanimous but it is now more unified than it has ever been in the past. The unification occurred when Carroll (1993) produced a convincing demonstration that one of the many competing models of cognitive abilities was largely correct, the Horn-Cattell model. Carroll's demonstration was accomplished by re-analyzing hundreds of datasets that measured the relations between various cognitive abilities. The datasets he analyzed were collected over the span of many decades and consisted of all of the relevant studies Carroll could identify at that time. Carroll made a number of modifications to the Horn-Cattell model. Some of these were minor but a major difference is that Carroll believed that general intelligence is a real ability whereas Horn and Cattell believed that it was an unnecessary concept and that there were better explanations of the positive correlations between cognitive abilities. Despite their difference of opinion, Horn and Carroll agreed to have their two theories yoked together under a common framework. The integration, accomplished primarily by McGrew (1997, 2005, 2009), is known as the Cattell-Horn-Carroll theory of cognitive abilities (CHC theory). The most recent summary of CHC theory is that by Schneider and McGrew (2012).

Cattell's Gf-Gc Theory

After conducting many studies on general intelligence and reading many more studies conducted by others, Raymond Cattell (1943) noticed an interesting pattern of results. Certain abilities tended to be affected by brain injuries more than others. These abilities were also the ones most likely to decline in old age. Furthermore, these abilities tended to be measured by tests that required reasoning and did not require much previously learned knowledge. Indeed, some of them were useful for measuring cognitive abilities in cross-cultural research.

Knowledge tests measure skills and information that are highly valued by one's culture. For this reason, they are not useful for cross-cultural research. Cattell noticed that such knowledge tended to remain relatively intact after brain injuries and did not decline much as people age.

Cattell hypothesized that the reason for these findings was that there was not one general intelligence but two general intelligences: fluid intelligence and crystallized intelligence. Fluid intelligence was thought to represent the natural raw talent and overall biological integrity of the brain. Crystallized intelligence was hypothesized to be acquired via investment of fluid intelligence during the learning process. The abbreviations for these abilities (Gf and Gc, respectively) reflect that they are general abilities. That is, they are not tied to any particular sensory system, academic subject, or occupational skill. They influence a very wide set of skills.

Fluid Intelligence (Gf)

Fluid intelligence is the ability to solve unfamiliar problems using logical reasoning. It requires the effortful control of attention to understand what the problem is and to work toward a logically sound answer. People with high fluid intelligence are able to figure out solutions to problems with very little instruction. Once they have found a good solution to a problem, they are able to see how it might apply to other similar problems. People with low fluid intelligence typically need hands-on, structured instruction to solve unfamiliar problems. Once they have mastered a certain skill or solution to a problem, they may have trouble seeing how it might apply in other situations. That is, their newfound knowledge does not generalize easily to other situations.

Fluid intelligence appears to have a special relationship with working memory capacity. Working memory is the site where difficult problems are solved for the first time. It is possible to have high fluid intelligence with only middling working memory capacity and it is possible to have low fluid intelligence with excellent working memory capacity. However, people with excellent short-term memory capacity and good control of their attention seem appear to have a significant advantage in solving novel problems.

Crystallized Intelligence (Gc)

Crystallized intelligence is acquired knowledge. When people solve important problems for the first time, they typically remember how they did it. The second time the problem is encountered , the solution is retrieved from memory rather than recreated anew using fluid intelligence. However, much of what constitutes crystallized intelligence is not the memory of solutions we personally have generated but the acquisition of the cumulative wisdom of those who have gone before us. That is, we are the intellectual heirs of all of the savants and geniuses throughout history. What they achieved with fluid intelligence adds to our crystallized intelligence. This is why even an average engineer can design machines that would have astounded Galileo, or even Newton. It is why ordinary high school students can use algebra to solve problems that baffled the great Greek mathematicians (who, for lack of a place-holding zero, could multiply large numbers only very clumsily).

Crystallized intelligence, broadly speaking, consists of one's understanding of the richness and complexity of one's native language and the general knowledge that members of one's culture consider important. Of all the broad abilities, crystallized intelligence is by far the best single predictor of academic and occupational success. A person with a rich vocabulary can communicate more clearly and precisely than a person with an impoverished vocabulary. A person with a nuanced understanding of language can understand and communicate complex and subtle ideas better than a person with only a rudimentary grasp of language. Each bit of knowledge can be considered a tool for solving new problems. Each fact learned enriches the interconnected network of associations in a person's memory. Even seemingly useless knowledge often has hidden virtues. For example, few adults know who Gaius and Tiberius Gracchus were (Don't feel bad if you do not!). However, people who know the story of how they tried and failed to reform the Roman Republic are probably able to understand local and national politics far better than equally bright people who do not. It is not the case that ignorance of the Gracchi brothers dooms anyone to folly. It is the case that a well-articulated story from history can serve as a template for understanding similar events in the present.

