

# How Uniform is the Structure of Ability Across Childhood?

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## Abstract

The DSM-IV implicitly assumes that development is uniform across ability domains, which implies that relationships between ability measures do not differ across development. We assessed whether correlations between measures of 9 ability constructs differ across samples of children aged 3 to 5 ( $n = 117$ ), 6 to 8 ( $n = 116$ ), 9 to 11 ( $n = 124$ ) and 12 to 14 years ( $n = 92$ ). LISREL analyses show that correlations in each age group differ from those of each other age group. Parallel analyses indicate that the latent structure of ability differs across age groups. We conclude that shared maturational processes, including changes in the connectivity of neural systems, are responsible for decreasingly and increasingly strong relationships between some ability measures.

It may be a truism that development *is* change, but when it comes to defining abnormal development, it is also widely assumed that normal development is characterized by uniformity and stasis. In the DSM-IV (American Psychiatric Association, 1994), definitions of some developmental disorders incorporate a *discrepancy criterion*, according to which a disorder may be diagnosed when achievement in a specific ability domain like reading or expressive language is substantially below what is expected based on a child's age and mental age. By using achievement discrepancies to define deviant development, the DSM-IV is characterizing normal development as relatively uniform across ability domains. Because development across domains can only be relatively uniform if 'different' developmental processes are strongly interrelated, they can only remain uniform across development if relationships between developmental processes also remain strong across development, that is, if relationships do not change. Can development be characterized both as change and as stasis?

#### *Measurement, Statistics, and the DSM-IV*

In its definitions of some specific developmental disorders, the DSM-IV requires that general intelligence and ability in specific domains are measured with individually administered standardized tests. This requirement means that any conclusions about a child's development, or about development in general, on the basis of test performance need to be qualified based on what is known about the distribution of each test's scores and about the relationship between scores on the two (or more) tests. As Dyck, Hay et al. (2004) have shown, the probability of observing an achievement discrepancy of any given size varies as a function of the correlation between the tests (as the correlation increases, the probability of observing a large

discrepancy decreases) and the child's IQ (as IQ increases, so too does the probability of observing a large discrepancy).

Even when scores on two tests are independent of each other ( $r = 0$ ), achievement will, within samples of typical children, usually appear to be relatively uniform across a set of standardized ability tests. For these tests, the expected level of achievement is the population mean, and about two thirds (68%) of individuals will achieve a score within 1 *SD* of the mean. For any two such independent tests, almost half (46%) of the population will score within 1 *SD* of the mean on both measures, and 92% of the population will achieve scores within 2 *SDs* of each other. Relatively uniform achievement across ability domains is a statistical necessity, and the observation that a given child's abilities are or are not uniform of itself provides no information about whether the child's development is normal or deviant.

### *Correlation and Development*

Correlations are an index of shared variability, and where large correlations between ability measures are observed, they prompt us to question the source or cause of the shared variance. In almost all cases, some of the shared variance reflects the part dependence of different tasks on the same basic abilities. For example, regardless of their main measurement function, almost all ability measures make demands on a person's language ability because they require a test-taker to follow instructions, and many measures make demands on sensory-motor abilities because they require a test-taker to decode or manipulate test stimuli (pictures, objects). In the context of developing children, shared variance may also reflect the dependence of different abilities on a core maturational process that is itself marked by increasing cognitive capacity and processing efficiency. Each of these sources of shared variance is unlikely to remain constant across development.

When performance on two or more different tasks partly depends on some more basic ability, a minimum level of competence in the basic ability is a necessary but insufficient condition for successful performance on tasks that depend on the basic ability. In general, minimum competence in the basic ability is least likely to be achieved when the absolute level of all abilities is low, that is, during earlier developmental epochs. As every infancy researcher knows, our capacity to assess most cognitive abilities increases in direct proportion to children's acquisition of language. What this implies is that scores on all other ability tests will share more variance with language measures—and, perhaps, with each other ability test—during early childhood than they will during subsequent phases of development.

Developmentalists have long assumed a relationship between the acquisition of new cognitive abilities and maturation-related increases in cognitive capacity. MRI research has produced evidence that is consistent with this assumption. Not only does brain size increase significantly until about age 5, the brain continues to develop throughout childhood, adolescence, and into adulthood (Durstun et al., 2001). The general pattern is for white matter volumes to increase throughout life, and for grey matter volumes first to increase up to about age 8 or 9 (Courchesne et al., 2000; Giedd, Blumenthal, Jeffries, Castellanos et al., 1999), and then to decrease before adulthood (Reiss et al., 1996). Within this general pattern, there are regional variations in the timing of change. Anterior regions associated with sensory and motor functions mature earlier (by age 5, as marked by increased white matter volume in the corpus callosum; Giedd, Blumenthal, Jeffries, Rajapkse et al., 1999), while posterior ones do not mature until adolescence. These differential maturation effects imply that if ability tests share variance related to the maturation of the neurological processes

subserving them, different sets of ability tests will show this specific maturation effect at different stages of development.

*A Baseline for Describing Normal and Abnormal Cognitive Development*

Correlations between ability tests are an index of how likely it is that a pattern of discrepant achievement will be observed because they reflect how much two or more different ability domains depend on the same basic processes. As children mature, the processes that are necessary for additional increments in a range of abilities can be expected to change. Such change would mean that what is shared by different pairs of abilities would also change as a function of maturation. For this reason, correlations between abilities would be expected to differ across age cohorts, and would represent a guide to how maturation differentially affects the acquisition of ability in different domains.

