Neural Bases of Giftedness

Sharlene D. Newman & Evie Malaia

Definition of Terms Used in the Research

The neural bases of giftedness will be examined in this chapter by focusing on a construct within giftedness: high levels of intelligence. Intelligence is very difficult to define, and in fact, there is little consensus among scientific researchers as to what is meant by intelligence (Jensen, 1998). A general definition provided by Sternberg and Salter (1982) that we will use is “goal-directed adaptive behavior” (p. 3). Intelligent behavior is adaptive in that it changes to confront and successfully meet challenges. Because it is not enough for intelligent behavior to simply be adaptive, it is also thought to be goal-directed or purposeful. However, it is the adaptive nature of intelligence that will be the primary focus of this chapter.

Conventional psychometric studies of behavioral performance have been accompanied by attempts to correlate individual differences in intelligence with biological measures. In some sense, these attempts have been in search of a definition of “mental energy” (a construct used by Spearman [1927] as a factor in determining general intelligence or g). The biological measure initially used was head size (Van Valen, 1974; Jensen & Sinha, 1992). In 1982, Jensen hypothesized that it was not necessarily the size of the head, or brain, but the speed of processing that was central to intelligence, showing a relationship between reaction time and intelligence (Brody, 1992; Vernon, 1992). This relationship suggested that the characteristics of the nervous system determine reaction time, and that individuals whose nervous systems function more effectively and rapidly develop more complex intellectual skills. This effective and rapid functioning nervous system is thought to be at the heart of giftedness.
Neuroimaging methods have replaced head circumference as the biological measure of choice. Electrophysiological recordings (EEG) of electrical activity measured on the scalp as well as functional magnetic resonance imaging (fMRI) of brain activation via measuring blood oxygenation changes have also shown a relationship between neural processing characteristics and intelligence. For example, studies using EEG have revealed consistent correlations with intelligence (Jensen, 1998; Jensen & Sinha, 1992). Additionally, diffusion tenor imaging (DTI) of the anatomical connectivity of the brain has also been used to explore structural differences as a function of intelligence (Schmithorst, Wilke, Dardzinski, & Holland, 2005).

**MAJOR QUESTIONS ADDRESSED IN THE RESEARCH ON THE NEURAL BASES OF INTELLIGENCE**

The overarching question addressed by the neural bases of intelligence literature focuses on identifying the neural underpinnings of $g$, or general intelligence. More specifically, the following questions are addressed:

1. Energy is consumed during the performance of cognitive tasks and each cortical area has a limited resource capacity. This principle begs two questions related to individual differences in intelligence. First, does the amount of resources available or the resource capacity within the neural system vary across individuals? Secondly, does the amount of resources required to perform a task differ across individuals due to variations in efficiency?

2. The topology (cortical composition) of neurocognitive networks associated with a given task changes dynamically, adapting itself to the demands of a given task. Does the efficiency with which this topological change occurs contribute to individual differences in task performance?

3. Cortical regions function collaboratively to perform tasks. Does variation in the degree of synchronization or efficiency of the communication between regions contribute to individual differences in task performance?

4. The quality of the white matter tracts connecting cortical areas may also affect processing speed. Does the variation in the degree or quality of the anatomical connections between processing regions contribute to individual differences in task performance?
Defensible Conclusions From the Empirical Research on the Neural Bases of Intelligence

Processing Capacity

Thinking is biological work that requires resources and is thus constrained by their availability. In any biological system, there is an upper limit on resource availability. Certainly there are upper bounds on thinking, such that one can do only so much thinking per unit time. It turns out to be helpful to consider such limitations as resource availability. Tasks that attempt to impose a load greater than the maximum that the resources permit will produce performance that is errorful, slow, or does not meet some task requirements, showing deficits in performance that are consistent with decreased resources.

One of the implications of the resource consumption approach is that individuals may differ in resource availability and/or the efficiency of their use. In other words, those with above-average performance may have either a greater computational capacity, use the available resources more efficiently, or both. There is evidence that lends support to the efficiency hypothesis: Several studies have reported negative correlations between psychometrically measured abilities and the volume of cortical activation produced by tasks that draw upon these abilities (Haier et al., 1988; Newman, Carpenter, Varma, & Just, 2003; Parks et al., 1988, 1989; Prat, Keller, & Just, 2007). For example, Prat and colleagues (2007) showed that high working memory capacity readers elicited significantly less activation during a reading comprehension task than low capacity readers.

There is also evidence to support the resource availability hypothesis. Grey matter (the processing unit of the neuron) density has been used as a proxy for processing capacity and a number of studies have found grey matter density or volume differences as a function of intelligence (Colom, Jung, & Haier, 2007). For example, in an unpublished study conducted in our lab, voxel based morphometry (VBM) was used to examine grey matter density in 75 participants whose spatial ability scores, as measured by the Vandenberg mental rotation task, ranged from 2 to 38.5 with a mean of 21.4. The grey matter density in the cerebellum, along with other regions, was correlated with spatial ability scores such that those with a high score had more grey matter in these regions. These types of results imply a relationship between brain structure and ability and suggest that high-ability individuals may also have more processing resources.

To summarize, the above discussion provides evidence for two points. First, fMRI studies indicate less activation (i.e., resource consumption) among high-ability individuals, suggesting that highly proficient individuals use their resources more efficiently. Second, high proficiency individuals tend to have
higher levels of grey matter density, suggesting the availability of more processing resources.

**Malleability of Processing Networks**

Intelligent responding at the cortical level must include the ability to arbitrarily map inputs and outputs (Garlick, 2002). At the large-scale cortical network level, this suggests that the network of cortical areas activated in a given task—its composition and topological pattern of collaboration—is neither structurally fixed nor static. Rather, it varies dynamically during task performance. The previous conception of the neural basis of intelligence was that some fixed volume of brain tissue in a fixed set of brain areas (i.e., a fixed hardware infrastructure) is used to perform a particular task, like mental rotation or reasoning. According to the dynamic view, the “underlying hardware” is a moving target, changing not only from one type of stimulus item to another, but also changing from moment to moment during the processing of a given item.

There are at least two circumstances that may necessitate a dynamic change in the neural underpinnings of a cognitive task: (1) changes in the availability of neural resources and (2) fluctuations in the computational demands of a task. As the resource pool of an area with a given set of specializations is exhausted, some overflow of its functions migrates from a more specialized area to less specialized areas. Although there is a typical set of areas activated in a given type of task, additional areas can become activated if the task is made significantly more demanding. For example, when a sentence comprehension task is made progressively more difficult by increasing the structural complexity of the sentences, activation in the right hemisphere homolog of Wernicke’s area (left posterior superior temporal gyrus) systematically increases from a negligible level to a substantial level (Just, Carpenter, Keller, Eddy, & Thulborn, 1996). One of the sources of individual differences in cognition may be flexibility with which additional regions are recruited.

The second situation that may necessitate dynamic self-assembly of a large-scale cortical network is a fluctuation in the computational demands of a given task. The dynamic assembly of neurocognitive networks is incremental or continuous, not all-or-none. This provides for just-in-time, as-needed neural support for cognitive processing. This principle is demonstrated in a study of verbal reasoning conducted by Newman, Just, and Carpenter (2002). There, two conditions were presented that varied the location of the maximal reasoning load within a sentence. In the first (early/low load) condition, the reasoning load occurred early in the sentence; in the second (late/high load) condition, the maximal reasoning load occurred late in the sentence (see Table 33.1). The time of occurrence of the maximal activation of prefrontal cortex varied as a function of the location of the maximal reasoning load in the expected direction. This difference in the time course of activation supports the idea that
cortical regions are recruited as needed. The ability to dynamically recruit additional resources may very well be a source of individual differences.

