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REVIEW

Assessment of Intelligence in the Preschool Period

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Abstract Intelligence testing has a long and revered history in psychological measurement in childhood. Yet, the years between infancy and early childhood have been understudied with respect to emergent intellectual and cognitive functioning. Factor analytic models of intelligence that have demonstrated applicability when testing older children and adults often appear inadequate in the preschool period. As more is learned about brain development in typically developing children during these crucial years the distinctive relationships between neural system development and intellectual functioning are being revealed more completely. The aim of this paper was to provide a brief historical background as a foundation for discussion of intelligence testing, review what is known about the dynamic course of brain development during the preschool years, acknowledge limitations specific to intelligence testing in young children, and provide support for maintaining a comprehensive neuropsychological perspective that considers the wider range of variables that influence intellectual functioning in the preschool period.

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Introduction

A test of general intelligence is established protocol when a preschool-aged child is referred for a clinical psychological evaluation. Historically, an intelligence test was often the sole measure administered since the derived intelligence quotient (IQ) was considered a sufficiently reliable predictor of later academic and vocational outcomes. For many years, testing to discriminate discrete cognitive functions was rare between the ages of 2 and 5 years although supplemental tests of basic language, motor, or visual-motor skills might be administered and/or parental impressions about their child's behavior obtained through structured interview or questionnaire. A prevailing opinion was that reliable measurement of a child's general intelligence was only obtainable once a child reached 4 or 5 years of age (Sattler 1988). Assessment instruments for preschool aged children have improved considerably. Currently, advances in test construction inclusive of well-stratified normative data for very young children, clinicians with the training and experience to evaluate young children, and cross-discipline interest in both the normal developmental course as well as the adverse effects of disease or disorder incurred at a young age have combined to support efforts to better understand intellectual development over the preschool years.

However, a caveat should precede the discussion of intelligence that follows. That is, *an intelligence test provides merely a limited sampling of behavior at preschool age and, therefore, does not directly inform about the integrity of specific brain regions or general brain functioning*. Intelligence is but one construct that is of interest when evaluating young children. An overemphasis on intelligence testing to the exclusion of the other relevant domains that comprise any individual's more elaborated functioning has not served child, familial, or societal concerns well. A more thorough evaluation is required to reach a finer level of detail about neuropsychological competence.

This paper first summarizes several key historical developments in intelligence testing and studies that tested these theories and models in preschoolers. The paper continues with a brief review of brain development specific to the preschool years, a summary of contemporary preschool intelligence testing and its advantages and limitations, and concludes with suggestions for future directions.

Historical Foundations of Intelligence Testing

Intelligence has been a thoroughly studied construct within the psychological community for decades, and it continues to be defined, refined, theorized, and extensively researched. It is outside the purpose of this paper to choose among the many definitions of intelligence that have been proposed but coverage of these and of landmarks in intelligence theorizing and testing are available to the interested reader elsewhere, e.g., (Sternberg and Berg 1986; Sattler 2001). A brief summary of several key developments in intelligence theory and factor analytic models follows to facilitate an appreciation for the historical and contemporary perspectives that are the basis for any discussion of intelligence and its measurement (see also Table 1).

Table 1 Landmarks in Intelligence Testing

- Sir Francis Galton (b. 1822 – d. 1911) introduced application of statistical methods in study of individual differences, providing a foundation for intelligence test development
- 1905: Alfred Binet and Theodore Simon introduce the Binet-Simon Intelligence Test
- 1912: Wilhelm Stern introduced the use of a ratio measure of intelligence to calculate an Intelligence Quotient
- 1916: Lewis Terman revision of the Binet-Simon Intelligence Test, creating the Stanford-Binet Intelligence Scale
- 1923: Charles Spearman proposes a two-factor model of intelligence, originating the notion of psychometric *g* and a second special intelligence factor, *s*
- 1938: Louis Leon Thurstone proposes seven primary mental abilities
- 1939: David Wechsler incorporates deviation IQ, replacing use of the ratio IQ
- 1950s: Philip E. Vernon's two factor model: verbal-educational (v:ed) and spatial-mechanical (k:m)
- 1960s: Raymond Cattell's two factor model: Gf (fluid intelligence) and Gc (crystallized intelligence)
- 1975: J. P. Das re-introduces Alexsandr Luria's simultaneous and successive information processing/synthesis as a two-factor theory
- 1983: Howard Gardner's Theory of Multiple Intelligences
- 1990s: John Carroll's Three-stratum Theory, the Cattell-Horn-Carroll theory of intelligence
- 1986: Robert Sternberg's Triarchic Theory of Intelligence
- 2005: Wendy Johnson and Thomas J. Bouchard Jr.'s Four-stratum Model
- 2007: Rex Jung and Richard Haier Parieto-Frontal Integration Theory of Intelligence

In the late nineteenth century Sir Francis Galton demonstrated that the Laplace-Gauss "normal" distribution could be applied to such human psychological attributes as intelligence and initiated the discussion of individual differences and intellectual inheritance (Galton 1869; Simonton 2003). In 1905, Alfred Binet and Theodore Simon introduced the Binet-Simon Intelligence Test as a means to distinguish between children who had mental retardation or behavioral problems. In 1912, Wilhelm Stern introduced a ratio measure of intelligence to calculate an Intelligence Quotient (IQ), defined as Mental Age/Chronological Age x 100 (Stern 1912). Lewis Terman authored the "Stanford Revision and Extension of the Binet-Simon Intelligence Scale" in 1916, the first Stanford-Binet Intelligence Scale (Terman 1916).