Observing how relationships between cognitive abilities change as a function of maturation would complement research on the acquisition of ability, especially in terms of understanding which processes have been affected in groups of children whose development is deviant. The continuing use of discrepancy criteria to define developmental disorders is likely due to our neglect to consider how different ability domains relate to each other or how these relationships may differ across age cohorts. By focusing on relationships between ability domains, it can be shown that developmental disorders are at least as likely to be characterized by abnormally uniform underachievement as by unusually discrepant achievement. Dyck et al. (2006) have shown that correlations between measures of intelligence, language, motor coordination, and social cognition are unusually strong in samples of children with autism. They argued that these stronger than usual correlations reflect abnormal dependencies between neurocognitive processes and provide a guide to which

neurocognitive processes have been affected by disorder. However, understanding what is entailed by any set of unusual relationships between abilities depends on first understanding how relationships change during normal development.

With the exception of research on infant development, almost nothing is known about relationships between different abilities or whether these relationships are stable across developmental epochs. We know from the WISC-IV standardization sample that relationships between different WISC sub-tests are consistent across age cohorts (Wechsler, 2003), and from longitudinal research that the structure of intelligence is relatively stable across time (Gustafsson & Undheim, 1992).

Otherwise, old research informs us that both motor (Wallin, 1916) and language skills (Brandenburg, 1918) correlate positively with intelligence, and the age when developmental milestones like walking and speech are achieved correlates negatively with intelligence (Abt, Adler, & Bartelme, 1929). Early research also indicates that the correlation between motor skills and language is less consistently strong (Faris, 1919) than the correlation between either of these abilities and intelligence. A strong relationship between motor and language abilities in younger children is not observed in older children (Anderson, 1939; Seashore, 1930). Some of these results have been replicated with contemporary samples and measures (e.g., Goldstein & Britt, 1994), including a finding that age of learning to walk predicts executive functioning 33 to 35 years later (Murray et al., 2006), but no comprehensive study of relationships between ability domains and how those relationships may differ across development has been reported.

### *Research Aims and Hypotheses*

The aim of this study is to answer the question: are there systematic differences in relationships between abilities as a function of age? Based on

maturational changes in brain size and structure (e.g., Durston et al., 2001) and on developmental theory (e.g., Piaget, 1976), systematic differences are to be expected. Granted that the chronology of cognitive change is variable both within and across populations, MRI research on participants from developed societies suggests that at least four broad stages of maturational change can be identified. These stages consist of: (a) the period through age 5 years, during the preoperational stage, when brain size is increasing; (b) the period from age 6 through 8 years, during the transition from the preoperational to operational stage, when grey matter volume continues to increase; (c) the period from age 9 through 11 years, when the child is in the stage of concrete operations, when grey matter begins decreasing while white matter is increasing in anterior brain regions, and (d) the period from 12 through 14 years, which corresponds to the period of formal operations, when white matter continues to increase in posterior brain regions. If these stages are in fact meaningful, each should have psychological concomitants which will be reflected in different relationships between cognitive abilities.

The more difficult problem is to specify which relationships will differ between any two stages. The only prediction we can make with confidence is that *all relationships* will be stronger in the first stage than in subsequent stages. We base this prediction on what we presume is the strong dependence of all abilities on a core maturational process that is itself manifest by increasing brain size during this stage. We also base it on the mutual dependence of all cognitive abilities on shared basic processes like language, which is likely to constrain performance on all other tasks at this stage of absolute development. Finally, we base it on the fact that in the case of at least one broad class of ability, motor coordination, the neural structures subserving



the ability are among the first to mature, and have largely completed their maturation by the end of the first stage.

Apart from the contrast between stages one and two, differences between stages cannot be predicted because they result from an interaction between two developmental trends which can be expected to have contrary effects. The first trend is a continuation of the initial one, that is, towards decreasing relationships as ‘growth effects’ reach their asymptote. This trend would also lead to an expectation that the strength of relationships between abilities associated with neural connections in posterior regions of the corpus callosum would be the last to diminish in strength. The second trend is based on Piaget’s idea that successive stages of cognitive development are marked by the integration of earlier stages into later stages, and the related idea that in each stage of development there is a level of preparation (when capacity is being acquired) and a level of completion (when capacity is being demonstrated). These ideas imply that just as the acquisition of ability ‘B’ may have been dependent on the prior acquisition of ability ‘A’ (suggesting a strong relationship between A and B in earlier stages), the subsequent acquisition of ability ‘C’ depends on the prior acquisition of ability ‘B’ and suggests a strong relationship between B and C in later stages. If correct, this would imply the strengthening of relationships between some abilities in stages three or four compared with stages two or three.

### *Research Design*

Although our explicit hypotheses are developmental, because this research is also largely exploratory (between which age groups do relationships between abilities differ), we have opted for a simple cross-sectional rather than a longitudinal design. We think that we need better to understand how relationships may differ between age cohorts before testing more specific hypotheses about how relationships may change

as a function of maturation. We have selected groups of children aged 3 to 5, 6 to 8, 9 to 11, and 12 to 14 years because these age cut-offs approximate major shifts in brain maturation. We have excluded children less than 3 years old because of the inherent difficulty in constructing/obtaining ability measures that are valid both for very young and older children. We have opted to assess nine ability constructs that are important to defining and / or understanding developmental disorders: verbal comprehension and perceptual organization (baseline for all specific developmental disorders), receptive and expressive language (Communication Disorders), fine and gross motor coordination (Motor Skills Disorder), and the emotion recognition, emotion understanding, and theory of mind components of social cognitive ability (Autistic Disorder, Asperger's Disorder). If relationships between abilities are not constant across age groups, definitions of developmental disorders would need to be changed to reflect how these differences affect the probability of observing discrepancies in the acquisition of ability.