Horn's Expansion of Gf-Gc Theory

Cattell's student and collaborator, John Horn, conducted the first direct test of his mentor's theory. Horn's (1965) dissertation confirmed some of Cattell's ideas about fluid and crystallized intelligence, but it also suggested that the theory needed elaboration. Over the course of his career, Horn refined Gf-Gc theory several times, sometimes in collaboration with Cattell, sometimes not, and sometimes with other cognitive ability scholars (Cattell, 1987; Horn & Blankson, 2005; Horn & Cattell, 1966). In honor of the original theory, the model retained the name of Gf and Gc, but it identified a number of other broad abilities that Horn believed were just as important as Gf and Gc. Horn and Cattell identified abilities that were linked to specific perceptual systems. Although these abilities are not as broad as Gf and Gc, they are still very broad and thus are abbreviated with G, which stands for "general." They also distinguished between various memory-related abilities and abilities linked to the speed of information processing. In this discussion, the names and abbreviations are from modern CHC theory (see Schneider & McGrew, 2012) instead of the slightly different terms and abbreviations used by Horn.

Domain-Specific Abilities

Visual-Spatial Ability (Gv)

General visual-spatial ability consists of many different specific perceptual capabilities that are similar in that they all deal with complex processing of visual information (although touch and hearing sometimes play a role in visualizing objects and locating them in space). Rather, visual-spatial ability is not visual acuity—people with impaired vision often have excellent visual-spatial skills. Visual-spatial ability has to do with perceiving complex visual patterns, visualizing objects as they might appear from different angles, and being aware of where things are located in space, including oneself. Visual-spatial ability is in the "minds eye."

People with high levels of Gv are able to use their visual imagination to see more than what is before them. If they see part of an object, they imagine what the rest of it looks like. If they see it from one angle, they imagine how it would look from another, mentally rotating it in space. If they see a tool, they generate a moving image to simulate its operation. If they see a complex image, they mentally break it down to smaller, more basic parts (lines, angles, curves, basic 2D and 3D shapes such as triangles, rectangles, ellipses, spheres, cubes, and cylinders) and then mentally reassemble the parts to form a three-dimensional internal mental model. Their mental models are accurate which allows them to answer "what-if" questions (What if this stick is used like a lever to pry this stuck drawer loose? Will it pry the struck drawer loose or will it break the stick? Will it damage the drawer?). These mental simulations (movies in the mind's eye) allow people to experiment with various courses of action rapidly and inexpensively in mental space so that fewer trial-and-error solutions need be attempted in physical space and time.

People with low levels of Gv, are less able to perform mental simulations in working memory and thus have difficulty knowing how something will look until it is physically moved. While working with objects, they must rely more on trial-and-error problem-solving methods. While navigating, they must rely on memory of landmarks instead of using a mental map of their location in space.

Auditory Processing (Ga)

Auditory processing is the ability to make use of nonverbal information in sound. It is the ability to distinguish between sounds by their volume, pitch, and tonal quality. It is the ability to hear the melody in music and the rise and fall of pitch in ordinary language. It is the ability to hear the difference between phonemes in speech (e.g., hearing the difference between "pat" and "bat"). Although auditory processing is a precursor ability for oral language comprehension, it is not language comprehension itself (that is Gc). It is not sensory acuity, either. As vision is to visualization, hearing is to auditory processing. Auditory processing is what the brain does with sound after it has been detected, sometimes long after it has been heard. Thus even people who have suffered hearing loss, like Beethoven at the end of his life, can use their Ga abilities to simulate new sounds in their heads.

People with high Ga, if they like music, have a richer appreciation of the sounds in music because their perception of sound is more nuanced. They hear variations in volume, pitch, rhythm, and sound texture that people with low Ga cannot distinguish. People with high Ga have an advantage in learning foreign languages because they can hear subtle variations in phonemes (units of speech sounds) that differ across languages. People with low Ga abilities have difficulty pronouncing words with anything other than the phonemes from their native language. The ability to hear individual speech sounds distinctly gives people with high Ga an edge in learning to read alphabetic writing systems. People with low Ga are at risk of developing phonological dyslexia because it is hard for them to understand how individual letters correspond to individual phonemes, especially in long words. This puts them at a disadvantage in sounding out unfamiliar words.

Other Abilities Related to Specific Sensory Modalities and Motor Functions

It is likely that something analogous to Gv and Ga exists for each of the major senses. We know very little about these abilities because they are difficult to measure and few researchers have devoted sustained efforts to understand them.

Haptic processing (Gh) refers to higher-order cognitive related to touch (e.g., visualizing and naming objects by touch alone). Kinesthetic processing (Gk) refers to higher-order cognition related to proprioception (awareness of limb position and movement). Presumably this is what dancers and athletes use to employ to achieve artistry in their profession. It may be what people use to imitate the movements of others accurately. It may also refer to what is known as dynamic touch (Turvey, 1996), which is the ability to infer characteristic of objects by moving them (e.g., hefting a hammer before using it) and hitting them (e.g., tapping a piñata with a bat before swinging at it). Olfactory processing (Go) has to do with higher-order cognition related to smell (e.g, being about to identify plants, food, and other objects from odors, knowing when fruit is ripe or rotten from smell, even the ability to diagnose certain medical conditions from particular odors). Gustatory processing (Gg?) would be higher-order cognition related to taste and presumably would be analogous to olfactory processing.

