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ISBN

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Publication Date

2012-01-13

DOI

Part I

Language and Hemispheres: From Single-Word Recognition to Discourse

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Individual Differences in Brain Organization for Language

Christine Chiarello, Suzanne E. Welcome, and Christiana M. Leonard

Variation is a defining characteristic of biological entities. Complex gene-environment interactions within each organism endow all species with a rich assortment of unique individuals. Humans are no different. Look around – people come in all shapes and sizes, with varying talents and limitations across a range of motor, personality, linguistic, and cognitive domains. Our memory and perceptual systems have evolved to enable us to recognize a nearly endless number of individuals from seeing their faces or hearing their voices. Clearly, there are strong pressures on the evolution of neural systems to permit us to respond to conspecifics as individuals. Indeed, every parent, clinician, and teacher knows that an approach that succeeds with one person may fail miserably with another.

Yet although both biology and "folk wisdom" acknowledge the importance of understanding individual variation, until very recently the fields of cognitive science and cognitive neuroscience have been largely silent on this issue. Here the primary emphasis has been on understanding the cognitive architecture that underlies acts of thinking, speaking, perceiving, and remembering, and the neural instantiation of this architecture, as it applies to all persons regardless of variation in skill or strategy.[1] Once the "master plan" has been identified, then perhaps individual differences can be explored by tweaking parameters within a generalized model. In the meantime, individual differences are often treated as noise to be managed statistically.

We have been exploring a more biologically oriented approach in which individual variation is a primary phenomenon to be explained. We consider it plausible that the human brain can support cognitive and linguistic functions in a variety of ways, and that individual differences in brain structure may have functional significance. In this chapter we report initial findings from the Biological Substrates for

Language Project, which was designed to examine the range of variation in cortical morphology, reading skill, and visual field (VF) lateralization in a sample of 200 college students. One goal of the project was purely descriptive: to document the range of variation in brain anatomy and behavior within a large, normally function-ing group of young adults. It is often the case that such individuals are included as an undifferentiated control group in neuropsychological studies of impairment (such as dyslexia) or special talent. However, this approach often conceals the range of variation that exists within the normal population, and the frequency of unusual features (such as reversed planum temporale asymmetry) within this typically func-tioning group is not reported. Another goal was to examine the amount of this individual variation that can be attributed to easily measured subject variables such as sex and handedness, and then to explore other more novel dimensions of indi-vidual difference. In each case we considered variation in brain structure, in behav-ior, and in the relation between structure and behavior.

Our project was informed by a view of individual variation that was prompted by current work in developmental biology (Siegal & Bergman, 2002; Rice, 2008). Research in that field suggests that development is regulated by a complex genetic network that acts to buffer the developing organism from random influences. One outcome of this buffering is to quiet random genetic and environmental variation, thereby promoting regression toward the population mean, similar to the "canaliza-tion" idea originally proposed by Waddington (1957). We hypothesized that indi-viduals differ in the extent to which their neural development is buffered from random genetic and environmental influences. Those with well-buffered develop-ment should demonstrate cortical and behavioral features that approximate the population mean, while those with less buffered development should evidence more extreme values and a greater extent of inter- and intra-individual variation. At the conclusion of this chapter we propose a framework that acknowledges the very high dimensionality of the individual difference "space."

Project Methods

Two hundred native English-speaking college students (100 female) from the University of California, Riverside, volunteered to participate. There was no selec-tion criterion for hand preference in order to obtain a sample representative of the population as a whole. Each individual received the Wechsler Abbreviated Scale of Intelligence (WASI), three subtests (word identification, word attack, passage com-prehension) from the Woodcock Reading Mastery Test – Revised (WRMT-R), a hand preference inventory, and Annett's pegboard moving test of hand skill. Additional demographic data was obtained to assess familial sinistrality, socioeco-nomic status, college major, and a self-report measure of reading history. In addi-tion, each student participated in eight divided VF experiments. Due to the anatomy of the visual system, the divided VF method allows us to directly transmit visual information to a single hemisphere. Thus words or letter strings briefly presented

to the right visual field (RVF) are received in the left hemisphere, and vice versa. An advantage for stimuli presented in one VF allows us to infer a processing advantage for the opposite hemisphere. The divided VF tasks were selected to assess basic word recognition processes (word naming – 2 administrations, nonword naming, masked word recognition, lexical decision) and meaning access and retrieval (semantic decision, verb and category generation). Details about stimuli and experimental procedure have been described in previous publications (Chiarello, Welcome, Halderman, & Leonard, 2009a; Chiarello et al., 2009b; Chiarello, Welcome, & Leonard, submitted; Welcome et al., 2009).