## Method

### *Participants*

Participants were 449 children aged 3 to 14 years, approximately balanced for age in years and for sex (see Table 1; Dyck et al., 2006). Participants were recruited from 42 schools/preschools in the Perth metropolitan region. Schools were targeted for recruitment on the basis of their position on a state-wide index of average student achievement, that is, because they represented the distribution of academic achievement within Western Australia. Data on the family background or socioeconomic status of children were not collected, but we have no reason to doubt that they are broadly representative of the Western Australia population.

Insert Table 1 about here

Once a school had agreed to participate, participants were recruited in one of two ways. Parents of children aged 7 to 12 years received letters seeking permission to enroll their child in 'Project KIDS.' Project KIDS is conducted through a child study center during school holidays, and involves intensive data collection, for one day per child, with small groups of children (see Procedure below). This method resulted in the recruitment of 234 children, including all participants aged 7 to 11 years, 9 6-year-olds (typically siblings of target-age children), and 20 12-year-olds. Parents of children aged 3 to 6 years or 12 to 14 years received letters seeking permission to assess their child at the preschool/school in which the child was enrolled. This method resulted in the recruitment of 215 children, including all children aged 3 to 5 years or 13 to 14 years, and the balance of children aged 6 or 12 years. Across both forms of recruitment, approximately one sixth of the total number of parents contacted consented to their child's participation in this study.

### *Measures*

We administered measures that would allow us to obtain composite indices of nine ability constructs.

*Verbal comprehension and perceptual organization.* We used four subscales from the third edition of the *Wechsler Intelligence Scale for Children* (WISC; Wechsler, 1992) to estimate two of the four cognitive ability domains measured by the Wechsler tests. Verbal comprehension was measured with the Vocabulary and Information subscales, and perceptual organization was measured with the Block Design and Picture Completion subscales. We used the WISC rather than the Wechsler Preschool and Primary Scale of Intelligence with the youngest participants to ensure that all participants were measured on the same scale. We judged that the value of using one scale outweighed the risk of floor effects from administering 'too

difficult' items to the youngest children. Each test has excellent split-half and test-retest reliability, and both criterion and concurrent validity are well-established (Wechsler).

*Receptive and expressive language.* We used four subscales from the third edition of the *Clinical Evaluation of Language Fundamentals* (CELF; Semel, Wiig, & Secord, 1995) to assess the two main language ability domains. Receptive language was assessed with the Concepts and Directions and Word Classes subscales, and expressive language was assessed with the Recalling Sentences and Formulated Sentences subscales. We selected the CELF partly because it has been standardized across a wide range of ages, but like the WISC, not for the youngest children (aged 3 to 5 years) in our study. Again, the value of using one scale outweighed the risk of floor effects. Specific scales were selected because they are the only CELF scales which are administered to all children. These subscales have acceptable internal consistency (alphas from .54 to .91), test-retest reliability (.69 to .87), and concurrent validity (Semel et al.).

*Fine and gross motor coordination.* We used the *McCarron Assessment of Neuromuscular Development* (MAND; McCarron, 1997) to assess the two main motor coordination ability domains. The MAND comprises 10 tasks, of which five assess fine motor skills (beads in a box, beads on a rod, rod slide, finger tapping, nuts and bolts) and five assess gross motor skills (heel to toe walk, hand strength, standing on one foot, finger-nose-finger, jumping). The 10 MAND tasks have acceptable test-retest reliability (.67 to .98), criterion validity (prediction of work performance), and concurrent validity (McCarron).

*Theory of mind, emotion recognition, and emotion understanding.* Three major components of social cognitive ability were assessed. ToM ability was estimated with

a combination of three first order, one second order and an advanced ToM mind tasks.

First order ToM tasks are false belief tasks commonly used to assess differences between children with/without some disorder, and included the “Sally Ann” (Baron-Cohen, Leslie & Frith, 1985), “Smarties” (Perner, Frith, Leslie & Leekam, 1989; Wimmer & Perner, 1983), and “Ella the Elephant” tasks (Harris, Johnson, Hutton, Andrews & Cooke, 1989). In each task, a child is asked whether a protagonist will act consistently with the protagonist’s beliefs, known to be false, or consistently with what the test-taker knows to be the true state of the world. Responses which indicate action consistent with the protagonist’s false beliefs are scored correct and indicate that the test-taker has acquired a theory of mind. The second-order theory of mind task, the “John and Mary icecream story” (Perner & Wimmer, 1985), is identical except that a child must assess what the protagonist thinks that another person thinks. We treated these tasks as separate items on a 4-point theory of mind scale. The advanced ToM task was the *Strange Stories Test* (Happe, 1994), which assesses the ability to provide context-appropriate mental state explanations for non-literal (irony, sarcasm, lies) statements. The test consists of 12 stories (one for each form of non-literal statement), each accompanied by a picture. Subjects indicate whether a statement made by the protagonist is true or false (to establish that the story was understood), and then explain why the statement was made. In this study, responses were scored correct if an explanation was both adequate and relied on references to mental states.