Analogous to domain-specific abilities related to perception, there may be higher-order cognitive abilities related to motor functions. Psychomotor abilities (Gp) would include conscious control of muscle movement (e.g., aiming a ball at a target, playing the piano), the conscious control of body movement to maintain balance, and other movements that require higher order cognition.

Memory-Related Abilities

There are many different kinds of memory but the primary distinction in CHC theory is between short and long-term memory.

Short-Term Memory (Gsm)

The working memory system encompasses temporary storage and manipulation of information via attentional control (Unsworth & Engle, 2007). In terms of individual differences, it is possible to measure two distinct abilities. First, people differ in how much information they can store in working memory if few demands on attention are made. The classic measures of this ability are memory span tests in which people must repeat back increasingly long sequences of random numbers, letters, or words. Working memory capacity has to do with how well people can maintain information in working memory if they must simultaneously deploy attentional resources to manipulate information. For example, if a string of letters is presented in random order, having to repeat them back in alphabetical order requires more attentional resources than repeating the letters back in the same order as they are heard. The letters must be maintained in memory, usually by subvocal rehearsal (saying them over and over in one's head), and at the same time attentional resources are used to sort the letters.

People with high Gsm are able to engage in multistep problem-solving without getting lost in the process and making careless errors. They are able control the focus of attention adaptively and flexibly, depending on the needs of the moment. People with low Gsm are likely to make careless errors when performing attention demanding tasks. They are highly vulnerable to distraction because once there is a small lapse of attention, the information they were using in working memory is likely to be lost. This weakness results in difficulties in planning, implementing planned actions, and following through on plans until they are completed successfully. Sometimes people with low Gsm find planning effortful and unpleasant. The payoff for planning is lessened because their plans are less likely to be carried out successfully. Thus, people with low

Gsm often prefer to "take life as it comes" and live spontaneously. Of course, other factors unrelated to Gsm, such as personality preferences, can play an even larger role in influencing how much a person prefers to plan.

Long-Term Memory

An important distinction in long-term memory abilities is between the ability to learn efficiently and the ability to retrieve information fluently from long-term memory. People who can learn efficiently can associate new information with previously acquired knowledge. One of the most important ways in which they learn more efficiently is that they tend to remember the gist of things (i.e., distinguish between essential and nonessential details). Doing so requires some combination of fluid and crystallized knowledge. This is why people who reason well and who have broad knowledge tend to learn new information more efficiently. They see the logical connections between the new information and what they already know. The greater the number of connections, the more likely the new information will be retained permanently and used in the future. People who can retrieve memories fluently tend to speak fluently and often read fluently. A type of retrieval fluency called *divergent production* (being able to generate many responses to a prompt such as "name as many kinds of sports as you can" or "come up with as many ways as you can to use a pencil") appears to be an important component of creativity (Kaufman, Kaufman, & Lichtenberger, 2011). Deficits in a fluency ability called *naming fluency* (the ability to identify well known objects quickly and easily) are associated with reading comprehension problems (Neuhaus, Foorman, Francis, & Carlson, 2001), in part because the act of reading involves "naming" (identifying) printed words.

General Cognitive Speed

Before cognitive ability research was conducted on the speed at which people could perform various tasks, it was not entirely clear whether speediness would emerge as an ability distinct from other kinds of abilities. For example, it is possible that people who reason well also reason quickly and that the speed is irrelevant. It was also not obvious whether there would be a single mental speed ability, several speed abilities, or one speed ability for each kind of task. Research has suggested that there are at least three cognitive speed factors and a one psychomotor speed factor. The speed/fluency of memory retrieval has already been described. The psychomotor speed factor is the speed at which people can perform fine motor tasks (e.g., press a button quickly, articulate word sounds quickly, move a limb quickly). The remaining two speed factors appear at first glance to be very much alike. However, they have very low correlations with each other, suggesting that they represent very different aspects of mental speed.

Reaction and Decision Time (Gt)

Tasks in which this ability is measured are among the simplest tests ever devised. For example, in one test, a person is given a box with two buttons. Whenever one of the buttons lights up, the person hits the button as quickly as possible. In another test, a two lines flash briefly on the computer screen. One line is clearly longer than the other one. The person indicates which line is longer. The task is repeated many times. The duration of the display becomes shorter and shorter until the person can no longer tell which line is the longer of the two (i.e., the person's accuracy is at chance levels). These kinds of tests are so simple that they are called *elementary cognitive tasks*. They are used by researchers working to discover the essential cognitive roots of intelligence. The working hypothesis of this research is that the essence of general intelligence will be understood by breaking complex tasks down into very simple steps and measuring the millisecond speed of these simple perceptions and decisions. Research has reported that the correlations of such simple elementary cognitive tasks with IQ tests is surprisingly high (around 0.4). This suggests that a significant portion of what causes differences in overall intellectual ability is due to the speed at which basic perceptual processes executed. Although a correlation of 0.40 is meaningfully large, it must be put in proper context. This means that approximately 16% (.40 squared; the coefficient of determination) of general intelligence is related to performance on Gt tasks. Clearly this means that Gt abilities do not provide the whole explanation of intelligence, however intriguing the findings in this area of research.