Following the five behavioral test sessions, all participants received a structural MRI scan. Imaging procedure and measurement techniques are described elsewhere (Chiarello et al., 2009b, submitted; Leonard et al., 2008; Leonard, Towler, Welcome, & Chiarello, 2009). Hemispheric volumes of gray and white matter were estimated, and measurements of total corpus callosum area and seven callosal subdivisions were calculated. Left–right asymmetries were measured for seven cortical regions that show reliable asymmetries at the population level: pars opercularis and pars triangularis (Broca's area), Heschl's gyrus (primary auditory cortex), planum temporale (overlaps Wernicke's area), midparacingulate sulcus (all typically larger in left hemisphere), and planum parietale (supramarginal gyrus) and anterior cingulate sulcus (typically larger in right hemisphere) – see Figure 1.1. For a smaller,
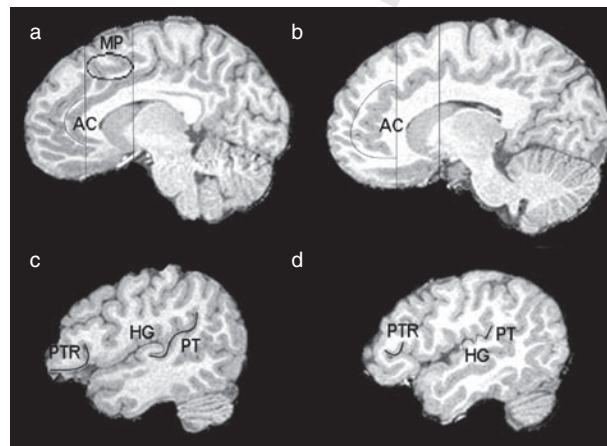

Figure 1.1   Sagittal MRI images depicting asymmetric structures in medial (top) and perisylvian (bottom) cortex. (a) Left hemisphere: Vertical lines through the genu of the corpus callosum and the anterior commissure separate anterior cingulate (AC) from midcingulate cortex. The paracingulate in midcingulate cortex (MP) is generally larger in the left hemisphere while the anterior cingulate cortex is larger in the right. (b) Right hemisphere: The paracingulate sulcus is absent in this example. (c) Left hemisphere: Thick lines outline the pars triangularis (PTR) and planum temporale (PT), while a thinner line outlines Heschl's gyrus (HG). These structures are typically larger in the left hemisphere. (d) Right hemisphere.
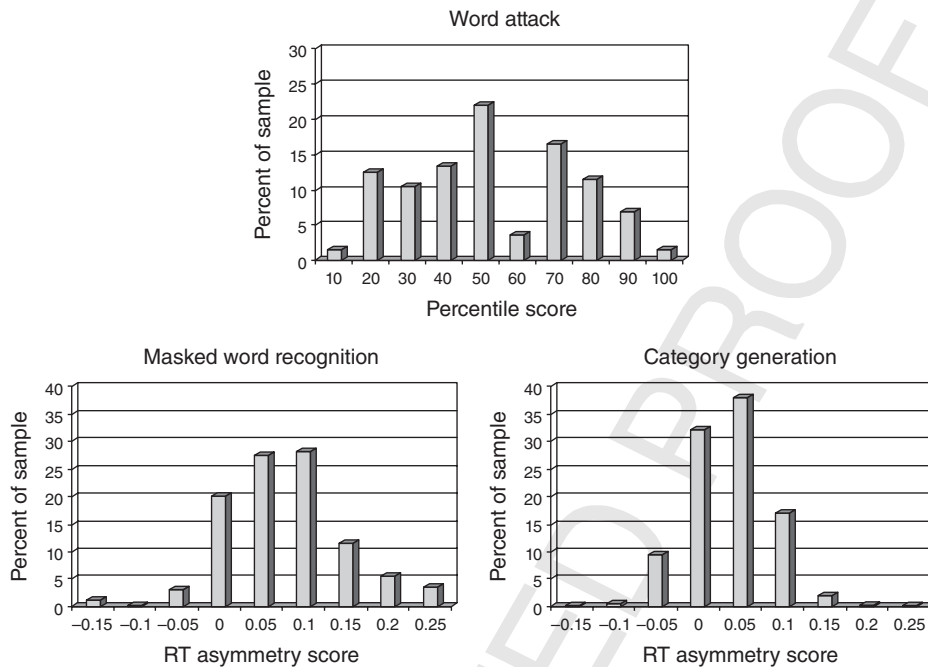
Figure 1.2   Variability in selected behavioral measures. Percentile scores for word attack have a broad, apparently bimodal distribution (upper). Asymmetry scores (response time – RT) for masked word recognition (lower left) and category generation (lower right) indicate both individual and task variation in asymmetry. Positive asymmetry scores represent a RVF/left hemisphere advantage.