Emotion recognition ability was assessed using three subscales from the Emotion Recognition Scales (ERS; Dyck, Ferguson & Shochet, 2001; Dyck, Farrugia et al., 2004), the Accuracy (ACC) and Speed Given Accuracy (SGA) scales from the Fluid Emotions Test and the Unreal Words scale from the Vocal Cues Test. The

Accuracy scale measures the ability to recognize static facial expressions of emotion, and the Speed Given Accuracy scale measures the ability to recognize changing/changed (morphed) facial expressions of emotion. Test items are drawn from Matsumoto and Ekman's (1995) color slides of adults expressing one of seven emotions (anger, contempt, disgust, fear, happiness, sadness, surprise) or a neutral expression. These scales are internally consistent (ACC,  $\alpha = .90$ ; SGA,  $\alpha = .94$ ), discriminate between children with and without autism spectrum disorders (Dyck et al.), and are useful for assessing the emotion recognition ability of hearing-impaired children (Dyck, Farrugia et al.). The Unreal Words Test measures the ability to recognize vocal intonations specific to different emotions. It consists of 43 items in which emotions are expressed using non-semantic content: numerals, letters, nonsense syllables. The emotions sampled are identical to those in the Fluid Emotions Test. Items are approximately balanced for sex of the speaker and for emotion category. This scale is internally consistent ( $\alpha = .93$ ) and has proved useful in assessing the emotion recognition ability of vision-impaired children (Dyck, Farrugia et al.).

Emotion understanding ability was assessed using three subscales of the Emotion Recognition Scales. The Emotion Vocabulary Test measures the ability to define emotion words (e.g., what does the word "angry" mean?). The response format is open-ended and initial responses may be queried in order to resolve ambiguities in the initial response. The test is internally consistent ( $\alpha = .82 - .89$ ), moderately related to other ERS, and strongly related to other measures of vocabulary (Dyck et al., Dyck Farrugia et al.). The Comprehension Test measures the ability to understand the emotional consequences of exposure to an emotion-eliciting context (e.g., Susan is given a new bicycle for her birthday. What will Susan feel?). CT items sample the 7 emotions in the FET, 'social variants' of emotions (e.g., pride, embarrassment, shame,

pity) and variations in the intensity of emotions (e.g., terror versus fear). The CT has acceptable reliability ( $\alpha = .64 - .79$ ) and is moderately related to other ERS and to measures of intelligence (Dyck et al.; Dyck, Farrugia et al.). The Unexpected Outcomes Test (UOT) measures the ability to apply reasoning skills and knowledge of the causes of emotions to explaining apparent incongruities between an emotion-eliciting context and the emotion elicited by the context. UOT items provide information about a situation that is likely to cause an emotional response in a protagonist (e.g., “John likes a girl called Susan, and he wants her to go to the movies with him. When he asks her, she says yes”). Items then indicate what emotion has been experienced (e.g., “On their way to the movies, he is very angry”). In each case, the emotion differs from what is usually expected to occur in the situation. The test-taker is asked to explain the apparent incongruity. The UOT has adequate reliability ( $\alpha = .73 - .81$ ) and is moderately to strongly related to other ERS and to measures of intelligence (Dyck et al.; Dyck, Farrugia et al.).

### *Procedure*

Procedure varied depending on whether the child was or was not assessed as part of Project KIDS. For children participating in Project KIDS, groups of up to 12 children were scheduled for a full day (8:45 a.m. to 4:30 p.m.) of activities. Upon arrival at the child study center, children participated in a “getting to know you” activity. Testing was then conducted in three 90-minute sessions, each of which was divided into three 30-minute testing blocks. The first test session was followed by a 30-minute recess, and the second by a 60-minute lunch break. Testing was administered by a team of researchers. During breaks, children were provided with coloring books, pencil puzzles, and age-appropriate movies; they were also given access to an outdoor playground.

The order of test administration was not uniform. Rather, each child had his/her own schedule. Adherence to the test schedule was essential to the smooth running of the program; if scheduled activities could not be completed, they were deferred to the end of the day where one hour of unallocated time was available to administer deferred tasks. Testing was usually completed within 4.5 hours, but sometimes required up to 5.5 hours. Except for working memory, response inhibition, and inspection time tests which were administered simultaneously to up to four children, all tests were individually administered according to the instructions in the relevant manuals.

For children not in Project KIDS, testing was done at the school of recruitment. For these children, testing was less rigidly scheduled in order to accommodate the shorter attention span of younger children and to minimize disruption to school activities. Because of test discontinuation rules, younger children usually completed fewer test items, which reduced the total time required. In most cases, testing was completed in a single day; otherwise, testing was completed within two days.

#### *Data transformations, composite scores, and missing data*

Before calculating composite scores, raw scores on each measure were age-standardized to create scores with a mean of 100 and a standard deviation of 15. Composite ability scores were the average age-standardized score on the set of relevant tasks (e.g., for verbal comprehension, the average of Wechsler Information and Vocabulary). Within each age group, a small proportion of cases had missing data on one or more of the nine measures. These data appeared to be missing at random, so these cases were dropped from the analyses, reducing group sizes to 98, 114, 121, and 91 for Groups 1 to 4 (from youngest to oldest), respectively.