People with fast reaction and decision times and perception speeds are better able to perform complex tasks such as flying fighter planes. Note that people who perform well on decision speed tests are not necessarily hasty people who make rash decisions. They perceive and respond to events and stimuli quickly when that is the required task demand. When making important decisions, they are no more likely to rush into risky investments or ill-advised marriages than anybody else.

Processing Speed (Gs)

This broad ability is measured by tasks in which a person performs a very simple task repeatedly (e.g., underlining all of the 3s on a paper full of single digit numbers). Such tasks are so simple that almost anyone can complete them without error if they were given unlimited time to complete the task. It might seem that such tasks are just like the tasks described in the Gt section. However, there is an important difference. In the Gt tasks, each stimulus is presented one-at-a-time and the experimenter controls the rate of presentation. In Gs tasks, the stimuli are presented all at once on a screen or a piece of paper. The evaluee then sets his or her own sustained pace in completing the items. In the Gt tasks, the role of attentional control is minimized, although the evaluee must remain reasonably vigilant. To minimize differences in vigilance, a cue, such as a cross in the center of the screen, flashes so that an evaluee with a meandering mind will re-orient to the task before the next item appears. In Gs tasks, there are no such safeguards. People with problems of attentional fluency will attempt to perform the simple tasks quickly but their speed will be uneven, proceeding in fits and starts. What happens is that certain items briefly "capture" their attention and then it is difficult to move on to the next item smoothly. Thus, the name "processing speed" may be a bit of a misnomer, suggesting too broad a construct. It is not the speed of all types of processing. It is the speed and fluency with which a person can perform a self-paced, attention-demanding task.

People who perform well in Gs tasks tend to be able to learn tasks well and can "automatize" them so that they can be performed without consuming attentional resources. For example, when people first learn to drive a car, it requires all of their attention to operate the vehicle safely. After a few weeks of driving, they can drive long distances without being mentally fatigued by the activity. They can even converse with other people in the car without appreciably increasing the risk of accidents. For people with high Gs, this automatization process seems to occur more rapidly and more thoroughly.

Processing speed (Gs) is the ability that declines the most with age and decreases the most after almost any kind of brain injury. It is for this reason that neuropsychologists use processing speed tests to screen for the effects of possible brain injuries. Gs is also extremely sensitive to minor fluctuations in alertness and sobriety. Most people are fairly consistent in their performance on these tests, but some people are extremely variable. Sometimes people with below normal processing speed deficits can, on a particularly good day, perform at an average level. For this reason, it is a good idea to measure this ability in several ways across different days to make sure that an accurate estimate of the individual's Gs ability is obtained.

Other Kinds of Acquired Knowledge (Gkn, Grw, and Gq)

For Horn and Cattell (1966), crystallized intelligence originally encompassed all acquired knowledge. Later in their careers, however, they independently had misgivings about the unitary nature of Gc (Cattell, 1987; Horn & Blankson, 2005). There seems to be something different about general knowledge (measured by Gc tests) and knowledge that can only come from deep involvement with a subject matter. In particular, experts in a subject seem to be able to maintain huge amounts of information in working memory as they solve problems related to their field of expertise. When faced with problems outside their area of mastery, experts no longer are able to perform extraordinary feats of memory. For this reason, CHC theory distinguishes between general knowledge, Gc, and domain-specific or specialized knowledge, Gkn.

Two additional kinds of acquired knowledge are so important that they are named separately. They are reading/writing ability (Grw) and quantitative ability (Gq). These refer to specific skills of reading decoding, spelling, calculations procedures and other low-level academic skills. When a student performs complex academic tasks such as writing an essay, Grw skills are used, but also general knowledge (Gc) is employed and, if the essays involves reasoning that is novel to the student, fluid reasoning (Gf).

A Cognitive Performance Model Applied to Individuals

The mind is certainly more complex than can be captured via any single proposed cognitive performance model. However, it is better to start with a simple model that approximates the truth than to have no model at all and flounder in uncertainty. Here, in Figure 64.1, we present a variation of a model that we proposed in Schneider and McGrew (2011). Both models draw heavily from cognitive processing models proposed by Woodcock (1993) and Kyllonen (2002) but differ from both those models in that our models are more detailed and more closely aligned with developments in CHC Theory. The major difference between this model and the Schneider and McGrew (2011) model is how working memory is conceptualized. Many researchers represent working memory as a gateway from perception to long-term memory (e.g., Baddeley, 1986). However, many researchers are reporting findings that suggest that perceptual systems interact directly with long-term memory and that working memory is simply the activated portion of long-term memory (e.g., Cowan, 1995). It will likely be a long time before this debate is settled conclusively. Fortunately, in