partially overlapping sample stratified by reading subskills, local brain size and gray matter thickness were calculated (Welcome, Chiarello, Thompson, & Sowell, submitted).

Normal Variation in Brain Anatomy and Behavior

Figure 1.2 displays the range of variation in some of our behavioral measures. The word attack subtest of the WRMT-R requires participants to pronounce increasingly difficult nonword letter strings – a measure of phonological decoding. As can be seen, even in a group of typical college students there is extensive variation in this reading skill, with an apparent bimodal distribution – some individuals can perform this task with relative ease while others have great difficulty. Figure 1.2 also indicates the variation in VF asymmetries for two representative tasks, one involving word recognition (masked word recognition) and one requiring semantic retrieval (category generation). Reaction time asymmetries were calculated using a standard asymmetry index (LVF – RVF/LVF + RVF) such that a positive score indicates a RVF/left hemisphere (LH) processing advantage. Although reliable RVF advantages
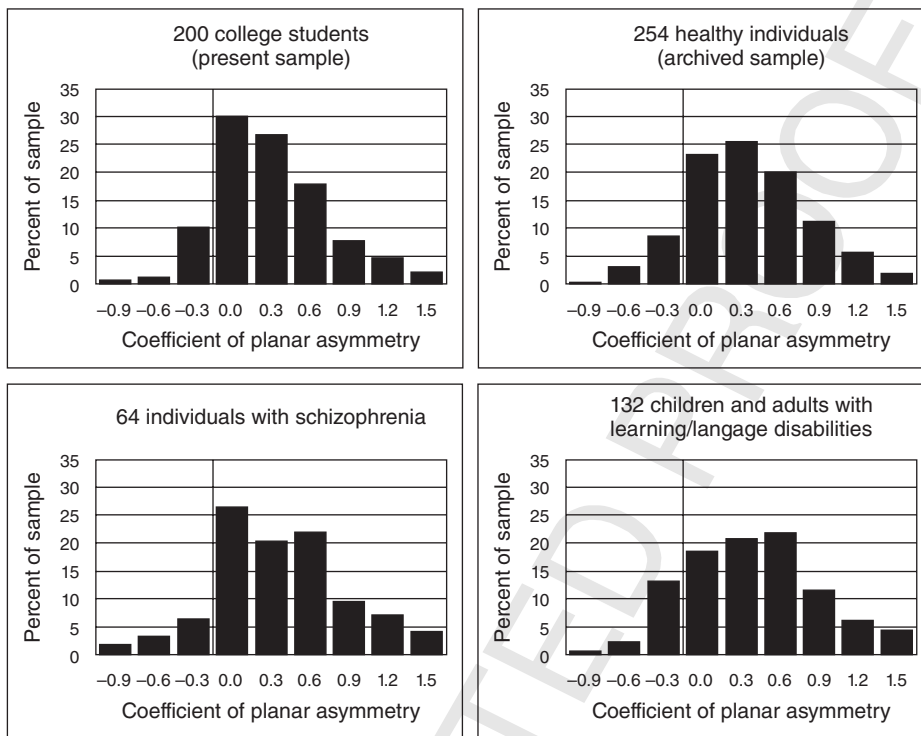
Figure 1.3 Variability in asymmetry of the planum temporale in the present sample (upper left), another control sample (upper right), and two samples with clinical diagnoses: schizophrenia (lower left), and language/learning disabilities (lower right). Coefficient of asymmetry is calculated by subtracting the left measure from the right and dividing by the average, so that leftward asymmetries yielded positive coefficients.

were obtained in our tasks at the group level, there is considerable individual variation in the degree and direction of asymmetry, with some individuals demonstrating reversed or exaggerated asymmetries.