This dynamic recruitment of neural resources may also be seen as differences in processing strategy between individuals. Recent studies have suggested that different ability groups may employ different strategies while performing the same task; this has been particularly observed in language (Malaia, Wilbur, & Weber-Fox, 2009; Newman, Lee, & Ratliff, 2009; Pakulak & Neville, 2009). For example, Malaia et al. (2009) found that high- and low-capacity readers employed two distinct strategies—one semantic and one syntactic—when comprehending reduced relative clauses (e.g., The child observed by the teacher walked to class). Event-related potentials (ERP) measured from the EEG of participants with high-syntactic proficiency, determined by tests of auditory comprehension, indicated that they integrated the verb and nouns when reading the preposition “by,” suggesting a reliance on the syntactic structure. ERPs from the normal syntactic proficiency group indicated that they did not attempt “who did what?” processing until after reading the second argument (i.e., until the semantics was clear). The use of different, more efficient strategies by higher ability groups may be a core characteristic of high ability; however, more research examining the neural bases of these strategy differences is essential.

Dynamic self-assembly may be the physiological manifestation of the adaptive nature of thought. When a task becomes too difficult for the current strategy, a new one is “devised.” The ability to switch strategies and dynamically change the cortical landscape related to a given task may contribute to individual differences. In fact, Garlick (2002) showed that an artificial neural network that was better able to adapt its connections to the environment learned to read faster, accommodated information from the environment better, and scored higher on fluid intelligence tests. Each of these properties is characteristic of individuals with higher ability.

<table>
<thead>
<tr>
<th>Early/Low load</th>
<th>Late/High load</th>
</tr>
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<tbody>
<tr>
<td>The first month after April is the month before my favorite month.</td>
<td>The day before my favorite day is the first day after Monday.</td>
</tr>
<tr>
<td>What is my favorite month?</td>
<td>What is my favorite day?</td>
</tr>
<tr>
<td>June, July, Other</td>
<td>Thursday, Friday, Other</td>
</tr>
</tbody>
</table>

**TABLE 33.1**

*Early/Low and Late/High Load Tasks in the Newman et al. (2002) Study*
**Functional Connectivity**

A number of cortical regions are involved in performing any cognitive task. These regions must be coordinated, possibly by passing information back and forth. Evidence of such intercommunication pathways between cortical areas in humans performing a cognitive task comes from two sources. The first is the existence of anatomical pathways between areas (discussed in the next section). The corpus callosum is a prime example of an anatomical pathway between potentially collaborating cortical areas. In addition, many cortico-cortico pathways are known from primate neuroanatomical studies (see Mesulam, 2000) as well as from more recent diffusion tensor imaging studies of white matter tracts in humans (Klingberg et al., 2000; Schmithorst, Holland, & Plante, 2012; Schmithorst et al., 2005; Tamnes et al., 2012; Xu et al., 2012).

The second source of evidence for coordination among the activated areas during cognitive activity is found in functional neuroimaging using measures of the correlation of the activation levels in two activated areas over some time period, which generally shows systematic synchronization between areas modulated by a number of variables. The synchronization is taken as evidence of functional connectivity (Horwitz, Rumsey, & Donohue, 1998). Functional connectivity in the context of brain imaging refers to indirect evidence of communication or collaboration between various brain areas. The general assumption is that the functioning of voxels whose activation levels rise and fall together is coordinated. There are a number of methods that have been developed to explore functional connectivity including dynamic causal modeling, Granger analysis, and psychophysiological interaction analysis.

Researchers have identified a direct relationship between ability and functional connectivity measures (Osaka et al., 2003a, 2003b; Prat et al., 2007). Osaka et al. (2003b), for example, found that individuals with a high reading span revealed greater functional connectivity between the anterior cingulate and Broca’s area than did low span individuals. Buchel, Coull, and Friston (1999) also found evidence that functional connectivity increases with learning in a study using fMRI to examine the neural basis of associative learning of visual objects and their locations. In addition to identifying an increase in the functional connectivity between cortical regions associated with spatial and object processing with learning in the task, the researchers documented that the time course of the changes in functional connectivity was closely correlated with the time course of the changes in behavioral performance. The functional connectivity became higher at those times when performance improved.

Functional connectivity can also be assessed with an EEG. Attempts to relate activity of individual neurons to EEG data has led to the development of techniques that rely on measuring power in specific oscillatory frequency bands. For example, localized activity in the gamma band (40Hz and higher) has been associated with higher level cognitive processing (Pulvermüller, Birbaumer, Lutzenberger, & Mohr, 1997), while oscillatory activity in the higher alpha
band (9-12Hz) has been related to suppression of activation. Recent EEG analyses also suggest that assimilation of higher alpha power across cortical regions might be indicative of functional connectivity, or task-related cross-talk among those regions, as opposed to localized neural processing (Obleser & Weisz, 2011). For example, Obleser and Weisz (2011) presented a gradient of spectrally degraded auditory words. They found that comprehension ratings correlated with suppressed alpha power across multiple regions and proposed that this network-wide suppression was related to sound-to-meaning processing, suggesting network-level opposed to region-level activation.

In addition to examining functional connectivity during active tasks, an increasingly useful analysis is to explore connectivity at rest, or examining the default-mode network (DMN). The term default-mode network refers to the set of regions most active during spontaneous activity of the brain when it is not actively engaged in a task. An intact DMN is thought to be critical for normal brain function and has been found to be altered in studies of disorders such as schizophrenia, autism, and Alzheimer’s disease (Bluhm et al., 2007; Buckner et al., 2009; Whitfield-Gabrieli et al., 2009; Zhou et al., 2008). The functioning of the DMN has also been linked to intelligence (Song et al., 2008). Song and colleagues (2008) found that participants’ scores on the Wechsler intelligence scales were significantly correlated with functional connectivity among brain regions distributed in the frontal, parietal, occipital, and limbic lobes—during rest. Especially predictive of intelligence scores was the strength of functional connectivity between frontal and parietal regions.

All of these adaptations (the increase in functional connectivity with task difficulty, with ability and with learning) provide support for the idea that a systemwide attribute of brain function may be a key characteristic of intelligence. Even though functional connectivity analysis does not indicate the underlying causality, this technique allows for the exploration of the level of coordination between cortical regions across individuals, which may provide further insights to the biological underpinnings of individual differences in task performance.

**Anatomical Connectivity**

Diffusion tensor imaging, or DTI, provides information regarding the microstructure of white matter in vivo (Basser, Mattiello, & LeBihan, 1994). DTI has been used to examine anatomical connectivity, or the physical neuronal connections between regions. The anatomical connections between cortical regions are essential to interregion communication. In fact, the quality of these connections has been suggested to affect processing speed directly. For example, developmental research has shown that the neural changes that take place during the first 2 years of life include a dramatic increase in the number of synaptic connections and an increase in the thickness of the myelin sheath that envelops nerve cell axons (Anderson, 2000; Siegler, 1998). These two changes
are important because they both affect conduction speed, which is thought to, in turn, affect processing speed. Combined with fMRI, information about white-matter tracts has the potential to reveal important information about neurocognitive networks, which may help to elucidate the neural basis of individual differences.

The benefit of DTI is that it allows for a virtual dissection of neural pathways in the living and performing brain. In one of the first studies using DTI, Klingberg and colleagues (2000) compared the white matter tracts within the temporoparietal region of poor and normal readers. There, Klingberg et al. found a high positive correlation between the DTI measure of the left hemisphere and reading ability, as measured by the Word ID test (Woodcock, 1987), showing that differences in white matter contribute significantly to individual differences observed in reading.

Recently, there has been a push to explore not just localized white matter differences but to investigate instead the intricate and complex connectivity of the whole brain with the use of graph theoretic analysis combined with fiber tractography (Bassett, Brown, Deshpande, Carlson, & Grafton, 2011; Gong et al., 2009; Honey et al., 2009; van den Heuvel, Mandl, Stam, Kahn, & Pol, 2010). This type of analysis allows for the examination of both local and global network parameters and provides a more complete look at how the brain is connected. Although these methods have not been used to explore individual differences in ability, researchers have used them to explore other differences, for example, between heavy cannabis users and nonusers (Kim et al., 2012). Cannabis (CB) users showed significantly decreased global network efficiency and significantly increased clustering coefficients (degree to which nodes tend to cluster around individual nodes). Further, across CB and non-CB subjects’ verbal abilities and schizotypal and impulsive personality characteristics correlated with global efficiency. These data indicate that structural brain networks in CB subjects are less efficiently integrated than nonusers. They also demonstrate the potential of these methods in the study of individual differences in ability.