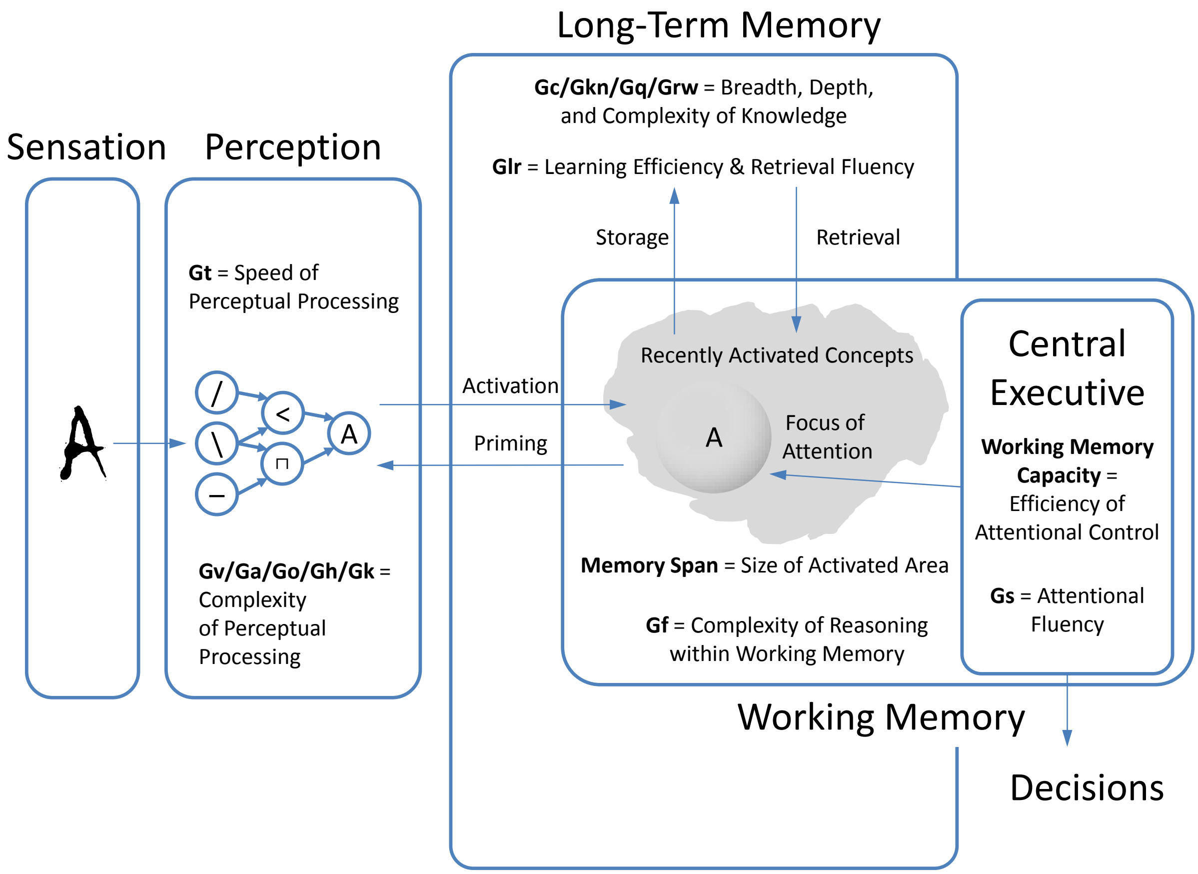


Figure 64.1 Cognitive performance model with CHC abilities as parameters of information processing.

terms of predicting the performance of individuals, this difference may not matter that much.

Performance Parameters of Sensation and Perception

In the cognitive performance model in Figure 64.1, sensations are perceived by their respective sensory organs and then processed by different perceptual systems. People vary not only in their sensory acuity, but also in the speed of perception (Gt, and possibly Gs). Some people are able to extract much more detailed and complex information from their perceptions and these differences are often driven by domain-specific abilities such as Gv, visual-spatial ability. Of course, experience alters how much a person can take in all at once. Any videogame novice is daunted by observing how much experienced gamers can simultaneously process on screens that seem to be, at first, scenes of blooming, buzzing confusion. However, after deep immersion in the game, the novice is no longer confused. However, some individuals are better at processing complex sensory information than others and these differences persist even after extensive practice and training.

In the domain of reading, the higher-order perceptual skills associated with sound (auditory processing ability) have a special relationship with the ability to use phonics skills to sound out unfamiliar words (Gathercole, 2006). Skilled readers do not usually sound out familiar words; they simply retrieve the word's sounds and meaning directly from memory. For very skilled readers, this process occurs automatically; skilled readers can't help reading words they see. However, when encountering unfamiliar words, even skilled readers sound them out. For people with poor auditory processing ability, the process of mapping sounds to letters is effortful and error-prone. Thus, when learning to read, a child with low Ga must rely heavily on rote memory to recognize words. If a child is unable to do so, the child's reading problems may become serious enough to warrant a diagnosis of *phonological dyslexia* (word reading problems caused primarily by the inability to hear speech sounds distinctly).