A significant theoretical formulation was Charles Spearman's proposal of a two-factor model of intelligence in the 1920s. He originated the notion of psychometric "*g*" as an innate general mental ability factor that accounted for individual differences in ability. In this seminal conceptualization, *g* is a general mental factor and *s* is a second tier "special intelligence" factor representing one or more other specific factors (Spearman 1923). Thus, *g* is a highly heritable component of intellectual function common to multiple cognitive tests and more heritable than specific cognitive abilities (Thompson et al. 2001). Notably, while all intelligence tests measure *g* to some degree, all intelligence tests do not measure *g* to the same degree (Jensen 1998). The *g*-loading of a given intelligence test is increased if the test measures a large number of mental processes (Arend et al. 2003), and as *g*-loading increases more widespread brain areas become involved (Colom et al. 2006). Test heterogeneity with respect to measurement of *g* has resulted from differing perspectives on how to measure such a complex construct as human intelligence (Colom 2007). Many tests of intelligence tend to confound *g* with other cognitive abilities and skills whereas a test with a perfect *g*-loading would encompass most mental processes relevant to *g* (Colom et al. 2002). However, no specific cortical regions underlie intelligence. Instead, individual differences in intelligence reflect aspects of brain function that enable more efficient use of cortical structures and resources that are associated with specific cognitive abilities (Blair 2007).

In the 1930s, Louis Thurstone expressed an alternative to Spearman's two-factor theory, identifying seven primary mental abilities (but not including Spearman's general factor): numerical reasoning, word fluency, verbal meaning or comprehension, memory, reasoning, spatial, and perceptual speed. These were the foundation of the Primary Abilities Test

(Thurstone 1938). Also in the 1930s, Stern's ratio IQ was replaced by the deviation IQ in use today in which the individual's performance is compared to that of similarly aged peers along a normal distribution of scores. The deviation IQ is a means by which intelligence can be measured with stability over time (Bjorklund 2005). It came into wide use with the development of the Wechsler series of intelligence tests (Wechsler 1939), and replaced the use of the ratio IQ in the 1960 revision of the Stanford-Binet Intelligence Scale. Unlike prior intelligence tests, the Wechsler intelligence test extended sampling of behaviors to include subtests that do not load highly on *g*. Thus, the summary full scale IQ may best be considered a measure of "intelligence in general," comprising an array of cognitive abilities and skills in addition to *g*, the central component of the intelligence construct (Lubinski 2004; Colom 2007).

The mid-twentieth century saw an expansion of theories about intelligence. In 1950, Philip Vernon published an hierarchical group-factor theory of the structure of cognitive abilities with general ability, similar to Spearman's *g,* at the peak, two major group factors below [verbal-educational (v:ed); spatial-mechanical (k:m)] that were subdivided into six minor group factors and with lower specific factors at the base (Vernon 1950). In the 1960s, Cattell theorized *g* as a different two-factor model than specified in Spearman's model, postulating fluid intelligence (*g*F) and crystallized intelligence (*g*C) factors (Cattell 1963). According to this prominent model, *g*F is a measure of such flexible capacities as broad reasoning, novel problem solving, and procedural knowledge whereas *g*C is dependent on educational experiences and stored factual information acquired over one's lifetime, such as lexical (vocabulary) and arithmetical knowledge, i.e., skills and knowledge learned by experience or through the cultural milieu. Empirical data subsequently demonstrated that *g*C is more resistant than *g*F to the effects of a brain insult or other interruption in the course of normal development, and that *g*C is more stable than *g*F over the lifespan (Waltz et al. 1999). This suggested the clinical relevance of the Wechsler vocabulary and information subtests as preliminary indicators of premorbid intellectual functioning. Cattell and John Horn subsequently identified additional factors (Horn and Cattell 1966) that were the basis for the construction of both the Stanford-Binet Intelligence Scale-Fourth Edition (Thorndike et al. 1986) and the Woodcock-Johnson Psychoeducational Battery-Revised (Woodcock and Johnson 1989). In the 1990s, John Carroll proposed a hierarchical Three-stratum Theory, with *narrow* specialized abilities at the lower level, a subset of *broad* abilities at a higher mid-level, and a *general* overall measure of ability (similar to full scale IQ) at the peak (Carroll 1993; McGrew 2005). This further refinement, the Cattell-Horn-Carroll (C-H-C) theory of intelligence, has received substantial empirical and statistical support and became the theoretical foundation of the Stanford-Binet-Fifth Edition (SB-V), and other tests as shown in Table 2. The theory was later extended to include additional components besides *g*F and *g*C*:* quantitative reasoning (*g*Q*),* reading and writing *(g*RW*),* visual processing (*g*V*),* auditory processing *(g*A*)* short-term memory (*g*SM*)*, and long-term retrieval (*g*LR).