**Limitations of the Research on the Neural Bases of Intelligence**

The neuroimaging research on intelligence relies heavily on correlational approaches. Because correlations provide no information regarding causality, we cannot determine whether the neural differences observed are due to the differences in ability or vice versa. In support of ability changing the biology hypothesis, there are studies that suggest that skilled practice changes the neurobiology (e.g., Keller & Just, 2009). However, it is not clear how much change
is possible. It is important to understand how much the neurobiology or genetics is a limiting factor in cognitive performance.

Many of the previous studies examining the neural underpinnings of intelligence have generally relied upon a composite score of IQ that is obtained from combining a number of individual tests of cognitive ability (Colom, Jung, & Haier, 2006; Haier, Jung, Yeo, Head, & Alkire, 2004), or they are based on a single test thought to load highly on g (Duncan et al., 2000). Performance on all cognitive tasks is correlated to some degree, presumably due to g, with g accounting for about 40% of the variance when examining test batteries consisting of 10–15 cognitive tasks (Deary, Penke, & Johnson, 2009). But to use only g may bias the results to a particular brain region and ignore other regions that may also make significant contributions to intelligent behavior.

Conclusions Often Drawn From the Research on the Neural Bases of Intelligence That Are Not Defensible

Both g and the frontal lobes have often been linked to executive functions such as control processing, strategy formulation, planning, and monitoring the contents of working memory (Duncan, Emslie, & Williams, 1996; Luria, 1966; Norman & Shallice, 1980; Snow, 1981). Support for this idea has come from both behavioral studies of normal and patient populations (Duncan et al., 1996) and neuroimaging studies (Duncan et al., 2000). For example, in a neuroimaging study conducted by Duncan and colleagues (2000), an attempt was made to determine the cortical area that underpins g. In that study, two variables were manipulated, the g loading (low or high) and test type (verbal or spatial). Duncan et al. (2000) found that in both the verbal and spatial conditions, the frontal cortex revealed greater activation for the high-g compared to the low-g condition, supporting the idea that g reflects functions of the frontal lobe. Supporting this finding, the unpublished VBM study from our lab discussed above also found that grey matter differences for two disparate abilities—verbal working memory and spatial ability—were commonly located within the prefrontal cortex.

Because the frontal lobes appear to play such a prominent role in higher cognitive functioning, it has been suggested that intelligence resides there. This, in our opinion, is too simplistic a view. Although we do not dispute that the frontal lobes play an important role in problem solving and intelligence, we suggest instead that the biological basis of intelligence extends beyond the frontal lobe. In fact, intact frontal functions are somewhat unrelated to intelligence, as measured by psychometric tests (Teuber, 1972). IQ scores are rarely
affected by damage to the region. We argue here that intelligence does not lie in any particular brain region, but is instead a function of a more distributed, dynamically configured set of areas.

**Practical Implications of the Research on the Neural Bases of Intelligence**

The most important outcome of this research as it relates to fostering the development of gifted individuals is the importance of a well- and efficiently connected neural network. Although much of the biology is under the control of genetics, genetics do not fully determine the quality of neural processing. The environment plays a significant role. Throughout the lifespan, the human brain continues to change its connection patterns with many of these changes being driven by experience. Providing an enriched environment is essential to the development of gifted and talented individuals, and it has profound consequences on brain maturation and subsequent neuroplasticity. One such enriched environment is the appropriate educational intervention in order to adequately challenge the student (discussed in other chapters of this volume) and encourage the development of a well-connected neural network.

**Credible Sources of Research on the Neural Bases of Intelligence**

REFERENCES


About the Editors

Jonathan A. Plucker, Ph.D., is an endowed professor in the Neag School of Education at the University of Connecticut. His research, supported by more than $36 million in external funding, examines education policy and talent development, with more than 150 publications to his credit. Plucker is an American Psychological Association (APA) and American Association for the Advancement of Science (AAAS) Fellow and the 2012 recipient of the APA Arnheim Award for Outstanding Achievement for his research on creativity. His past leadership roles include serving as president of Division 10 of the American Psychological Association and chair of the Research and Evaluation Division of the National Association for Gifted Children. In 2011, he was ranked among the 100 most influential academics in education policy, and his work is widely mentioned in the media, including CNN, The Wall Street Journal, New York Times, and Newsweek.

Carolyn M. Callahan, Ph.D., is Commonwealth Professor in the Curry School of Education, University of Virginia, and the Associate Director of the National Research Center on the Gifted and Talented. She teaches courses in the area of education of the gifted and is executive director of the Summer and Saturday Enrichment Program. Dr. Callahan has authored more than 150 articles, 30 book chapters, and monographs in gifted education focusing on creativity, the identification of gifted students, program evaluation, and the issues faced by gifted females. Dr. Callahan has received recognition as Outstanding Faculty Member in the Commonwealth of Virginia and was awarded the Distinguished Scholar Award from the National Association for Gifted Children. She is a past-president of The Association for the Gifted and the National Association for Gifted Children. She has just completed a term as editor of Gifted Child Quarterly.
Cheryll M. Adams, Ph.D., is Director Emerita of the Center for Gifted Studies and Talent Development at Ball State University and teaches graduate courses in research and gifted education. She has authored or coauthored numerous publications in professional journals, as well as several books and book chapters. Dr. Adams has served as PI or Co-PI on three Jacob K. Javits grants. She serves on the editorial review board for Roeper Review, Gifted Child Quarterly, Journal of Advanced Academics, and Journal for the Education of the Gifted. She has received the NAGC Early Leader Award and BSU’s Outstanding Administrative Service Award. She has served on the Board of Directors of the National Association for Gifted Children and as president of the Indiana Association for the Gifted and of The Association for the Gifted. She currently serves on the board of the Florida Association for the Gifted.

Jill L. Adelson, Ph.D., is an assistant professor in the educational psychology, measurement, and evaluation program at the University of Louisville. She earned her Ph.D. in educational psychology with a joint emphasis in gifted education and in measurement, evaluation, and assessment from the University of Connecticut, and she earned her master’s degree in curriculum and instruction with an emphasis in gifted education from The College of William and Mary. During her time in Virginia, she taught fourth-grade self-contained gifted and talented students. Dr. Adelson’s research interests include the application of advanced statistical methods to examine issues in gifted and mathematics education, including the effects of gifted programming and elementary students’ attitudes toward mathematics.

Susan G. Assouline, Ph.D., is Director of the Belin-Blank Center and a professor of school psychology at The University of Iowa. She is especially interested in academically talented elementary students and is coauthor (with
Ann Shoplik of both editions of *Developing Math Talent* (2005, 2011). She is codeveloper of The Iowa Acceleration Scale (2009), a tool designed to guide educators and parents through decisions about accelerating students. In 2004, she coauthored *A Nation Deceived: How Schools Hold Back America’s Brightest Students* with Nicholas Colangelo and Miraca U. M. Gross

**Amy Price Azano, Ph.D.**, is an assistant professor of adolescent literacy at Virginia Tech. Prior to her current position, she was a researcher and project manager on the “What Works in Gifted Education” study at the National Research Center on the Gifted and Talented (NRC/GT) at the University of Virginia (UVA). As part of her work, she and her colleagues at the NRC/GT received a Curriculum Award from the National Association for Gifted Children. At Virginia Tech, her research focuses on rural gifted education, place-based pedagogy, and the literacy needs of rural youth. Prior to earning her Ph.D. in English Education from UVA, Dr. Azano taught high school English and served as codirector of UVA’s National Writing Project site. Her recent publications can be found in the *Journal of Research in Rural Education, Journal of Advanced Academics, English Education*, and *TEACHING Exceptional Children*.

**Jamie S. Baker** is currently the Acting Director of Secondary Education at New Mexico State University in Las Cruces, NM. Dr. Baker’s research interests include secondary preservice teacher preparation, program assessment, and development. She has also researched and published work related to understanding and serving diverse gifted youth. She is a National Board Certified Teacher in the area of Early Adolescent English Language Arts. She is also Co-Chair of a local Professional Development School (PDS) university-district partnership.

Ronald A. Beghetto, Ph.D., is the College of Education’s Associate Dean for Academic Affairs and Associate Professor of Education Studies at the University of Oregon. His research focuses on creativity in K–12 schools and the influence of past schooling experience on K–12 teacher development. Beghetto is a Fellow of the American Psychological Association (Division 10) and has received numerous awards for his teaching, including the University of Oregon’s highest teaching award for early career faculty (the Ersted Crystal Apple Award).