## Results

*Differences in relationships between ability measures*

The purpose of the first series of analyses was to test our prediction that relationships among all nine abilities differ across age groups and, in particular, would be stronger in the youngest age group than in any other group. As a first step in testing our prediction, we conducted a series of maximum likelihood LISREL analyses (Version 8.54; Jöreskog & Sörbom, 2003) using the Satorra-Bentler scaled chi-square to confirm that the covariance matrix for the youngest age group is significantly different to the covariance matrices of other groups. The Satorra-Bentler chi-square was used because it corrects for an inflation of the chi-square statistic that occurs when data are multivariate non-normal, which they were for the youngest and the oldest age groups. Results indicated that the covariance matrix for Group 1 differed significantly from that of Group 2 ( $\chi^2(45) = 136.37, p < .00001$ ), Group 3 ( $\chi^2(45) = 172.49, p < .00001$ ), and Group 4 ( $\chi^2(45) = 152.48, p < .00001$ ).

Having confirmed that the covariance matrix of the youngest group differs from those of other groups, we assessed whether relationships among ability scores are stronger in the youngest group. Pearson correlations for each pair of composite ability measures were calculated for each group. The correlations (see Table 2) are consistent with our prediction: 89% (32/36), 83% (30/36), and 83% (30/36) of the correlations in the 3 to 5 year old group were stronger than the corresponding correlations in Groups 2, 3, and 4, respectively.

We then used the same procedures to assess whether the covariance matrices of the 3 older groups differed from each other. The results indicate that the covariance matrix of each group differs from that of each other group [Group 2 vs. Group 3:  $\chi^2(45) = 84.49, p < .001$ ; Group 2 vs. Group 4:  $\chi^2(45) = 126.57, p < .00001$ ; Group 3

vs. Group 4:  $\chi^2(45) = 121.93, p < .00001$ ]. Pearson correlations (see Table 2) suggest that a main source of the differences is how motor coordination measures relate to all other measures. Among 6 to 8 year olds, there is only 1 significant relationship between a motor coordination measure and other measures. Among 9 to 11 year olds, there are 3 additional significant relationships, and among 12 to 14 year olds, there are 5 additional significant relationships (and 2 which have become non-significant).

Insert Table 2 about here

### *Differences in the structure of ability across childhood*

Our prediction that the relationships would be stronger in the youngest age group was based on the assumption that all abilities in the youngest age group are more strongly dependent on a core maturational process or a shared basic process like language than is true of older children. We are proposing, therefore, that the intercorrelations among the nine abilities for the 3 to 5 year-olds are driven by fewer latent variables—and possibly a single latent variable—than is the case in older children. To test this hypothesis, we used parallel analysis (O'Connor, 2000) to determine how many eigenvalues in principal component analyses of each set of group data exceed the eigenvalues that result from analyses of random data. Parallel analysis generates random data sets with the same dimensions (Participants X Variables) as the main analysis, conducts principal component analysis on each random data set, and specifies the mean value, and the 95<sup>th</sup> percentile value, of the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, ... eigenvalue across the random data sets. Comparison of eigenvalues from the main analysis with those at the 95<sup>th</sup> percentile in the parallel analyses (based, in this case, on 100 principal component analyses of random data for each age group) indicates how many latent variables are unlikely to be due to chance.

Results of parallel analyses are reported in Table 3, and show that only one component should be extracted in Group 1, two components in Groups 2 and 3, and one component in Group 4. Table 3 also shows that the same result would occur if the mean eigenvalue obtained from random data sets were used as the criterion rather than the 95<sup>th</sup> percentile value. We conducted the principal component analyses on our data, extracting one component for Groups 1 and 4, and extracting two components for the remaining groups. Where two components were extracted, they were rotated with the promax procedure. Component or pattern matrices are reported in Table 4.

The results (see Table 4) are consistent with our expectation that structure is simpler in the youngest group and that performance across domains is largely based on a basic ability like language. Table 4 shows that the first (or only) component in each analysis is defined by the very high loadings of the receptive / expressive language measures and verbal comprehension. The results are also consistent with our expectation that some relationships would be stronger in the older groups than in the younger groups. When a second component is extracted, it is clearly defined by the high loadings of the motor coordination scales. The motor component is independent of the language component in Group 2, is weakly related to it in Group 3 where it is also defined by the substantial loadings of the perceptual organization and emotion recognition measures, and is not a significant source of non-random variance in the Group 4, where it again loads on a single latent variable.

Insert Table 3 and Table 4 about here

## Discussion

The DSM-IV implicitly assumes that normal development is uniform development. Our results indicate that this assumption is incorrect. Relationships between cognitive domains differ across age cohorts, which means that the probability

of observing substantial discrepancies in performance across different domains varies as a function of a child's age. These results are directly relevant to how the structure of ability should be construed in children, but they also have important implications for how developmental disorders are defined, how research on developmental disorders is conducted and how the results of such research are understood. Finally, these results support the use of neurobiological markers of maturation as a basis for defining age groups.

### *The structure of ability*

Our results have two main implications for how the structure of ability is construed. First, they suggest that the everyday distinctions that are drawn between ability domains are invalid. Second, they suggest that the idea that there is *an* ability structure is not only wrong, but that structural metaphors may be inappropriate and counterproductive to understanding relationships between abilities.