Among other proposed models was a two-factor theory based on Luria's theory of simultaneous and successive information processing and synthesis that was the basis for development of the Kaufman Assessment Battery for Children (Das et al. 1975), a theory of multiple intelligences emphasizing that not all intelligences are measured by standard psychometric instruments (Gardner 1983), and the triarchic theory of intelligence with its emphasis on analytic skill and creative and practical aspects of individual functioning (Sternberg 1985, 1999). Models continue to be developed and advocated. For example, an alternative theory to the fluid-crystallized model added memory and higher-order image rotation factors in a four-stratum model (*g* and three third-stratum factors) emphasizing the importance of brain laterality and coordinated brain function in intellectual performance. The proponents consider *g* and *g*F as effectively equivalent (Johnson and Bouchard 2005). Another model, the Parieto-Frontal Integration Theory of intelligence relates frontal-parietal network efficiency in processing information with intelligence (Jung and Haier 2007); extrastriate cortex and fusiform gyrus are related to intelligence test performance because these structures are involved with the recognition and elaboration of visual input that is then processed in the supramarginal, superior parietal, and angular gyri of the parietal lobe concerned with symbolism and abstraction. Parietal regions then interact with frontal lobe regions in a working memory network to enable comparison of different tasks and responses, a process dependent on white matter fiber connections between different areas of the brain. This theory was published along with accompanying critical commentary by a number of other theorists [see for example (Blair 2007; Colom 2007)]. One critique was of the model's failure to recognize response selection and rapid information processing since IQ depends on an individual's ability to consider potential correct answers, choose from among alternatives, and process information rapidly (Kadosh et al. 2007). This latter opinion is of particular interest with respect to intelligence testing in preschoolers whose interaction style and cognitive effectiveness are closely linked to their ability to select responses and process information rapidly, among other factors often not measured psychometrically.

Finally, this admittedly brief history is not complete without mentioning that other theoreticians have critiqued intelligence tests and the construct "IQ," e.g., (Ceci 1990). Such critiques are shared to some extent by clinicians who repeatedly observe the flaws in presuming an IQ offers a complete or sufficient assessment for a very young child. An

Table 2 Selected preschool intelligence tests by age range, normative year, standardization sample size, and model

	Age range	Normative year	N	Model
Infant scales				
Mullen Scales of Early Learning	Birth to 5.8 years	1990	1,849	Developmental
Bayley Scales of Infant and Toddler Development, Third Edition	0 to 3 years	2000	1,700	Developmental
The Griffiths Mental Development Scales, Extended Revised	2 to 8 years	2004	1,026	Developmental
Preschool Tests				
Cattell Culture Fair Intelligence Test, Scale 1	4 to 8 years	1961	400+	Cattell-Horn-Carroll
McCarthy Scales of Children's Abilities	2.5 to 8.5 years	1970	1,032	*g*/general intelligence
NEPSY-II	3 to 16 years	1994–1996	1,000	Lurian
Das-Naglieri Cognitive Assessment System	5.0 to 17.11 years	1997	2,200	Planning, Attention-Arousal, Simultaneous and Successive (PASS)
Stanford-Binet Intelligence Scales, Fifth Edition	2 to 85+ years	2000	4,800	Cattell-Horn-Carroll
Woodcock-Johnson Tests of Cognitive Ability, Third Edition	2 to 90+ years	2000	8,818	Cattell-Horn-Carroll
Reynolds Intellectual Assessment Scales	3 to 94 years	2001	2,438	Cattell-Horn-Carroll
Kaufman Assessment Battery for Children, Second Edition	3 to 18 years	2001–2003	3,025	Lurian & Cattell-Horn-Carroll
Differential Ability Scales, Second Edition	2.6 to 17.11 years	2002	3,480	*g*/general intelligence
Wechsler Preschool and Primary Scale of Intelligence, Third Edition	2.6 to 7.3 years	2002–2003	1,700	*g*/general intelligence & Cattell-Horn-Carroll

IQ score by its very nature fails to indicate the type or severity of underlying brain dysfunction, making unique reliance on this well-established method of assessment a questionable protocol that deserves qualification and reconsideration with respect to the distinctive genetic, biological, sociocultural, experiential, and behavioral factors associated with the individual being assessed.