Performance Parameters of Working Memory

Different cognitive ability factors are associated with different aspects of attention and attentional control. Within the Short-Term Memory (Gsm) factor, a person's memory span is a measure of how much information a person can maintain in an activated state. In Figure 64.1, memory span is associated with the size of the activated area of long term memory. Being able to hold more information in an activated state is advantageous in complex tasks such as reading comprehension, text composition, and applied math problems because information can be combined in working memory in ways that facilitate comprehension and problem-solving.

More complex measures of Gsm (ones that require simultaneous storage and processing of information) measure not only how much information can be maintained in an activated state but also the efficiency of attentional control (i.e., divided attention, selective attention, and concentration). Measures of processing speed (Gs) are measures of attentional fluency, speed at which attention can be accurately and smoothly directed to tasks as they are completed. No test, however, is a pure measure of any ability. Tests measuring Gs are influenced by many other abilities as well.

If your reading decoding skills are very poor, sounding out the words is likely to consume almost all of your available attentional resources. That is, the size of the activated area in working memory shrinks and it becomes much harder to understand what your read because most texts require that you hold information in mind across sentences and paragraphs to make connections, particularly understanding complex aspects of language such as irony and humor.

If your decoding skills are good but your working memory capacity is poor, the risk of developing reading comprehension problems increases. Working memory capacity has a strong connection with vocabulary acquisition during reading. Some words occur only in high-level text and most of us learn them by inference rather than by looking them up in a dictionary. That is, looked up words are hard to remember but words that are embedded in the context a narrative are easier to recall and use correctly. Inferring the meaning of an unfamiliar word in context often requires that the preceding sentence or two is held in mind. Sometimes the meaning of an unfamiliar word (e.g., "decadence") can only be inferred after reading the sentence after the one in which it occurred (e.g., "The corporate sponsors of the party at the conference spared no expense to impress the academic researchers. Overwhelmed, the shy professor could not allow himself to be at ease in the midst of so much decadence. Watching his colleagues partaking of and enjoying the indulgences a little too much, he sneered 'First comes wealth, then comfort, then weakness, decay, and corruption.'"). To guess that decadence is related to the corrupting influence of too much luxury and comfort, the preceding sentences need to be maintained in memory while the last sentence is processed and interpreted. Then the inference is made by combining the information in all three sentences. Skilled readers, of course, look backward and reread sentences they do not quite understand. However, this is an effortful process. People with high working memory seem to be able to infer more meaning from of text with less effort (Calvo, 2005).

One way to conceptualize measures of fluid intelligence (Gf) is that they represent the complexity of mental representations that a person can assemble for the first time in working memory. For people with high Gf abilities, complex ideas with multiple parts can be held in working memory, analyzed (broken down), synthesized (integrated with other ideas), and evaluated (judging the relevance and the implications of the ideas to new situations). People with low Gf have find complex ideas particularly hard to understand unless they are broken down into simple parts so that they can be mastered independently. Only then can the parts be integrated to a coherent whole, typically with the assistance and guidance of a gifted teacher.

Performance Parameters of Long-Term Memory

The speed and ease with which new information is stored in long-term memory is measured by tests associated with the Long-term Storage and Retrieval (Glr) ability factor. To estimate how easily a person learns, we present the evaluee with information (sometimes all at once, sometimes in a structured sequence) and then test the person's recall of the material. In most tests, the new information is presented and recalled many times, often with delays in between so that we are measuring long-term memory processes rather than working memory processes.

Sometimes people have learned information but they cannot recall it easily. The way that we distinguish between a person's ability to learn and the person's ability to recall is to give memory tests in two different formats: one in which the person has to recall the information with no cues and one which the person has to recognize whether or not the information was presented previously. Recognizing information is much easier than recalling it. This is why a multiple-choice test is much easier than a free recall test that asks the same question. For example, could you recall the capital of Poland? If not, could you identify it from among these European capitals? Athens Berlin Lisbon London Madrid Moscow Oslo Paris Rome Warsaw Vienna. A person with memory retrieval problems often performs reasonably well on multiple choice tests but has difficulty with free recall formats, even more so than most people.

The act of reading is the act of retrieving from memory the meaning of a series of words and then assembling those ideas into a coherent whole. A reader with slow retrieval fluency may find reading too effortful to be enjoyable. If word retrieval takes too long, attention starts to wander and it is difficult to extract meaning, much less enjoyment from the text. Something similar happens with solving complex problems in mathematics. If a person cannot retrieve basic math facts fluently ($8 + 6$, 7×9, $15 - 6$, etc.), during the time that a person has to recall (or calculate) the basic math fact, attention has time to wander and the person can become lost in the larger math problem. Thus, poor retrieval fluency disrupts the flow of reasoning and problem-solving, consuming attentional resources and increasing the likelihood of careless errors.

The contents of long-term memory are measured with tests of crystallized intelligence (or specialized knowledge tests). After basic reading decoding skills have been mastered, a primary determinant of reading comprehension is the breath, depth, and complexity of knowledge a person has already acquired. Most writers assume that the reader knows a lot of information and leaves the reader to read between the lines. Without the requisite vocabulary, language comprehension skills, and general knowledge, many kinds of text are very difficult to understand.