**James H. Borland, Ph.D.**, is professor of education in the Department of Curriculum and Teaching at Teachers College, Columbia University, where he directs the programs in the education of gifted students. Dr. Borland is the author of numerous books, journal articles, and book chapters. He is editor of the *Education and Psychology of the Gifted* series of Teachers College Press and is past coeditor of the Section on Teaching, Learning, and Human Development
of the *American Educational Research Journal*. He has lectured on the education of gifted students across the U.S. and abroad, and he has consulted with numerous school districts, primarily as an evaluator of programs for gifted students. Dr. Borland was awarded the *Gifted Child Quarterly* Paper of the Year Award for 1994 and 2000 and the Award for Excellence in Research from the Mensa Education and Research Foundation in 1989–1990 and 1999–2000.

**Marguerite Brunner** is a doctoral student at the Curry School of Education at the University of Virginia. Currently she works with preservice and in-service teachers seeking endorsement in gifted education. Her research interests include teacher education, assessment, and underrepresented populations in gifted education. Marguerite has also worked at the National Research Center on the Gifted and Talented (NRC/GT) at the University of Virginia where she investigated best practice in gifted education as part of the research entitled “What Works in Gifted Education,” a study of the National Research Center on the Gifted and Talented.

**Thomas Brush, Ph.D.**, is currently the Barbara B. Jacobs Chair in Education and Technology, as well as Chair of the Department of Instructional Systems Technology in the School of Education at Indiana University, Bloomington. Dr. Brush’s research interests focus on developing methods and strategies to promote inquiry-oriented learning, particularly with more open-ended instruction. This involves studying methods for integrating tools to promote collaborative problem-based learning strategies into the learning environment itself and developing alternative techniques to deliver instruction to students.

**Nathan Burroughs, Ph.D.**, is a researcher at the Center for the Study of Curriculum at Michigan State University. His work focuses on issues related to educational inequality, with a recent emphasis on teacher preparation and opportunity to learn. Previously a researcher at the Center for Evaluation and Education Policy at Indiana University, he received his Ph.D. in Political Science from the University of Georgia.

**Tanya Chichekian** holds a bachelor’s degree in secondary mathematics education and an master’s degree in educational psychology with a specialization in the learning sciences from McGill University. She is currently pursuing her Ph.D. in educational psychology (learning sciences concentration). Tanya has received an Fonds de Recherche du Québec —Société et Culture (FQRSC) doctoral fellowship and was selected as the Ph.D. recipient of the Walter A. and K. Mary Marsh fellowship in Teaching and Learning. She has taught senior level mathematics for 3 years and served as the honors science program’s academic adviser at Dawson College in Montreal. Her research interests include mathematics and science education, inquiry-based teach-
ing and learning, high-ability learners’ cognitive and metacognitive skills, and the development of learners’ and new teachers’ identity, knowledge, skills, and motivation as inquirers.

Pamela Clinkenbeard is professor of educational foundations at the University of Wisconsin-Whitewater. She codirects the master’s degree emphasis in challenging advanced learners and the licensure program in gifted education. Dr. Clinkenbeard has been a member of the Board of Directors and Recording Secretary of the National Association for Gifted Children and she received the NAGC Early Researcher Award. She is a past president and current board member of the Wisconsin Association for Talented and Gifted and serves on the advisory boards of the Center for Talent Development at Northwestern University and the Gifted Education Resource Institute (GERI) at Purdue University. Dr. Clinkenbeard directed educational programs for the Duke University TIP, coordinated the graduate program in gifted education at the University of Georgia, and served on the faculty of Yale University. She has written several book chapters and has published in *Gifted Child Quarterly* and *the Journal for Education of the Gifted*.

Nicholas Colangelo, Ph.D., is the Myron and Jacqueline Blank Professor of Gifted Education and Director Emeritus of the Belin-Blank Center at The University of Iowa (UI). In December 2012, he was appointed interim dean of the UI College of Education. He is coeditor of *The Handbook of Gifted Education* (three editions) and coauthor of *A Nation Deceived: How Schools Hold Back America’s brightest Students*. Dr. Colangelo’s areas of expertise are the social-emotional needs of gifted students and academic acceleration. He has presented keynotes at major conferences in the nation and around the world. He received the Distinguished Scholar Award, the President’s Award, and the Anne Isaacs Founders Memorial Award from NAGC.

Mary Ruth Coleman, Ph.D., is a senior scientist at the Frank Porter Graham Child Development Institute at the University of North Carolina at Chapel Hill. She directs Project U-STAR-PLUS (Using Science, Talents and Abilities to Recognize Students—Promoting Learning in Underrepresented Students). Other projects have included ACCESS (Achievement in Content and Curriculum for Every Student’s Success), a National Significance Project, and applications of RtI for young children through the Recognition & Response Project sponsored by the Emily Hall Tremaine Foundation. Dr. Coleman’s publications include the 13th edition of *Educating Exceptional Children* by Samuel A. Kirk, James J. Gallagher, Mary Ruth Coleman, and Nicholas J. Anastasiow. She has served as President and on the Board of Directors for the Association for Gifted (TAG), on the Board of the National Association for Gifted Children (NAGC), and was on the Board of Directors for the Council for Exceptional Children (CEC). She was president of CEC in 2007.
**Kristina Henry Collins** is a Ph.D. student at the University of Georgia (UGA), majoring in educational psychology with a concentration in gifted and creative education. Her research focuses on STEM identity development, parent engagement, and multicultural gifted education. Mrs. Collins holds a bachelor’s degree in Engineering (University of Alabama); master’s degree in Mathematics Education (Jacksonville State University); and an Ed.S. in Educational Psychology (UGA) with certification in educational leadership. Mrs. Collins has 18+ years as an educator and administrator, teaching and providing leadership in Title I middle and high school, and undergraduate settings. Mrs. Collins has worked as a Regional Program Coordinator for the Alabama Supercomputing Program to Inspire Research in Education; Program Development Coordinator of the Academy of Liberal Arts at Newton High School, a school-within-a-school magnet program designed for gifted and advanced students; and District-Level Professional Development Instructor of Instructional Technology and Teacher Leader for Georgia Keys to Quality.

**David Yun Dai, Ph.D.,** is an associate professor of educational psychology and methodology at University at Albany, State University of New York. He received his Ph.D. from Purdue University and worked as a postdoctoral fellow at the National Research Center on the Gifted and Talented, University of Connecticut. He teaches courses pertaining to instruction, learning, motivation, and cognition. His research interests include the psychology of talent development and conceptual foundations of gifted education. He has published several books and many journal articles and book chapters on talent development and gifted education. He currently serves on the editorial boards of *Gifted Child Quarterly, Journal for the Education of the Gifted,* and *Roeper Review.*

**Ken Dickson,** a K–12 administrator for more than 30 years, focuses his research and practice on cultural diversity and advanced academics relationships particularly with regard to students with special needs who are traditionally underrepresented in advanced programs. Ken frequently presents on cultural diversity and academic relationships topics in a variety of forums. His advocacy for children with exceptional needs is evidenced by decades of services to various educational groups including service as a board member of the National Association for Gifted Children (NAGC); past chair of NAGC’s Special Populations Network; and membership on many NAGC committees; the board of the Council for Exceptional Children (CEC); the board of The Association for the Gifted; CEC’s Children and Youth Action Network; the board of CEC’s Culturally and Linguistically Diverse Exceptional Learners Division; and the National Alliance of Black School Educators Commission on Special Projects, Research & Evaluation and District Administration.
Robin K. Dickson, Ph.D., is an assistant professor working with a hybrid Ph.D. program in educational psychology and educational technology at Michigan State University. A graduate of the University of Virginia's Curry School of Education in educational psychology with emphasis on gifted and talented education, Dickson pursues her passion for understanding how rich learning environments nurture creativity and high achievement. At the Michigan Virtual School, she helped create “virtual summer camps” and online afterschool programs for middle school students in mathematics and science, as well as enrichment opportunities in research for high school students. Dr. Dickson's current work focuses on how hybrid and online programs, from K–12 through Ph.D., can use new technologies and social media to empower a diversity of learners. She conducts evaluations of gifted and talented programs in K–12 schools, has spoken at state and national conferences, and published numerous book chapters and articles.