In Figure 1.3, we plot the distribution of asymmetry for the planum temporale for the current sample (upper left), a heterogeneous sample of healthy adults and children (N = 258; upper right), a sample of 64 schizophrenics (lower left), and a group of individuals with dyslexia and/or specific learning impairment (N = 132; lower right). The latter three samples were obtained from numerous studies imaged at various sites but analyzed at the University of Florida using the same methods. It is striking that the mean and range of planar asymmetry is nearly identical across all samples, with approximately two thirds of each sample demonstrating leftward asymmetry. Although measurement error is likely a source for some of the observed variation, the consistency of the mean and range of variation across samples points to powerful underlying biological mechanisms. It also suggests that the probability of reversed asymmetry is similar within normal "control" samples and large clinically diagnosed samples.[2] These findings belie simplistic attempts to associate

complex behavioral disorders with a single aberrant structural feature. However, this should not imply that structural variation is behaviorally insignificant.

Examination of variability for other tasks and brain regions has yielded similar findings in our sample. The data described thus far document a range of ability, and behavioral and structural asymmetry even within a seemingly homogeneous college student sample. We can now consider the success of different approaches in identifying the relationship of variation across the three domains of reading skill, VF asymmetry, and brain structure.

Potential Sex and Handedness Effects

In neuropsychological studies, the influence of sex and handedness on brain organization has been widely studied. Non-right-handers often display reduced asymmetries as compared to right-handers, and it is often claimed that women have more symmetrical brain organization than men, although the latter claim is controversial (Sommer, Aleman, Bouma, & Kahn, 2004; Wallentin, 2009). We have thoroughly examined sex differences in our sample, and have concluded that this variable accounts for very little of the individual variation in behavioral and anatomical measurements. Males and females performed similarly in passage comprehension and word attack, although males had somewhat greater accuracy in word identification (Chiarello et al., 2009b). Composite measures of VF asymmetry across all our tasks also obtained no evidence of sex differences. We also considered whether men and women might differ in the variability of their VF asymmetries. However, there were no sex differences in the variability of visual lexical asymmetry across different tasks, within any given task, or within a task across two different administrations (Chiarello et al., 2009b). Women did demonstrate reduced asymmetry for two of our eight VF tasks (nonword naming, category generation), but only for the accuracy measure. Furthermore, this sex difference only accounted for 2% of the variance in asymmetry, and follow-up analyses were unable to replicate the sex difference using a split-sample technique.

Asymmetry of the planum temporale, planum parietale, Heschl's gyrus, pars triangularis, pars opercularis, and the anterior cingulate sulcus did not differ by sex (Chiarello et al., 2009b; Leonard et al., 2009). The size of the total corpus callosum, and all seven callosal subregions was also similar for males and females, when the effects of brain volume were partialled out (Welcome et al., 2009b). As expected, males had significantly greater brain volume, but most previously reported sex differences in regional brain size (e.g., Harasty, Seldon, Chan, Halliday, & Harding, 2003) were not observed when the effects of overall brain volume were removed (Leonard et al., 2008). We recently found evidence for one sex difference in structural asymmetry that could not be attributed to brain volume confounds (Leonard et al., 2009). Leftward asymmetry of the midparacingulate sulcus was significantly *greater* for female, than for male, participants. In general, however, very little of the readily observable variation in cortical morphology could be attributed to sex, and

there was no evidence for reduced structural asymmetry in women. These findings comport with other large-scale investigations of behavioral and neuroanatomical asymmetry (e.g., Boles, 2005; Sommer et al., 2004).