This is not the place to consider how it came about, but the set of human abilities is routinely divided into such subsets as intelligence, language, and motor coordination which are then studied in isolation from each other. Although measures of language are known to be highly correlated with the verbal ( $r = .66$ ), quantitative ( $r = .60$ ), and spatial ( $r = .52$ ) components of intelligence (Canivez, 2000), the structure of language is frequently studied as if it were independent of the structure of intelligence. And although the correlation between the *mental* and *psychomotor* indices of the Bayley Scales of Infant Development at two to six months is .6 (Cronbach, 1990), as soon as it is possible to assess a broad set of 'cognitive' abilities without also assessing motor coordination, the idea that there may be important relationships between motor coordination and intellectual processes is largely ignored (for exceptions, see Gardner, 1983; Kornhaber & Gardner, 1991; Murray et al., 2006).

The view of each ability domain as distinct from others has been reified by professional boundaries (e.g., intelligence: psychologist; language: speech therapist; motor coordination: physiotherapist or occupational therapist) and a diagnostic system that treats each ability domain as if it were independent of other ability domains (Mental Retardation, Communication Disorders, Motor Skills Disorder; American Psychiatric Association, 1994). These distinctions appear to be arbitrary and invalid.

Our results indicate that most variability in our broad set of measures is shared: more than 50% of variance in our youngest group is associated with a single latent variable, and this latent variable still accounts for 42% of variance in our oldest group. The fact that receptive language has the highest loading on this latent variable might be taken to indicate that this variable is essentially a marker of language abilities, but the fact that 36% to 46% of variance in motor coordination measures is also associated with this variable in the youngest group indicates that such an interpretation would be inappropriate. Rather, the result points to how ‘different’ abilities are interrelated, to how they jointly depend on more basic processes. What they may all depend on is a core maturational process that affects the acquisition of all abilities and the dynamic processes that determine the ‘connectivity’ of neural systems (cf. Thelen & Bates, 2003).

Recent findings support this idea. In humans as in other mammals, neurons, dendrites and synapses are overproduced during early development (Huttenlocher, 1984), and as many as 50% of synapses are eliminated (Spessot et al., 2004) during three phases of life: before birth and during the transitions from childhood to adolescence and adolescence to adulthood (Andersen, 2003). Reorganization and fine-tuning of immature synaptic networks results in the mature brain. Although we continue to produce cortical neurons throughout childhood and into adulthood (e.g.,

Gould et al., 1999; Shankle et al., 1998; Shankle et al., 1999), these new cells appear to last only one to two weeks unless they are involved in new experiences or learning. Experience affects brain development, and this brain plasticity may partly explain the changing nature of abilities with age.

The major difference between our youngest group and other groups was the differentiation of the motor measures in the 6 to 8 and, to a lesser extent, 9 to 11-year-old groups. This result is consistent with the observation that anterior brain regions associated with sensory and motor functions mature by age 5 years (Giedd, Blumenthal, Jeffries, Rajapakse et al., 1999), while other regions mature more slowly. This would mean that the acquisition of enhanced motor skills after age 5 years would not depend on the same maturational process (continuing improved connectivity) that the acquisition of other skills depend upon. Rather, over time as white matter volumes increase across other brain regions, the processes driving development across domains are again increasingly shared, and may reflect the elimination of synapses in the transition from childhood to adolescence.

Our results are also consistent with the recently proposed dynamic model of general intelligence (van der Maas et al., 2006). In this model, the well-known positive manifold evident in cognitive ability measures is not due to *g* (a general intelligence factor) or a single biological process, but arises from the reciprocal or mutual and beneficial interactions of cognitive processes during development. This model is able to account for diverse findings related to *g*, including its apparent heritability and patterns of differentiation and integration of ability that have been thought to occur during development. According to this model, the apparent differentiation that we observed in the 6 to 8 and 9 to 11-year-old groups and the subsequent integration of ability that we observed in the 12 to 14-year-olds can be

accounted for by changes in the strength of mutualism between specific processes during certain phases of development.

### *Developmental Disorders*

The fact that relationships between abilities differ across age groups has major implications for how developmental disorders are defined and for how developmental disorders are understood. First, these results add to the growing body of evidence indicating that current definitions of specific developmental disorders—Learning Disorders, most Communication Disorders, and Motor Skills Disorder—are invalid. Second, these results suggest that if typical development is marked by a series of changes in relationships between abilities, developmental disorders will be marked by deviant relationships between abilities rather than, or in addition to, achievement deficits.

It has traditionally been viewed that some neurological structure is characteristically impaired in a developmental disorder, and it is typically assumed that this impairment will be associated with a specific performance deficit. Recently, however, there is evidence from neuroimaging techniques that suggests multiple structure involvement in developmental disorders such as ADHD and autism (Castellanos et al., 2002; Volkmar et al., 2004). Rather than specific structures being impaired, it is thought that the connections between brain structures may hold the key to understanding the causes of these developmental disorders. Our findings support this view, as we suggest that the impairment will necessarily be associated with deviant relationships between ability measures, which implicates multiple brain structures.