Stephanie L. D'Souza is currently a Ph.D. candidate in the Counselor Education and Counseling Psychology doctoral program at the University of Connecticut. She is pursuing a specialty track in gifted and talented education. She received her bachelor's degree in psychology and her master's degree in community counseling from the University of Oklahoma. She has worked in a variety of counseling settings and was a graduate research assistant at the National Research Center on the Gifted and Talented at the University of Connecticut. Her research interests include twice-exceptional student needs, twice-exceptional postsecondary students, qualitative research, and the counseling needs of marginalized groups.

Samantha Fields is currently working toward her doctorate in experimental psychology at East Tennessee State University. She is interested in quantitative psychology and has research interests in individual differences, maladaptive outcomes, trauma and stress events and resilience, and creativity and decision making.

Brent Gault, Ph.D., is an associate professor of music education at the Indiana University Jacobs School of Music. He has taught elementary and early childhood music courses in Texas, Wisconsin, Connecticut, Pennsylvania, and Indiana and specializes in elementary and early childhood music education. Gault has presented at conferences of the American Orff-Schulwerk Association, the Dalcroze Society of America, the International Kodály Society, the International Society for Music Education, the Organization of American Kodály Educators, and MENC: The National Association for Music Education. In addition, he has presented and lectured at colleges and for music education organizations in the United States, Canada, Europe, and China. Gault has published articles in various music education periodicals, including the Bulletin of the Council for Research in Music Education, the Journal
Katherine Gavin, Ph.D., is an Associate Professor at the Neag Center for Gifted Education and Talent Development at the University of Connecticut. The main focus of her research is the development and evaluation of advanced math curriculum for elementary students. Dr. Gavin received the 2006 National Association for Gifted Children Early Leader award and the Neag School of Education Distinguished Researcher Award from the University of Connecticut. She has published more than 100 articles, book chapters, and curriculum materials on mathematics education with a focus on gifted students. She has more than 30 years experience in education as a math teacher, curriculum coordinator, math department chair, and assistant principal. She works with teachers nationally and internationally who are interested in developing mathematical thinking and talent in their students.

Marcia Gentry, Ph.D., directs the Gifted Education Resource Institute at Purdue University where she enjoys working with doctoral students, engaging in research, providing direct services to gifted youth, and working with educators from around the world to improve services for gifted, creative, and talented youth. Her research has focused on the use of cluster grouping; the application of gifted education pedagogy to improve teaching and learning; student perceptions of school; and on nontraditional services and underserved populations. Dr. Gentry developed and studied the Total School Cluster Grouping Model and is engaged in continued research on its effects concerning student achievement and identification and on teacher practices. She is currently directing several research projects aimed toward discovering and developing talents among students from underrepresented populations. She remains active in the field through service to the National Association for Gifted Children and the American Education Research Association and by writing, reviewing, and presenting research aimed to improve education for children, youth, and teachers.

Krista D. Glazewski, Ph.D., is an associate professor of instructional systems technology at Indiana University. Her research examines the use of technology to support student inquiry and problem-solving. A former middle school teacher herself, she also explores means of supporting teachers as they adopt new technological and curricular innovations. She has been a part of leading or directing three large-scale university/school/community partnerships.

Tarek C. Grantham, Ph.D., is an associate professor in the Department of Educational Psychology at the University of Georgia. He teaches in the gifted and creative education program, leading the diversity and equity strand. Dr. Grantham’s research addresses the problem of underrepresentation among ethnic minority students, particularly Black males, in advanced programs. He has
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Miraca U. M. Gross, Ph.D., is Emeritus Professor in the School of Education and Honorary Director of GERRIC at The University of New South Wales in Sydney, Australia. Her research has focused on issues of equity for gifted students, ability grouping, acceleration, socioaffective development, and the highly gifted. She has won several international research awards including the Hollingworth Award for Excellence in Research in Gifted Education and the Mensa International Education and Research Foundation Awards for Excellence. In 2008, Mensa further honored her with their Lifetime Achievement Award. In 2005, the National Association for Gifted Children honored her with their Distinguished Scholar Award (the first time this was awarded to a scholar outside North America). In retirement, she retains her keen interest and involvement in teaching and research within the field of gifted education.

E. Jean Gubbins, Ph.D., is Associate Director of The National Research Center on the Gifted and Talented and professor of educational psychology at the University of Connecticut. Dr. Gubbins is involved in research studies focusing on STEM high schools, math education, and using gifted education pedagogy with all students. Her research interests stem from prior experiences as a classroom teacher, teacher of gifted and talented students, evaluator, educational consultant, and professional developer. She teaches graduate courses in gifted education and talent development related to identification, programming, curriculum development, and program evaluation.

Thomas P. Hébert, Ph.D., is professor of educational studies at the University of South Carolina, where he teaches graduate courses in gifted education. He was a teacher for 13 years, 10 of which were spent working with gifted students at the elementary, middle, and high school levels. He served on the board of directors of the National Association for Gifted Children (NAGC). He was the inaugural recipient of the Mary M. Frasier Equity and Excellence Award from the Georgia Association for Gifted Children for his research contributions on diverse students, received the Neag School of Education Outstanding Alumnus Research Award from The University of Connecticut, and was named an NAGC Early Scholar. He conducts workshops nationally and internationally on topics related to gifted education. His
areas of research interest include social and emotional development of gifted children, underachievement, culturally diverse gifted students, and problems faced by gifted young men.

Nanseol Heo is a Ph.D. candidate in the counselor education and supervision program at The University of Iowa. She is also a research assistant at The Connie Belin & Jacqueline N. Blank International Center for Gifted Education and Talent Development. In 2011, she was awarded the exceptional graduate student recognition from The University of Iowa College of Education. Her research focuses on the social maladaptation of creative and gifted students and career counseling for gifted and talented students.

Holly Hertberg-Davis, Ph.D., is an educational consultant specializing in differentiation of instruction, development of advanced curriculum, and the delivery of effective professional development. She is a former faculty member of the Curry School of Education at the University of Virginia, where she taught courses in the education of the gifted and was a principal investigator for the National Research Center on the Gifted and Talented. She has written and presented extensively on her primary research interests: differentiation of instruction, staff development, and equity in Advanced Placement and International Baccalaureate courses.

Nancy Hertzog, Ph.D., is professor of educational psychology at the University of Washington and the Director of the Halbert and Nancy Robinson Center for Young Scholars. From 1995–2010, she held a faculty position in the Department of Special Education and directed University Primary School (serves children from preschool through first grade) at the University of Illinois at Urbana-Champaign. Her primary area of interest relates to ways that teachers engage and challenge all students. Currently, Dr. Hertzog’s research focuses on how teachers differentiate their instruction to address the diverse needs of their students. She is the author of two books related to early childhood gifted education, and has published in the Journal of Curriculum Studies, Gifted Child Quarterly, Journal for the Education of the Gifted, Roeper Review, Teaching Exceptional Children, Early Childhood Research and Practice, and Young Exceptional Children.

Jessica A. Hockett, Ph.D., is an education consultant specializing in differentiated instruction, curriculum design, and teacher professional development. She has worked with more than 60 school districts on various initiatives related to curricular, instructional, and program improvement. Before earning her Ph.D. in educational psychology from the University of Virginia, Dr. Hockett was a secondary English, social studies, and math teacher in both general and gifted program settings. Her book Exam Schools: Inside America’s
Jennifer L. Jolly received her Ph.D. in educational psychology with a concentration in gifted education from Baylor University. Currently she is an associate professor in elementary and gifted education at Louisiana State University. Her research interests include the history of gifted education and parents of gifted learners. Jolly is the vice-president of The Association of the Gifted (CEC-TAG) and also serves as editor-in-chief of NAGC’s *Parenting for High Potential*. She also is on the editorial advisory board for *Gifted Child Today* and the *Journal for the Education of the Gifted*. She received the Michael Pyryt Collaboration Award from AERA/Research on Creativity, Giftedness, and Talent SIG (with Dr. Alex Garn and Dr. Michael Matthews), the Louisiana Council for Exceptional Children Higher Education Professional of the Year, and the American MENSA Research Award. Before her tenure at LSU, she taught in both gifted and regular education classrooms as a public school teacher.