Intelligence Theories in Practice

A relatively sparse literature on intelligence testing at preschool age contrasts with extensive reports about older children and adults. While intelligence tests are mostly developed with a defined theoretical basis, not all specify a specific factor analytic model of intelligence (Elliott 2007). Of essential importance in preschool evaluation is knowledge that even when a test is constructed based on one or another factor analytic model, its factor structure may not be universally applicable at all chronological ages. A meaningful and consistent finding in intelligence test research has been that intelligence refers to qualitatively different abilities in preschoolers compared with older children, irrespective of which model of intelligence is endorsed.

Intelligence is more homogeneous during the preschool years than during later childhood (Bjorklund 1999). For example, whether measures of discrete component factors that are identifiable in older children and adults might be similarly discriminated in preschoolers was studied in typically developing children. The C-H-C factor analytic model of intelligence underlying the SB-V measured separable C-H-C factors in older children but not at the preschool age for whom a simple one-factor model better represented their abilities (Ward et al. 2011), consistent with the notion of homogeneity of intelligence. In another study, preschool Piagetian preoperational tasks of cognitive ability had only a low correlation with later intelligence testing whereas Piagetian formal operational cognitive tasks by school-age children were more highly correlated with later intelligence testing (Schneider et al. 1999). Such data add an interesting dimension to considerations regarding the early trajectory of normal brain development and highly variable inter-individual stages of normal child maturational progress. Consequently, there is a greater likelihood that an assessment of a young child will be less stable compared with results obtained for an older child whose cognitive abilities are separable into distinct areas of intellect, i.e., independent from *g*. That intelligence testing at a young age is not predictive of test results at an older age is only partly due to differences in the cognitive functions measured at preschool and older ages. It is also the result of extenuating circumstances that complicate any attempt to assess a very young child, for example, the quality of the rapport established between examiner and examinee.

Studies of child clinical diagnostic groups have affirmed conclusions reached from those of typically developing children. The ability to predict different cognitive abilities at age five (Wechsler Preschool and Primary Scales of Intelligence-III) from results of cognitive development at ages two and three (Bayley Scales of Infant Development-

II, the Child Behavior Checklist, and neurological examination) was studied in children born before 30 weeks' of gestation and/or with birth weight below 1,000 g. Cognitive development at ages 2 and 3 years explained 44 % and 57 % of the variance of full scale IQ at age 5, respectively. Although psychomotor, neurological, and behavioral variables did not improve prediction, the addition of perinatal and sociodemographic characteristics explained 57 % and 64 % of the variance, respectively. However, the Bayley Mental Development Index (MDI) at ages two and three did not predict all aspects of intelligence well, with processing speed and performance intelligence predicted less accurately (Potharst et al. 2012). While the Bayley MDI, and by inference other infant developmental scales, is acknowledged to be limited with regard to prediction of later IQ (Hack et al. 2005) it was interesting that Bayley-II MDIs obtained at 24 months were better at predicting IQ at age 8–9 years than MDI scores obtained at 18 months in an extremely low birth weight cohort (Doyle et al. 2012). Such data suggest that the abilities of infants and young children mature especially rapidly and that prediction becomes more reliable with even relatively small increments of increasing chronological age. The participants' prematurity further underscores the importance of awaiting sufficient maturational progress before concluding that any IQ measurement is reliable at such an early age. Notably, infant development scales such as the Bayley Scales were not designed to assess *g* and are instead most useful as a means to assess whether there is evidence of a developmental delay. Moreover, even a child of intact intellectual ability may demonstrate an initially slow rate of development during their infancy.

The clinical utility of psychometrically sound preschool intelligence tests relates largely to the insights made possible by the administration of their diverse subtests. The clinician may then compare an individual child's summary, index, and subtest scores with the normative sample, i.e. children of similar chronological age, and generate informed hypotheses while also incorporating qualitative features of the child's behavior observed during the course of the testing. Additionally, intelligence testing is well known to practitioners in other disciplines and the IQ concept is broadly understood by non-psychologists (Baron 2004).

Brain Development at Preschool Age

Human brain development is a protracted process influenced by prenatal and postnatal events that cumulatively contribute to an individual's unique characteristics and proficiency carrying out highly specialized cognitive functions. Until recently much of what was known about the correspondence between neuroanatomy and intellectual performance had been extrapolated to preschoolers from studies of older individuals, often from data collected on clinical rather than typically developing populations. The rapid brain development of the human gestational period is followed postnatally by a slower rate of structural neuroanatomical change that continues into the preschool years. This development provides a foundation for the formation of distributed neural network systems that underlie intelligence, more complex cognitive activities, and the mechanisms supporting brain plasticity, i.e., the reorganization in response to insult as intact structures assume cognitive functions previously mediated by now dysfunctional brain regions.