An Example of Qualitatively Applying a Cognitive Performance Model

In Figure 64.1, a stimulus that is shaped like the letter A is perceived and is currently at the center of attention. In order to recognize it, you need reasonable visual acuity (corrected with glasses, if need be). If there is sufficient visual acuity, your feature detectors must be unimpaired and must work efficiently. The results of the simple feature detectors are fed to complex feature detectors and those results are mapped onto schemas stored in long-term memory. In this case, the letter A is recognized.

Suppose you are reading a novel and this letter A is the first letter of the name of a new character: "Dr. Amuchástegui." The novelty of the name captures your attention. You might decide to phonetically sound out the name and this will require focused attention. If you decide you want to remember the name, you might repeat it a few times. To make the name stick in memory, you might visualize what Dr. Amuchástegui might look like as you repeat the name aloud. The success of this attempt to remember the name will depend on many factors, some of which are not included in the model (e.g., your motivation to remember, your experience with Basque surnames, your level of mental fatigue, and many others). However, if you have good auditory processing (Ga) and have specialized knowledge (Gkn) of how to sound out Spanish words, you are likely to succeed in sounding out the name correctly. If your learning abilities (Glr) are efficient, the name is likely to be stored in long-term memory. If your memory span is reasonably large, you'll be able to recall and integrate the details surrounding this character and the memory is likely to be more vivid than it otherwise would have been. This is particularly true if your memory representation of the events in the novel is extremely rich, nuanced, and interconnected. Later, if you run into a friend who is also reading the book, initiating a conversation about the book might trigger the memory of the unusual name and you are likely to remember it.

If, on the other hand, the book is assigned reading and you are not a skilled decoder (low Grw), the name may look like gibberish ("Dr. Amhgtigiu"). If your auditory processing ability (Ga) is low, you may never have mastered the art of phonetic decoding and you might not even try to remember the name. You might remember the character simply as "That doctor with the weird name that started with an A or something." Without a verbal label on which to link the character's unique attributes, you are less likely to remember what he did in the story, especially if the story is filled with other characters with unusual names.

Future Developments in Cognitive Performance Models

In the discussion of reading and the cognitive performance model above, we have taken a narrative, nonquantitative approach. However, it is possible to measure a child's relevant cognitive abilities and use sophisticated statistical methods to obtain an empirically-based prediction of which kinds of academic problems the child will face. If the child's academic weaknesses are already known, it is possible to use a cognitive performance model to estimate how much improvement in complex academic skills (e.g., reading comprehension and applied math problem-solving) would result from the remediation of cognitive deficits (e.g., attention deficits) or deficits in simple academic skills (e.g., word decoding or math fact fluency).

Recently Schneider (2010) developed methods and software that allows clinicians to create their own cognitive performance models and apply them to individuals. This program, the Compositator is available for free from the Woodcock-Muñoz Foundation to users of the Woodcock-Johnson III, Normative Update (Woodcock, McGrew, Schrank, & Mather, 2007), a comprehensive battery of tests of cognitive abilities and academic skills. It is likely that a more general version of the software will be developed for users of other measures of cognitive and academic abilities at some point in the future.

In Figure 64.2, the Compositator was used to create a very simple cognitive performance model that predicts that mathematics reasoning is a function of fluid reasoning, short-term memory, and basic math skills. It is unlikely that a well-developed model would be this simple. This model is only for purposes of illustration.

The model's predictions were applied to an individual who struggles with math calculation and applied math problems that require quantitative reasoning. The lines and numbers represent a statistical procedure called path analysis. A path analysis is a set of multiple regression equations that use some variables to predict other variables. The numbers and lines may look like visual gobbledygook but they represent a precise set of predictions about what is likely to happen if any one of the student's cognitive or academic abilities were to change. For example, this cognitive performance model predicts that if the student's weaknesses in short-term memory (and the attentional control deficits associated with those weaknesses) were remediated, the student's math calculation and math reasoning skills are expected to rise as well. Figure 64.3 shows how much, if the model in Figure 64.2 is correct, the student's math skills would improve if the short-term memory problems were remediated to the average range (the gray area in the middle). Predictions are not expected to be perfectly accurate and the model gives an estimate of the likely range of scores that might occur if the remediation of short-term memory were to be achieved. The improvements are not expected to happen instantly and it is not expected to occur if the new math skills are not explicitly taught. However, the model does provide parents, teachers, and clinicians some direction about what to do and some hope that the remediation efforts could pay off. Such predictions, of course, are only likely to be accurate if the model upon which it is based is valid. An inaccurate cognitive performance model will result in predictions that are unlikely to come true. Thus, the clinician creating the cognitive performance model must base it on solid science.

Future research will need to be conducted to see if the use of such cognitive performance models results in better outcomes for students. For now, the use of cognitive performance models applied to individuals in this manner is experimental. It is hoped that better methods and practical tools for clinicians will inspire researchers to develop better and more sophisticated cognitive performance models that will be truly useful for struggling children.