Susan K. Johnsen, Ph.D., is a professor in the Department of Educational Psychology at Baylor University where she directs the programs related to gifted and talented education. She is editor of *Gifted Child Today*, coauthor of *Identifying Gifted Students: A Practical Guide*, the *Independent Study Program, RtI for Gifted Students, Using the National Gifted Education Standards for University Teacher Preparation Programs, Using the National Gifted Education Standards for PreK–12 Professional Development*; and author of more than 200 articles, monographs, technical reports, and other books related to gifted education. She has authored three tests used in identifying gifted students. She serves on the Board of Examiners of the National Council for Accreditation of Teacher Education (NCATE) and is a reviewer and auditor of programs in gifted education. She is past president of The Association for the Gifted (TAG) and past president of the Texas Association for Gifted and Talented (TAGT).

Jae Yup Jung, Ph.D., is a senior lecturer in the School of Education and a Senior Research Fellow at the Gifted Education Research, Resource and Information Centre (GERRIC) at The University of New South Wales, Australia. His major research interest is in the decision making of gifted and nongifted adolescents on topics such as careers, university entrance and friendships, usually incorporating motivational and cultural perspectives. He has published in a range of journals including *Gifted Child Quarterly, Journal for the Education of the Gifted, Roeper Review, Journal of Career Assessment, Journal of Career Development*, and *Research in Higher Education*.

M. Layne Kalbfleisch, Ph.D., is an associate professor of educational psychology and Director of KIDLAB at George Mason University.
the Chair of the Brain, Neuroscience, and Education SIG in the American Educational Research Association and a founding associate editor of *Frontiers in Educational Psychology*. Her transdisciplinary research examines twice exceptionality and the relationship between talent and disability in autism, attention disorders, and constructivist learning to better understand the roles of physical, emotional, and social information in problem solving. She has more than 30 scholarly publications across educational psychology, special and gifted education, neuroethics, and cognitive neuroscience. She received the inaugural “Scientist Idol” award for messaging science to the public from the National Science Foundation and contributed to the 2007 OECD-CERI publication, “Understanding the Brain: The Birth of a Learning Science.”

**James C. Kaufman, Ph.D.**, is professor of educational psychology at the University of Connecticut. He is the author/editor of more than 20 books and 200 papers on creativity. Kaufman is the President of APA’s Division 10 and was the cofounding editor of *Psychology of Aesthetics, Creativity, and the Arts*. He is currently the founding editor of *Psychology of Popular Media Culture*. His awards include the Daniel E. Berlyne Award and the Paul Farnsworth Award from APA’s Division 10, the E. Paul Torrance Award from the National Association of Gifted Children, the Mensa Education & Research Foundation’s Award for Excellence in Research, and the Early Career Research Award from the Western Psychological Association.

**Stephanie Klupinski** is the Vice President of Legal and Legislative Affairs at the Ohio Alliance for Public Charter Schools. She holds a J.D. from the Moritz College of Law at the Ohio State University, an M.P.P. from the Ford School of Public Policy at the University of Michigan, and a B.A. in English from the University of Pennsylvania. Her research areas include labor relations in charter schools and legal issues in gifted education.

**Robert Kunzman** is professor of education at Indiana University and the managing director of the International Center for Home Education Research (http://icher.og). He has studied homeschooling intensively for 10 years, and is the author of *Write These Laws on Your Children: Inside the World of Conservative Christian Homeschooling*.

**Qin Li** is a Ph.D. student at Claremont Graduate University where she is pursuing a degree in positive developmental psychology. Her primary research goal is to gain a better understanding of the creative process in order to develop methods of creativity enhancement. Her areas of research include creativity, talent development, and other topics related to creativity, such as mental illness, expertise, and aging. She has presented her work at the conferences of the American Psychological Association, the Western Psychological Association, and the Society for Research in Child Development.
Matthew Makel, Ph.D., is a gifted education research specialist at the Duke University Talent Identification Program. He received his Ph.D. from Indiana University. His research examines the nature and development of the abilities, perceptions, and environments of academically talented youth to better understand the factors that lead to the expression of talent. He focuses primarily on academic self-concept, implicit beliefs, long-term outcomes, replication, talent development, and time allocation. He also seeks to communicate and translate research findings to nonresearchers.

Evie Malaia, Ph.D., investigates how linguistic structure (syntax) and meaning (semantics) emerge through network interaction during neural processing of sensory information. Her research employs a combination of motion capture, electrophysiology, and neuroimaging in studying language as a complex system. After earning her Ph.D. at Purdue University working on sign language processing, she trained in the Cognitive Neuroimaging Laboratory at Indiana University. She is currently an assistant professor at the University of Texas at Arlington Southwest Center for Mind, Brain, and Education, Department of Curriculum and Instruction.

Maureen A. Marron, Ph.D., served as an associate research scientist at the Belin-Blank Center’s Institute for Research and Policy on Acceleration from 2006–2013. She was actively involved in the establishment of the Institute for Research and Policy on Acceleration (IRPA) and made a major contribution to the Guidelines for Developing and Academic Acceleration Policy (coauthored by IRPA, the National Association for Gifted Children, and The Council of State Directors of Programs for the Gifted). In fall 2013, she became an assistant professor of education at Iowa Wesleyan College.

Michael S. Matthews, Ph.D., is associate professor and Coordinator of the Academically & Intellectually Gifted graduate programs at the University of North Carolina at Charlotte. He is coeditor of the Journal of Advanced Academics, and is active in the National Association for Gifted Children (which awarded him the Early Scholar Award), and the American Educational Research Association. Dr. Matthews is also a board member and past vice president of the North Carolina Association for the Gifted & Talented. His research focuses on motivation and achievement, including underachievement and dropping out; science learning; gifted education policy; parenting; and issues related to the assessment and identification of gifted learners from diverse backgrounds, particularly English language learners.

Matthew McBee, Ph.D., is assistant professor of experimental psychology at East Tennessee State University where he teaches courses on statistics, experimental design, and quantitative research methodology. He is interested in many aspects of gifted and talented education, with a particular focus on the
identification of gifted students. He has also contributed statistical expertise to research in disciplines such as autism spectrum disorders, reading and writing, pediatric obesity, and transfusion medicine.

**D. Betsy McCoach, Ph.D.**, is an associate professor in the Department of Educational Psychology at the University of Connecticut. Betsy has published more than 75 journal articles, book chapters, and books. Betsy served as the founding coeditor for the *Journal of Advanced Academics*, and she is the current coeditor of *Gifted Child Quarterly*. Betsy serves as a Co-Principal Investigator and research methodologist on several federally funded research grants, and she has served as the Research Methodologist for the National Research Center on the Gifted and Talented for the last 7 years.

**Kimberly McCormick, Ph.D.**, is an assistant professor of learning and assessment in the Teacher Education Department at Salisbury University. She holds a bachelor’s degree in elementary education from Butler University and a master’s degree in educational psychology with a specialization in gifted and talented education from Ball State University. She attended graduate school at Indiana University, where she earned a Ph.D. in learning and developmental sciences with a specialization in educational psychology. She teaches courses in educational psychology, assessment, and gifted and talented education. Her research interests include gifted and talented education, connecting student engagement to the academic and social needs of gifted and talented students, and understanding and measuring student engagement in schools.

**Tracy C. Missett, Ph.D.**, is an assistant professor at Sweet Briar College. She holds a bachelor’s degree in rhetoric and communications studies from the University of Virginia, a law degree from the University of California, Hastings College of the Law, a master’s degree in education from Teachers College, Columbia University, and a Ph.D. in Educational Psychology from the University of Virginia. Her research interests include twice-exceptional students, particularly those with emotional disabilities, and creativity as a component of giftedness.