Adult studies have demonstrated positive correlations between general intelligence and brain volume, particularly in prefrontal cortex [PFC], the temporal lobes, and areas of multimodal association (Haier et al. 2004; Choi et al. 2008; Karama et al. 2009; Narr et al. 2007; Rushton and Ankney 2009), and modest associations between intelligence and the size of some specific areas, i.e., hippocampal, parietal, and temporal regions (Andreasen et al. 1993; Flashman et al. 1997; MacLullich et al. 2002; McDaniel 2005; Witelson et al. 2006). Total brain volume has been shown to have a positive and moderate correlation with intelligence (0.33) (McDaniel 2005). In particular, frontal gray matter volume was significantly positively correlated with *g* (Thompson et al. 2001).

Normal early human brain development is characterized by variable brain volume growth across cerebral cortical regions that together with changes in neuronal density from infancy through the preschool years support more efficient information processing (Tsujimoto 2008). Density increases to a maximum around ages 1 to 2 years before declining. By age 7 years, neuronal density in layer III of PFC was reduced from 55 % to 10 % above the adult mean (Huttenlocher 1979). A rapid increase in gray matter volume over the first four years of life is followed by reduction into adulthood, following an inverted U shaped trajectory (Giedd et al. 1999, 2010; Johnson 2001), during which time connectivity among different cortical and subcortical regions becomes more efficient (Amso and Casey 2006). Changes in gray matter volume that occur during early childhood appear to parallel the establishment of neural circuitry in PFC (Giedd, et al. 1999; Tsujimoto 2008), and variance in IQ may be partly accounted for by PFC volume (Reiss et al. 1996). A volumetric study of the relationship between intelligence and brain structures in typically developing boys (8 to 18 years) found total gray matter and hippocampal volume significantly correlated with full scale and verbal IQ, and a strong correlation between the hippocampus and verbal IQ suggested that the hippocampal contribution to declarative and semantic learning was more notable for verbal IQ (Schumann et al. 2007).

Cortical surface area is associated with intelligence and other cognitive performances although no specific cortical region underlies intelligence. In one study, preterm preschoolers were administered an infant developmental scale at age 2 years and measures of complex cognition and motor functioning at age 6 years. Total brain volume has been shown not to be related to a specific intelligence domain; however, participants who had a higher rate of perinatal cortical surface area growth between 24 and 44 weeks of gestation achieved higher scores on the measures of complex cognition, but not motor functioning. A one standard deviation difference was associated with a 5–11 % difference in cortical surface area (Rathbone et al. 2011). In another study using near-infrared spectroscopy with individuals aged five to adulthood, oxy-hemoglobin concentrations in frontopolar regions of PFC significantly increased with older age during performance of a verbal fluency task, independent of gender from childhood to adolescence and showing concentrations to be lowest during the preschool years (Kawakubo et al. 2011).

Myelination, which allows for more efficient transmission and processing of information between brain regions (Huttenlocher 1979; Lebel and Beaulieu 2011), occurs along a temporal gradient with visual, auditory and limbic cortices myelinating early and along a linear pattern of aging whereas the frontal and parietal neocortices continue to myelinate into adulthood (Sowell et al. 2003). Brain white matter increases 12.4 % from age 4 to 22 years, with males showing a greater increase than females (Giedd, et al. 1999). A longitudinal study of white matter development using diffusion tensor imaging (DTI) tractography in individuals aged 5 to 32 years found within-subject maturation and increased myelination and axon growth in most major white matter tracts, providing evidence that there is less white matter volume during the preschool years and increases at older age (Lebel and Beaulieu 2011).

Other changes in the young developing brain include that glucose uptake peaks for most cortical areas at preschool age, reaching about 150 % of adult levels before declining to normal adult levels (Johnson 2001). Lengthened frontolateral connections have been noted in EEG's of children from ages 1 to 5 years, and intra- and inter-regional cortical connections are strengthened from infancy to preschool ages as children interact with their environment (Thatcher 1991). By age 2 to 3 years a child's brain structures already appear similar to an adult brain (Johnson 2001). Prefrontal cortex fractionation of neural systems to perform individual functions begins at an early age, and while PFC is functional in preschoolers it becomes better organized in later childhood (Tsujimoto 2008). As summarized by Tsujimoto (2008), "1) the fractionation of cognitive abilities is associated with more efficient processing of general intellectual abilities, 2) more efficient control of *g* is associated with better performance of working memory, and 3) better performance of working memory is associated with efficient use of the PFC" (p. 355) (Tsujimoto 2008). Thus, the individual differences in intelligence that result reflect aspects of brain function that enable more efficient use of cortical structures and resources that are associated with specific cognitive abilities (Blair 2007).