Most specific developmental disorders (Learning, Communication, and Motor Skills Disorders) are defined when a child's achievement in a specific ability domain

(reading, expressive language, motor coordination) is substantially less than expected based on the child's age and intelligence (American Psychiatric Association, 1994). Dyck, Hay and colleagues (2004) argued that this discrepancy criterion must be unreliable (and, for this reason, invalid) because it does not take into account how a child's level of intelligence and the correlation between intelligence and specific ability measures affect the probability of observing an achievement discrepancy of any given size. Because we have now demonstrated that the correlation between intelligence and other ability measures differs across age groups, it follows that the probability of observing a large discrepancy between intelligence and other abilities also differs across age groups. In general, large achievement discrepancies are much less likely among children aged 3 to 5 years or 12 to 14 years than among children aged 6 to 11 years. This additional source of unreliability of the discrepancy criterion strengthens the case for abandoning its use in defining any developmental disorder.

Most research on children with developmental disorders effectively adopts this discrepancy criterion when disorder-specific impairments (e.g., theory of mind or executive functioning deficits in autism) are being investigated. Typically and atypically developing children will be matched on age and on mental age, on the assumption that relationships between the intelligence measure and the dependent variable should be the same in the (usually) younger mental age-matched typically developing children as in the atypically developing children. Our results indicate that this assumption is not warranted. Greater consistency in ability scores is to be expected among 3 to 5 year-olds than among 6 to 11 year-olds.

However, there is a more fundamental problem with current definitions of developmental disorders: they are based on an inaccurate model of the structure of ability. As our discussion of the structure of ability suggested, the DSM assumes that



intelligence, language, motor coordination are discrete ability structures that can be dissociated from each other, and that it is the dissociation of language, motor coordination, or specific academic skills from intelligence that is the hallmark of disorder. An alternative view which is consistent with the dynamic model of intelligence is that pathological development disrupts the mutuality of cognitive systems and so impairs performance not only in the domains directly subserved by those systems, but, by the lessening and/or increasing of mutuality, in more or less all cognitive systems. This view would lead to the expectation that among children with developmental disorders, relationships between ability measures would be unusually strong (in the case of increased mutuality; Dyck et al., 2006), and ability profiles would be more uniformly low, not more discrepant, than normal (Wisdom et al., 2006).

#### *Implications for Future Research*

In his discussion of the use of correlational methods in developmental research, Wohlwill (1973, p. 288) indicated the basic limitation of methods of the kind we have used: “individual differences within an age group represent in fact differences in the subject’s standing on the developmental dimension. In other words, the variation is actually attributable to, or interpretable in terms of differences in *rates* of development” (emphasis in original). In order to assess the structure of ability and how it changes within individuals, quite different methods will be needed.

Wohlwill (1973) recommended using Cattell’s ‘P-technique’ in which the latent structure of a matrix is assessed across occasions (repeated measures) within an individual rather than across individuals. The latent variables are expected to include a time dimension (whether as the first or as a higher order factor) and other sources of shared variation that may be more or less independent of time. Factor scores on each

dimension can be used to plot how the individual changes over time, that is, how performance at later occasions differs from that of earlier occasions. The procedure can also be used to integrate individual and group data, by comparing the structure across cases and by comparing the structures yielded by individuals with those yielded by groups (cf. Zevon & Tellegen, 1982). Although not in common use, the P-technique and its modern variants have been used to assess within-person changes related to development and learning (Molenaar, 1985; Nesselroade, 2001; Nesselroade & Ford, 1985). The main problem with this approach is a pragmatic one, i.e., the challenge of administering a broad range of ability tests to a given child on many occasions.

An alternative approach that we have used to study changes in motor coordination during infancy (Piek & Gasson, 1997, 1999) has been to assess changes in cross-correlation functions over time. We used it to assess intralimb and interlimb movement a/symmetries where the potential relationships are obvious, but the approach is equally suited to assessing less obvious relationships, including between the development of motor coordination and language production variables, perceptual reasoning tasks, and so on. Changes in cross-correlations do not provide evidence of structure as a whole, but indicate the extent of mutuality between processes which contribute to the appearance of structure in psychometric test data (van der Maas et al., 2006). Time series analyses build on this approach by utilizing time- and cross-lag correlations within and between variables. According to Wohlwill, this approach is especially useful for examining cyclical trends. Finally, where strong relationships between seemingly disparate processes are observed, the nature and extent of actual connectivity between systems could be assessed by functional imaging.

*Limitations and Conclusions*

We defined our age groups so that they would approximate the major epochs in the Piagetian model of development and so that they were consistent with neurophysiological evidence on the maturation of the nervous system. Our results provide convergent evidence that there are important changes in the form of development that occur as children move from one epoch to the next. Our results also suggest that individual differences methods have an important role to play in increasing our understanding of normal development.

Because ours was not a longitudinal study, we cannot exclude the possibility that our major results reflect cohort effects rather than developmental effects. However, were it the case that cohort effects were responsible for the different relationships and structures that were observed, this would have almost identical implications for our understanding of human development. Our observation that relationships differ across age groups is consistent with the truism that development is change, but in this case its significance is that it shows that the assumption of uniform development, made when developmental disorders are defined, is incorrect. Indeed, our results suggest that we need to pay much less attention to how well a child performs in any given domain and pay much more attention to how performance in one domain may be affecting performance in others. When abilities as seemingly disparate as pointing at one's own nose and recalling a spoken sentence are related to the same fundamental processes, then it is understanding what it is that these abilities share that should be the research priority.