**Sidney M. Moon, Ph.D.**, is professor of gifted, creative, and talented studies and Associate Dean for Learning and Engagement in the College of Education at Purdue University. She has been involved in the field of gifted, creative, and talented studies for 31 years. In that time, she has contributed more than 75 books, articles, and chapters to the field. Sidney is active in the National Association for Gifted Children where she has served as Chair of the Research and Evaluation Division, a member of the Board of Directors, and Association Editor. Currently, she is serving as treasurer of the American Educational Research Association Special Interest Group (SIG), Research on Giftedness, Creativity, and Talent. Her research interests include talent devel-
development in the STEM disciplines (science, technology, engineering, and mathematics), academic talent development, and personal talent development.

**Sharlene Newman, Ph.D.**, is a cognitive neuroscientist in the Department of Psychological and Brain Sciences and the programs in cognitive science and neuroscience at Indiana University. Her research is very much concerned with questions of how different regions of the brain work together, and how the functional connectivity (or the communication) between regions vary with task, context, and individual differences in ability. To date, she has worked to obtain a clearer perspective of the functional and synergistic activities of neuro-cognitive networks. The investigation of individual differences is a thread that runs through her research on language processing and problem solving. The research tool that she has primarily used is functional MRI. However, recently she has begun to incorporate diffusion tensor imaging to explore structural connectivity, as well as electrophysiological techniques, in order to more precisely examine the temporal dynamics of cognition.

**Paula Olszewski-Kubilius, Ph.D.**, is the Director of the Center for Talent Development and a professor in the School of Education and Social Policy at Northwestern University. Her most recent work is a coauthored monograph: “Rethinking Giftedness and Gifted Education: A Proposed Direction Forward Based on Psychological Science.” She has served as editor of *Gifted Child Quarterly*, coeditor of the *Journal of Secondary Gifted Education*, and on the editorial review boards of *Gifted and Talented International*, *Roeper Review*, and *Gifted Child Today*. She currently is on the board of trustees of the Illinois Mathematics and Science Academy and the Illinois Association for the Gifted and serves on advisory boards for the Center for Gifted Education at The College of William and Mary and the Robinson Center for Young Scholars at the University of Washington. She has served as president of the National Association for Gifted Children from whom she received the Distinguished Scholar Award.

**Stuart Omdal, Ph.D.**, was an elementary teacher for 15 years, both in the regular classroom and as a gifted education coordinator facilitating the Schoolwide Enrichment Model. Since completing graduate school at the University of Connecticut in 1995, he has been a professor of gifted education at the University of Northern Colorado (UNC). He is the Director of the Summer Enrichment Program and Director of the Center for the Education & Study of Gifted, Talented, Creative Learners at UNC. His professional interests include creativity in education, twice-exceptionality, underachievement of students from nondominant cultural and language groups, and the implementation of Response to Intervention in gifted education. He is on the board of directors for the Association for the Education of Gifted Underachieving Students (AEGUS) and the Colorado Association for Gifted and Talented
(CAGT), and has served on board of directors for the National Association for Gifted Children.

Anne T. Ottenbreit-Leftwich, Ph.D., is an associate professor of instructional systems technology at Indiana University. Her expertise lies in the areas of the design of digital curriculum resources, the use of technology to support preservice teacher training, and development/implementation of professional development for teachers and teacher educators. Her current research focuses on teachers’ value beliefs related to technology and how those beliefs influence teachers’ technology uses and integration.

Jean Sunde Peterson, Ph.D., Professor Emerita at Purdue University, was a classroom teacher for many years and was named State Teacher of the Year. She developed summer foreign language day camps for children prior to graduate work in counseling and development at the University of Iowa. She directed school counselor preparation for several years at Purdue University and continues to focus most of her research and writing on concerns related to the social and emotional development of high-ability youth. Her national and international workshops, conference keynotes, and presentations address those areas, as well as academic underachievement, bullying, negative life events, development-oriented group work with children and adolescents, and listening/responding skills for teachers and parents. She has authored more than 100 books, invited chapters, and journal articles; has received national awards for scholarship; and has received awards at Purdue for teaching, research, and service.

Rebecca L. Pierce, Ph.D., is associate professor of mathematical sciences at Ball State University, Director of Undergraduate Programs, and a former fellow at the Center for Gifted Studies and Talent Development. Dr. Pierce has taught mathematics and statistics to elementary, middle school, high school, and college students. Dr. Pierce directs the Ball State Institute for the Gifted in Mathematics. She has authored or coauthored numerous publications in professional journals, as well as several books and book chapters and has made presentations on statistics, statistical methods and career opportunities for mathematics and statistics majors. With other Ball State colleagues, she was awarded several Javits’ grants. She serves as a reviewer for Roeper Review, Gifted Child Quarterly, Journal for the Education of the Gifted, and Teaching Statistics and as an editor for The Statistics Teacher Network. She received the Leadership Award from the Indiana Association for the Gifted.

Jane Piirto, Ph.D., is Trustees’ Distinguished Professor at Ashland University. She is the author of 17 books, both scholarly and literary, including Talented Children and Adults: Their Development and Education (three editions), Understanding Creativity, Understanding Those Who Create (2 editions),
“My Teeming Brain”: Understanding Creative Writers, Creativity for 21st Century Skills, The Three-Week Trance Diet, A Location in the Upper Peninsula, Saunas, six poetry and creative nonfiction chapbooks, and many scholarly articles and chapters. She was awarded Distinguished Scholar of the National Association for Gifted Children and won a Lifetime Achievement Award from the Mensa Education and Research Foundation.

**Sally M. Reis, Ph.D.,** is the Interim Vice Provost for Academic Administration, a Board of Trustees Distinguished Professor, and Teaching Fellow in Educational Psychology at the University of Connecticut where she also serves as Principal Investigator at The National Research Center on the Gifted and Talented. She was a teacher for 15 years, 11 of which were spent working with gifted students on the elementary, junior high, and high school levels. She has authored more than 130 articles, 14 books, 60 book chapters, and numerous monographs and technical reports. Dr. Reis serves on several editorial boards and is the past president of the National Association for Gifted Children.

**Ronald Reeve, Ph.D.,** is Director of the Curry Programs in Clinical and School Psychology at the University of Virginia. He completed his Ph.D. in Education and Psychology at the University of Michigan. For 3 years, prior to joining the faculty at the University of Virginia, he served as a school psychologist in Michigan. He has conducted research and engaged in public policy work in the areas of high incidence disabilities in children, including learning disabilities and attention deficit hyperactivity disorders. For the past several years, Dr. Reeve’s work has focused on children with autism spectrum disorders. He serves as the supervising psychologist for the Curry Autism Spectrum Services specialty clinic, where he and his research team are actively researching a range of ASD-related topics, including parent stress and coping, validity of assessment techniques, and enhancing safe driving among adolescents and young adults with high functioning levels of ASD, among others.

**Joseph S. Renzulli, Ph.D.,** is a professor in the Department of Educational Psychology at the University of Connecticut and was selected as a Board of Trustees Distinguished Professor. He holds dual directorships at the Neag Center for Gifted Education and Talent Development and the federally funded The National Research for the Gifted and Talented. He is noted for developing the three-ring conception of giftedness and the Schoolwide Enrichment Model. His research has focused on the broadening of the process of identification and the development of giftedness in young people and on organizational models and curricular strategies for total school improvement. A focus of his work has been on applying the strategies of gifted education to the improvement of learning for all students. He is a Fellow in the American
M. R. E. Richards, Ed.D., is an educational consultant in gifted education, curriculum design, and differentiation and is an adjunct professor at the University of Northern Colorado in both gifted and science education. Her background in science and education allows her to understand the needs of both fields and design curriculum to meet the educational growth of a diverse student population while including the background content and skills in science that are needed in high school and postsecondary education.

Anne N. Rinn, Ph.D., is an associate professor of educational psychology and the coordinator of the graduate program in gifted and talented education in the Department of Educational Psychology at the University of North Texas. She holds a Ph.D. in educational psychology, with a minor in higher education and student affairs, from Indiana University. Her research focuses on the academic, social, and emotional development of gifted adolescents and college students, as well as the effects of gifted programming on student development as a whole. She is an active member of the National Association for Gifted Children, the Texas Association for the Gifted and Talented, and the American Educational Research Association.