Neural Correlates of Intelligence

Studies of the neural correlates of intelligence in healthy children and of their brain structure, function, and connectivity have expanded greatly with neuroimaging advances. Among these investigations, brain specialization for categorical and symbolic information integral for abstract thinking and reasoning (*g*F*)* was demonstrated to actively develop at an early age, enabling more efficient processing and encoding. This was demonstrated in a functional magnetic resonance imaging study in which brain activity was monitored while pictures of objects, faces, letters, and numbers were presented to preschoolers. Dissociation was found in occipitotemporal cortex between faces and symbols, with more activity in the right mid-fusiform gyrus in response to faces and in the left lateral fusiform/inferior temporal gyrus in response to symbols (Cantlon et al. 2011). Thus, the preschool years of brain development involve critical periods of learning related to increased recruitment of task-specific brain regions that will contribute to performance of highly specialized task-specific cognitive functions in adulthood (Johnson 2001). A characteristic of learning and improved performance across a wide variety of cognitive tasks is an anterior to posterior shift with increasing expertise. That is, as tasks become less difficult individuals utilize posterior cortical regions more actively than the frontal regions on which they previously relied (Blair 2007).

Adult brain neuroimaging studies have demonstrated that complex abstraction and reasoning skills may best represent the construct of intelligence (*g*), that *g* is closely related to PFC and working memory, that posterior parietal cortex as well as PFC are recruited for novel problem solving and general fluid reasoning, that *g*F may mediate brain regions supporting executive attentional control and working memory, that high-*g* tasks are correlated with the selective recruitment of lateral PFC in either one or both hemispheres, and that functional neural fractionation of PFC may underlie general intellectual abilities (Prabhakaran et al. 1997; Duncan et al. 2000; Gray et al. 2003; Tsujimoto 2008). Since verbal, nonverbal, and spatial tasks with high *g*-loadings all recruit lateral PFC, a specific system is suggested rather than a broad integration of cognitive functions, located in the frontal cortex of the brain regardless of domain (Duncan, et al. 2000). When adults first completed the Raven's Advanced Progressive Matrices measure of *g*F and then performed verbal and nonverbal three-back working-memory tasks, those participants who had higher *g*F were more accurate and showed greater event-related neural activity on high-interference trials involving cognitive conflict. Lateral prefrontal, dorsal anterior cingulate, and inferior parietal regions were recruited and mediated the relationship between ability (*g*F) and performance (accuracy despite interference), as well as superior temporal lobes and lateral cerebellum (Gray, et al. 2003). In another study of neural activity, young adults were administered analytic and figural/visuospatial reasoning tasks and a control pattern-matching task. Right frontal and bilateral parietal regions were activated more by figural problems whereas analytic (*g*F) problems were activated more by greater bilateral frontal and left parietal, occipital, and temporal activation. Activations were found in regions recruited for working memory (figural reasoning with spatial and object working memory; analytic reasoning with verbal working memory and domain-independent associative and executive processes), suggesting that fluid reasoning is mediated by a composite of working memory systems (Prabhakaran, et al. 1997).

The above-noted correspondence between working memory and *g*F in adults has been demonstrated as well in preschoolers (ages 4 to 6 years). Functional near-infrared spectroscopy (fNIRS) brain-imaging and optical topography were used to examine the hypothesis that *g*F and visuospatial working memory share a common neural system within the lateral PFC. Initially, spatio-temporal features of neural activity in the PFC were similar for both the visuospatial working memory task (a spatial matching-to-sample task) and the *g*F task (Cattell's Culture Fair Intelligence Test). However, after two months of training on the visuospatial working memory task *g*F increased significantly suggesting that a common neural system in the PFC was recruited that improved the preschoolers' visuospatial working memory and *g*F (Kuwajima and Sawaguchi 2010). Such data showing training in a simple visuospatial working memory task to be associated with greater activity in the lateral PFC should be of interest to those designing preschool intervention strategies, ostensibly to improve *g*F and intellectual ability.

Gender Differences in Intelligence

Male and female brains develop differently, but considerable difference can be found within gender as well (Giedd, et al. 2010). Total brain size in males is approximately 8–10 % larger than in females, a difference associated with increased cortical gray matter in males (Lenroot et al. 2007) but which alone imparts no consistent functional advantage with respect to intellectual ability (Giedd, et al. 2010). Notably, neither males nor females showed significant change in total cerebral volume after age five indicating that most of the brain's cerebral volume is acquired during the preschool years (Reiss, et al. 1996). Brain volume correlation with intelligence was higher in females than males, and in adults compared with children (McDaniel 2005). A longitudinal neuroimaging study of gender differences in participants aged 3 to 27 years demonstrated the importance of examining size-by-age trajectories of brain development rather than relying on group averages across broad age ranges. The trajectory of cortical growth, not total cortical volume, best predicted intelligence in the preschool years, and there was a negative correlation between cortical volume and intelligence in early childhood. Children scoring within a superior range of intelligence had more rapid increase in cortical volume and thicker cortex, and more rapid cortical thinning during late adolescence; young children with the most plastic cortices (initial accelerated and prolonged cortical increase then active cortical thinning) by early adolescence demonstrated higher levels of intelligence (Shaw et al. 2006). In one study, an infant mental scale score for girls was more strongly related to preschool IQ than was the score for boys; however, preschool IQ scores of boys were more strongly related to paternal education and environmental variables than those of the girls and boys were more influenced by the quality of their environmental influences, e.g., whether they had well educated parents and were provided creative toys (Andersson et al. 1998). In another study, girls scored significantly higher than boys at age 2 years on both verbal and non-verbal tasks. Yet, the data suggested that there were gender-specific differences in verbal cognitive ability, with boys showing greater heritability in verbal tasks; opposite-sex twins had a lower correlation of verbal intelligence compared with non-identical same-sex twins (Galsworthy et al. 2000).