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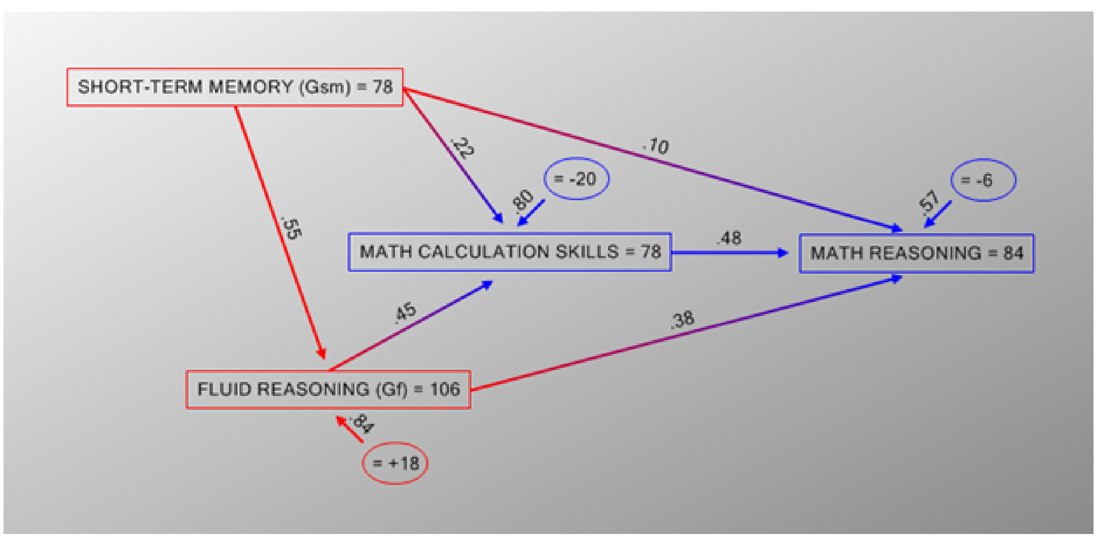

Figure 64.2 Path Analysis applied to an individual with average fluid reasoning but with difficulties in short-term memory, math calculation skills and math reasoning.

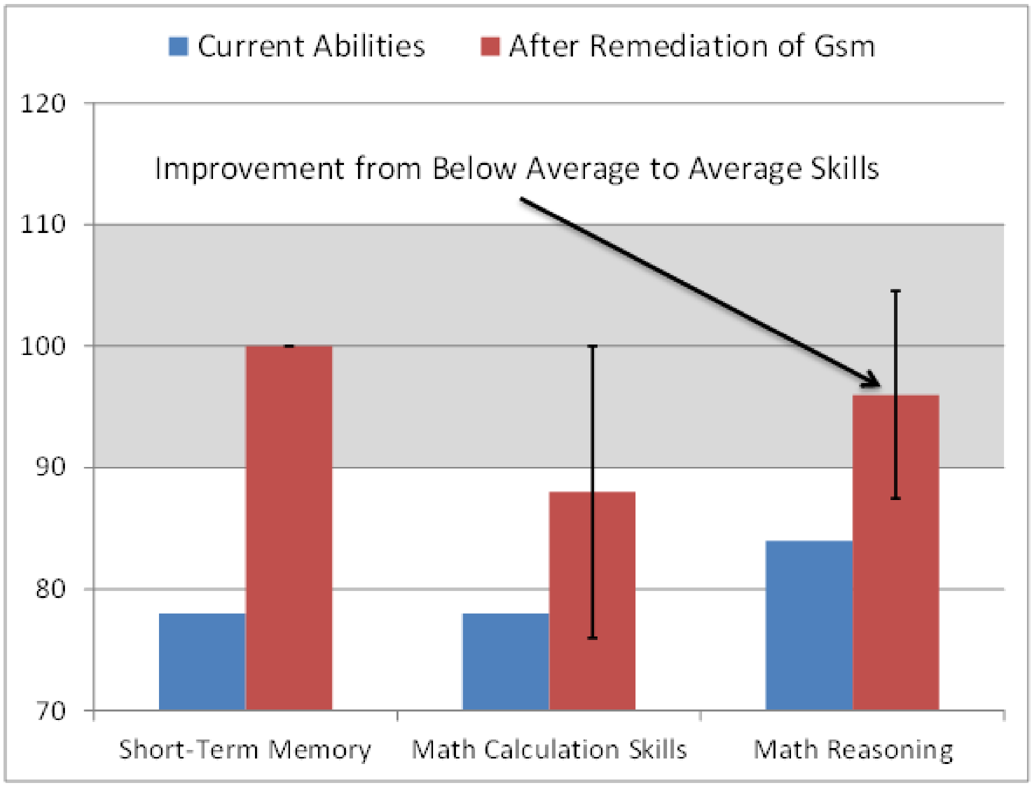

Figure 64.3. A forecast based on the model in Figure 64.2 of the likely improvement in an individual student's math skills if the student's short term memory deficits could be remediated.

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Author Contact Information: W. Joel Schneider, PhD, Department of Psychology, Illinois State University, Normal, IL 61790 4620. E mail: wjschne@ilstu.edu