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Table 1

## Age and Sex of Participants

Age	Female	Male	n
3.0 – 3.99	15	16	31
4.0 – 4.99	23	19	42
5.0 – 5.99	20	24	44
6.0 – 6.99	16	19	35
7.0 – 7.99	21	20	41
8.0 – 8.99	20	20	40
9.0 – 9.99	21	20	41
10.0 – 10.99	24	20	44
11.0 – 11.99	18	21	39
12.0 – 12.99	22	16	38
13.0 – 13.99	20	15	35
14.0 – 14.99	9	10	19
	229	220	449

Table 2

*Correlations among abilities in children aged 3 to 5 years*

	PO	VC	ER	EU	TM	LE	LR	MCF
VC	.67**							
ER	.37**	.48**						
EU	.39**	.44**	.57**					
TM	.42**	.50**	.27**	.45**				
LE	.56**	.57**	.32**	.41**	.44**			
LR	.65**	.62**	.49**	.55**	.53**	.63**		
MCF	.39**	.29**	.26**	.26**	.37**	.28**	.41**	
MCG	.37**	.32**	.38**	.39**	.40**	.39**	.51**	.71**

*Correlations among abilities in children aged 6 to 8 years*

	PO	VC	ER	EU	TM	LE	LR	MCF
VC	.38**							
ER	.25**	.38**						
EU	.19*	.27**	.32**					
TM	.25**	.34**	.27**	.32**				
LE	.44**	.66**	.37**	.32**	.50**			
LR	.48**	.62**	.35**	.32**	.35**	.72**		
MCF	.10	-.05	.15	-.14	-.01	-.03	.11	
MCG	.00	.02	.25**	-.07	.03	-.03	.15	.59**

*Correlations among abilities in children aged 9 to 11 years*

	PO	VC	ER	EU	TM	LE	LR	MCF
VC	.59**							
ER	.35**	.32**						
EU	.16	.48**	.18*					
TM	.28**	.41**	.25**	.19*				
LE	.31**	.67**	.14	.62**	.39**			
LR	.35**	.59**	.18*	.55**	.34**	.67**		
MCF	.30**	.12	.33**	.14	.17	.07	.18*	
MCG	.13	.14	.23*	.16	.09	.16	.06	.45**

*Correlations among abilities in children aged 12 to 14 years*

	PO	VC	ER	EU	TM	LE	LR	MCF
VC	.55**							
ER	.27**	.24*						
EU	.33**	.59**	.37**					
TM	.14	.40**	.10	.42**				
LE	.34**	.59**	.34**	.47**	.36**			
LR	.58**	.65**	.40**	.41**	.34**	.62**		
MCF	.29**	.19	.12	.01	-.04	.16	.24*	
MCG	.33**	.31**	.10	.32**	.12	.37**	.26*	.50**

Abbreviations: PO = Perceptual Organization; VC = Verbal Comprehension; LE = Expressive Language; LR = Receptive Language; MCF = Fine Motor Coordination; MCG = Gross Motor Coordination; ER = Emotion Recognition; EU = Emotion Understanding; TM = Theory of Mind

Table 3

*Eigenvalues resulting from principal component analyses of group versus random data*

	Age Group			
	3 to 5	6 to 8	9 to 11	12 to 14
1 <sup>st</sup> Observed eigenvalue	4.71	3.62	3.79	3.99
Mean random 1 <sup>st</sup> eigenvalue	1.48	1.44	1.44	1.50
95 <sup>th</sup> percentile random 1 <sup>st</sup> eigenvalue	1.61	1.57	1.57	1.61
2 <sup>nd</sup> Observed eigenvalue	1.14	1.70	1.56	1.30
Mean random 2 <sup>nd</sup> eigenvalue	1.31	1.29	1.28	1.32
95 <sup>th</sup> percentile random 2 <sup>nd</sup> eigenvalue	1.40	1.39	1.37	1.43
3 <sup>rd</sup> Observed eigenvalue	0.91	0.93	1.02	0.97
Mean random 3 <sup>rd</sup> eigenvalue	1.19	1.17	1.16	1.19
95 <sup>th</sup> percentile random 3 <sup>rd</sup> eigenvalue	1.28	1.24	1.23	1.27

Table 4

*Latent structure of ability across age groups: Unrotated component matrices for 3 to 5 and 12 to 14 year old groups, and promax rotated pattern matrices for 6 to 8 and 9 to 11 year old groups*

	Age 3 to 5	Age 6 to 8		Age 9 to 11		Age 12 to 14
	1	1 <sup>a</sup>	2 <sup>a</sup>	1 <sup>b</sup>	2 <sup>b</sup>	1
PO	.76	.60	.06	.41	.41	.68
VC	.77	.78	-.04	.82	.08	.82
ER	.63	.55	.29	.12	.63	.49
EU	.69	.54	-.23	.74	-.07	.70
TM	.68	.62	-.06	.48	.18	.49
LE	.73	.87	-.09	.91	-.12	.77
LR	.85	.81	.12	.85	-.06	.81
MCF	.60	-.04	.88	-.09	.84	.35
MCG	.68	.00	.87	-.09	.72	.53

<sup>a</sup>The correlation between components 1 and 2 in this analysis is .07.

<sup>b</sup>The correlation between components 1 and 2 in this analysis is .30.

Abbreviations: PO = Perceptual Organization; VC = Verbal Comprehension; LE =

Expressive Language; LR = Receptive Language; MCF = Fine Motor Coordination;

MCG = Gross Motor Coordination; ER = Emotion Recognition; EU = Emotion

Understanding; TM = Theory of Mind