Preschool Intelligence Testing in the 2000s: Instruments, Limitations, Socioenvironmental Factors, and Heritability

Intelligence test instruments currently available for use with preschoolers differ with respect to their normative data census year sampling basis, the age range for which they are appropriate, the factor analytic model of intelligence on which they are based, and the types of behavior they sample. The purposes of the evaluation and theoretical basis of an instrument help determine which is the most appropriate measure to administer to a young child. For example, the DAS-II is constructed to provide a measure of *g* (conceptual and reasoning scores) as well as measures of specific abilities (the cluster scores) and additional diverse diagnostic scores, but avoids use of the terms "IQ" or "intelligence". The summary General Conceptual Ability score is calculated using scores obtained on those items that best measure *g*, i.e., those requiring verbal, visuospatial, and reasoning abilities. Wechsler measures, in contrast, calculate IQ based on more heterogeneous subtests that contribute to IQ even if their *g*-loading is low. In addition, the DAS-II has been normed on a wide variety of childhood clinical classifications and spans a wide age range, making it an especially useful multi-componential measure when longitudinal neuropsychological study is planned (see Table 2).

A wider range of tests assessing specific neuropsychological functions has become available for preschoolers allowing for evaluation of a broad range of abilities during the critical preschool years and better delineation of the intellectual *and* neuropsychological profile. The structure of intelligence develops from a relatively general, homogeneous ability to more differentiated cognitive abilities, a course important to consider when closely monitoring either an emerging neuropsychological profile in a typically developing child or the effects of disruption secondary to neurologic or systemic illness, injury, or disorder. Interruption during the preschool years of brain development and refinement has the potential to result in adverse long-term effects on intelligence. For example, preschoolers who had severe traumatic brain injury had worse intellectual outcomes five years post-injury than preschoolers who experienced only mild or moderate injury (Anderson et al. 2009). Plasticity and resilience of the young brain may facilitate reorganization in response to insult as intact structures assume cognitive functions previously mediated by dysfunctional brain regions, presumably why children who had an ischemic perinatal stroke at preschool age did not show a decline in IQ scores during their school years (Ballantyne et al. 2008). However, early insult is neither protective nor predictive as many other factors also directly influence general intelligence, including genetic, familial, medical, educational, emotional, sociocultural, and socioenvironmental circumstances.

Intelligence tests may be critiqued despite their long history of use and considerable psychometric support. Intelligence tests are inadequate measures of neuropsychological competence. They are generally comprised of interrelated subtests that are multicomponential, i.e., dependent on various cognitive abilities engaged simultaneously rather than separate, specific functions. The correlation among subtests of an intelligence test may decrease as general intellectual efficiency increases suggesting that brain efficiency correlates positively with intelligence (Deary et al. 2010). Intact brain systems, including sensorineural and attentional/executive, are necessary to engage in the cross-modal higher order information processing under either timed or untimed circumstances that most intelligence tests require. The psychometric strength of intelligence tests is more a function of the empirically derived index scores since the individual subtest scores are psychometrically weaker, and index scores are often interpreted as representing distinct capacities although they are not psychometrically independent. Individuals who receive high, average, or low scores on one cognitive domain generally perform similarly on other domains (Deary et al. 2010). As clinical neuropsychologists are acutely aware, summary index scores are often insensitive to the particular neuropsychological characteristics that may be associated with a specific neurological insult. Consequently, while index and subtest scores are useful in hypothesis generation and allow for meaningful comparison with others in an age-appropriate peer group, clinical interpretations within a neuropsychological context may be both inappropriate and misleading. A common example of their misuse is when a significantly lower performance IQ than verbal IQ is interpreted as confirmation of right cerebral hemisphere dysfunction although the lowered score is neither confirmatory nor sufficiently specific.

Additional limitations to obtaining reliable and valid assessment at preschool age are related to the dyadic interaction inherent to individual intelligence testing. Examiner proficiency in building rapport, eliciting optimal cooperation, maintaining target behavior, and recognizing subtle qualitative aspects of behavior positively influence the examiner validity that is crucial to obtaining valid results at preschool age whereas examiner bias and inexperience exert a negative effect. Preschoolers have uneven maturational trajectories and acquire skills at different times over the course of their development, limiting comparisons with other preschoolers and emphasizing the individualization of intelligence testing. The child's comfort in separating from the parent, compliance with the examiner, temperament, motivation, health, sleep and nutritional patterns, and other state and trait characteristics also will directly affect intelligence test performance (Baron 2004).