Julia Link Roberts, Ed.D., is the Mahurin Professor of Gifted Studies at Western Kentucky University. She is Executive Director of The Center for Gifted Studies and the Carol Martin Gatton Academy of Mathematics and Science in Kentucky. She is President of The Association for the Gifted, a division of the Council for Exceptional Children, and a member of the Executive Committee of the World Council for Gifted and Talented Children. Dr. Roberts received the National Association for Gifted Children Distinguished Service Award and the Acorn Award as the outstanding professor at a Kentucky college or university.

Ann Robinson, Ph.D., is professor of educational psychology and Director of the Jodie Mahony Center at the University of Arkansas at Little Rock where she coordinates the graduate programs in gifted education. She is a former editor of the Gifted Child Quarterly, was President of the National Association for Gifted Children, and received the Early Leader, the Early Scholar, and the Distinguished Service Awards from NAGC. In 2003, “A National Study on Local and State Advocacy in Gifted Education” was juried as the Gifted Child Quarterly Paper of the Year. She was recognized as the Purdue University Alumna of Distinction for the College of Education, was honored by the William Jefferson Clinton Presidential Library for her public service, and was the University of Arkansas recipient of the Faculty Excellence Award for Research. Ann publishes and presents nationally and internationally.
on advocacy, biographical inquiry, and evidence-based interventions for teachers and students.

**Bryan J. Rothenberg** is a Juris Doctorate Candidate, expected 2014, at Capital University Law School. He has a bachelor's degree from Ohio University with a focus in finance and economics. He was a legal intern at Ohio Alliance for Public Charter Schools, and his research interests include minority representation in gifted education.

**Stephen T. Schroth** holds a Ph.D. in educational psychology/gifted education from the University of Virginia. He serves as an assistant professor of educational studies at Knox College in Galesburg, IL, before which he worked as a classroom teacher, literacy coach, and gifted coordinator with the Los Angeles Unified School District. With Jason A. Helfer, Dr. Schroth has been the recipient of the 2008, 2010, and 2011 MENSA Education & Research Foundation Award for Excellence in Research and of the Philip Wright Green/Lombard College Prize for Distinguished Teaching, Knox College’s highest recognition for classroom excellence. The author of more than 300 monographs, articles, reviews, and other curricular materials, recent publications include “Identifying Gifted Students: Educators Beliefs Regarding Various Processes and Procedures” in the *Journal for the Education of the Gifted* (with J. Helfer). He is a past Chair of the Arts Network of the National Association for Gifted Children.

**Bruce M. Shore, Ph.D.,** is Emeritus Professor of Educational Psychology at McGill University in Montreal, Fellow of the American Educational Research Association, and a licensed teacher and psychologist. For 21 years, he held a jointappointment in McGill’s teaching-improvement unit. He served as Department Chair, McGill Association of University Teachers President, and Dean of Students. Awards include the National Association for Gifted Children’s Distinguished Scholar, The McGill Faculty of Education Distinguished Teaching Award, the David Thomson Award for Graduate Supervision and Teaching, and the Principal’s Prize for Excellence in Teaching. His research is on intellectual giftedness and on inquiry-based teaching and learning.

**Del Siegle, Ph.D.,** is a professor in gifted and talented education and Head of the Department of Educational Psychology at the University of Connecticut. He is a past president of the National Association for Gifted Children (NAGC) and chair-elect of the Research on Giftedness, Creativity, and Talent SIG of the American Educational Research Association (AERA). Along with Betsy McCoach, he is coeditor of *Gifted Child Quarterly*. He also writes a technology column for *Gifted Child Today*. Dr. Siegle is coauthor with Gary Davis and Sylvia Rimm of the popular textbook, *Education of the Gifted*
and Talented. He is also author of a new book, The Underachieving Gifted Child: Recognizing, Understanding, and Reversing Underachievement.

Katherine Strand, Ph.D., is an associate professor of music education at the Indiana University Jacobs School of Music where she teaches undergraduate and graduate courses and directs the International Vocal Ensemble. She has taught pre-kindergarten through 12th-grade public school music in Virginia and Illinois. Strand specializes in classroom composition, action research, and integrated arts curriculum development. She has presented sessions at the national conferences of numerous music association conferences. Her articles have appeared in Music Education Research, the Journal of Research in Music Education, the Journal of Music Teacher Education, the Bulletin of the Council for Research in Music Education, Arts Education Policy Review, Philosophy of Music Education Review, General Music Today, Music Educators Journal, and Teaching Music.

Dana Thomson is Research Director at the Center for Talent Development at Northwestern University’s School of Education and Social Policy. Her research interests include the social and emotional development of gifted students, the role of the family in talent development, the development of creative potential, and the needs of special populations of gifted children. She received a bachelor’s degree in philosophy from Carleton College and a master’s degree in education, with a concentration in gifted, from Northwestern University.

Carol Ann Tomlinson, Ed.D., is William Clay Parrish, Jr. Professor and Chair of Educational Leadership, Foundations, and Policy at The University of Virginia’s (UVA) Curry School of Education and Co-Director of the Curry Institutes on Academic Diversity. She has been recognized as Outstanding Professor at Curry and has also received an All-University Teaching Award. She is author of many books on differentiated instruction, including How to Differentiate Instruction in Mixed-Ability Classrooms; The Differentiated Classroom: Responding to the Needs of All Learners; Integrating Differentiated Instruction and Understanding by Design (with Jay McTighe); and Leading and Managing a Differentiated Classroom (with Marcia Imbeau). Dr. Tomlinson has also served as President of NAGC. Prior to joining the faculty at UVA, she was a public school teacher and was selected Virginia’s Teacher of the Year in 1974. She works throughout the U.S. and internationally with educators who seek to develop classrooms that are responsive to the varied needs of learners.

Nicholas Uzl is a Juris Doctorate Candidate, expected 2014, at the Moritz College of Law at The Ohio State University. He earned a bachelor’s degree in political science, with a focus on American politics from Kent State University. He served as a legal intern with the Ohio Alliance for Public Charter Schools. His research interests include gifted education programs in charter schools.
Joyce VanTassel-Baska, Ed.D., is Professor Emerita at The College of William and Mary, where she founded the Center for Gifted Education. She directed the Center for Talent Development at Northwestern University, served as state director of gifted programs in Illinois, and also served as a regional director, a local coordinator of gifted programs, and a teacher of gifted high school students. Her major research interests are in the talent development process and effective curricular interventions with the gifted. An author of 22 books and more than 500 other publications on gifted education, she was the editor of Gifted and Talented International and received the Distinguished Scholar Award from the National Association for Gifted Children and the Outstanding Faculty Award from the State Council of Higher Education in Virginia. She has received the President’s Award from the World Council on Gifted and Talented and the Collaboration and Diversity Service Award from CEC-TAG.

Jordan Wade is a doctoral student in the Curry Programs in Clinical and School Psychology at the University of Virginia. Prior to beginning her graduate training, she worked at The Mariposa School in Cary, NC, which uses the principles of Verbal Behavior and Applied Behavior Analysis to teach functional communication skills to children with autism spectrum disorders. At Mariposa, she provided individualized instruction and taught social skills groups. Jordan is currently a member of the Curry Autism Spectrum Disorders Research Group; her research interests include evaluating outcomes of behavior-oriented early intervention programs for children with ASD and developing family support programs. Additionally, she conducts comprehensive diagnostic assessments within the Curry Autism Spectrum Services specialty clinic at the Sheila C. Johnson Center at the Curry School of Education.

Kristofor Wiley, Ph.D., is an assistant professor in education at Drury University. He developed curriculum and trained teachers with Project Parallax at the University of Virginia before completing his dissertation on the social and emotional traits of gifted students. His research interests also include teacher education, program evaluation, and the conceptual foundations of the field.

Frank Worrell, Ph.D., is a professor in the Graduate School of Education at the University of California, Berkeley. He also serves as director of the school’s psychology program, faculty director of the Academic Talent Development Program, and a faculty director of the California College Preparatory Academy. His research centers on academic talent development, the relationship of psychosocial variables to academic and psychological functioning and the translation of research findings into school-based practice. Dr. Worrell is a coeditor of the Review of Education Research; a Fellow of Divisions 5, 16, and 52 of the American Psychological Association; a Fellow of the Association of
Psychological Science; and an elected member of the Society for the Study of School Psychology.