Test item bias has been identified as an additional concern. For example, the unexpected finding that preschool boys had higher verbal IQ than preschool girls was interpreted as demonstrating that the information, vocabulary, and comprehension questions were constructed in a way that more strongly favored the boys (Quereshi and Seitz 1994). In this regard, cultural experiences and ability to attend to one's environment have been shown to correlate positively with intellectual outcome in the preschool years, affecting both familiarity with the types of questions asked on intelligence tests and the responses required (Schmitt et al. 2007).

Parental attitudes, education, and socioeconomic status may optimize or further delay a child's opportunity to engage in the kinds of tasks and experiences that foster success on IQ tests. Relatedly, the correlation between IQ and parental socioeconomic status is approximately .33 (White 1982). Infants with caretakers who actively encouraged them to attend to objects and events in their environment demonstrated more efficient visual processing at age 4 months, better verbal skills at age 2 years, and higher IQ at age 4 years than infants whose caretakers did not provide similar encouragement (Bornstein 1985). In another study, higher IQ scores were shown at age 40 months by children who had better sustained joint attention during observed free-play sessions between infant and mother at ages 2 and 6 months, with differences becoming greater between the two groups at older ages (Saxon et al. 2000). Caregiving during infancy influences the quality of the child's attention to the environment and IQ. Infants with greater distress in response to environmental novelty had higher IQ at age 3 years than those who showed less distress, suggesting that fear of new situations reflected a cognitive capacity to notice novelty and to recognize what had changed. The infants insecurely attached demonstrated greater distress to novelty and higher intelligence suggesting that a less-than-optimal caregiving environment might actually strengthen the ability to attend to the environment that, in turn, may in some circumstances enhance intellectual growth (Karrass and Braungart-Rieker 2004).

While there is much yet to learn about the heritability of intelligence, studies to date have found genetically mediated relationships between brain structure and intelligence (Schmitt et al. 2007). Genetic influences on general intelligence appear to be more limited during early childhood than at older ages. Heritability of intelligence was 26 % at preschool age (age 5) compared with 64 % at age 12 (Bartels et al. 2002). Similarly, heritability of *g* was 23 % in early childhood, with environmental factors responsible for 74 % of the variance, while in middle childhood heritability accounted for 62 % of *g* and the environment accounted for 33 % (Davis et al. 2009). Primary sensory and motor cortex show relatively greater genetic effects early in childhood and develop earlier than dorsal prefrontal and temporal cortical regions that show greater genetic effects over the maturational course (Lenroot et al. 2009). Those cortical regions involved in language, executive function, and emotional regulation are more heritable than other brain regions (Schmitt et al. 2007). It has been suggested that this heritability is due to genetic variations in brain structure and function, rather than a direct genetic influence on intelligence itself (Deary et al. 2010). Genetic factors may account for one half of phenotypic variance (Bouchard and McGue 1981). Although studies have demonstrated a relationship between specific genetic variations and intelligence, these have not been replicated and which phenotype may contribute most to higher levels of intellectual functioning remains unclear (Deary et al. 2010).

Summary and Future Directions

The preschool years continue the dynamic growth and cerebral development begun in the fetal period and infancy. Intelligence tests that will reliably assess functioning over the early maturational course and optimize predictive validity have proven to be a challenge to test developers. While having established broad acceptance, intelligence tests also have important limitations. These become especially apparent with advances in measurement of specific neuropsychological functions during the preschool years. These early years are now receiving greater attention from test developers and comprehensive neuropsychological evaluation in the preschool period holds greater promise for monitoring development throughout childhood and with more accurate predictive validity. Preschool test instruments should be developmentally sensitive, sufficiently attractive to engage the young child, require responses consistent with maturing capacities, sample a behavioral repertoire that matches the child's maturational level, and have strong psychometric properties across both typically developing and clinically diagnosed groups.

Data consistently demonstrate that intelligence is more homogeneous than heterogeneous in the preschool years. Consequently, a factor analytic model on which a particular intelligence test is based may be expected to have less relevance for a preschooler whose performance is more a measure of *g* than for an older child who demonstrates more differentiated cognitive functioning. Research intended to discern emergent abilities during the preschool years compared with the broader range of neuropsychological functions operational at later ages continues to be a valuable investigational direction.

Neural correlates of intelligence is an area for further study in the preschool years, made more exciting by the neuroimaging data being reported about typically developing young children. The trajectory of PFC development as it relates to measurement of intelligence and neuropsychological functioning holds particular promise for providing further insights about the timing and mechanisms on the emergence and then fractionation of brain regions from the preschool years into childhood. These will highlight potential interventional strategies intended to support optimal functioning, critical socioenvironmental variables, and influential genetic and epigenetic factors on the expression of intellectual competence. In addition, further investigation of the effects of gender differences observed in the preschool years, and the differential impact of *g* at different maturational periods should further understanding of how one may best understand intelligence at preschool age.

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