Our sample contained the expected number of left-handers (N = 32), and thus far we have not observed any significant differences between left- and right-handers for any of our measurements (and all reported effects remain significant when left-handers' data are removed). However, a much larger number of left-handed participants would be needed to draw any strong conclusions from this result. We have obtained some handedness-related effects when contrasting consistent handers (those strongly preferring one hand for all activities, N = 103) to mixed handers (N = 97). Using standard VF asymmetry indices no differences between these groups were observed (Chiarello et al., 2009a). However, when we examined the degree of VF asymmetry, independent of direction (i.e., absolute value of asymmetry index), then consistent handers had marginally greater asymmetries than mixed handers, due to somewhat greater frequency of extreme rightward and extreme leftward asymmetries for consistent handers. Structural asymmetries generally did not distinguish between these handedness groups. However, consistent handers had greater leftward asymmetry of the pars opercularis than did mixed handers, $p = .05$. Consistent and mixed handers did not differ in callosal area (Welcome et al., 2009).

One is left with the impression that only a small degree of the individual variation in reading skill, VF lateralization, or brain structure can be attributed to easily measured subject variables such as sex and handedness. However, it is also important to investigate the relationships between the domains of skill, behavioral laterality, and brain structure for groups differentiated by sex and/or handedness. Similar behavioral or neuroanatomical features across groups need not imply that the mapping between these domains is comparable. We have obtained some evidence for differences in these associations for sex/handedness groups.

First, we observed positive associations between reading skill and VF lateralization for consistent handers, but not for mixed handers. For consistent handers, larger VF asymmetries were associated with better reading performance (accounting for approximately 6% of the variance; Chiarello et al., 2009a). This effect was not moderated by sex. Second, planum temporale asymmetry was positively correlated (albeit weakly) with VF response-time asymmetry for men, but not for women (Chiarello et al., 2009b). Third, although there were minimal differences in either VF asymmetry or callosal area for sex X handedness groups, these groups did differ in the *relationship between* callosal area and VF asymmetry (Welcome et al., 2009). Among consistent handed males a negative association was observed – larger callosal area was associated with smaller RVF advantages, accounting for 12.4% of the variance. This relationship held for total callosal area, but was most robust for the splenium (no relationship was observed for any anterior subregion). In contrast, mixed handed females demonstrated a positive correlation – larger callosa were associated with larger RVF/LH advantages, accounting for 21.4% of the variance. For this group, the relationship was demonstrated for total callosal area, and

nearly all callosal subregions, with an especially robust relationship for the genu. For the remaining groups (mixed handed males, consistent handed females) no association was observed.

These data imply a rather different role for the corpus callosum in mediating interaction between lateralized processors for males with consistent handedness and females with mixed handedness. For male consistent handers, larger callosa appear to support a greater degree of bilateral processing, while smaller callosa support more highly lateralized processing. The splenium locus implies that, for this group, hemispheric interaction for reading processes may depend on the rapid transfer of visual sensory information, since large fast-conducting fibers predominate in the splenium. In contrast, for mixed handed females a very different functional organization is implied, as those with larger callosa had the most asymmetrical processing. This implies that the callosum in this group may function to inhibit information transfer between lateralized processors. There has been great debate in the literature as to whether the corpus callosum serves a primarily facilitatory or inhibitory function for interhemispheric interaction (Bloom & Hynd, 2005; Innocenti, 2009). Our data raise the intriguing possibility that there are subpopulations that differ in the balance between facilitatory and inhibitory callosal mediation. The fact that mixed handed males and consistent handed females display no net correlation of VF asymmetry and callosal size might indicate a combination of facilitatory and inhibitory influences (perhaps some reading subprocesses involve hemispheric interaction, while others require isolation between lateralized processors).

Findings such as these hint that individual differences, at least those related to subject characteristics such as sex and handedness, may be more evident when second-order relationships are examined. In our sample, group differences were difficult to observe for various measures of reading skill, VF lateralization, or neuroanatomy, when each domain was investigated separately. However, as described above, relationships across these domains revealed some interesting contrasts, suggesting that individual differences can become evident in cross-domain mappings. This implies that structure–function relationships can differ even for individuals with similar levels of skill, functional lateralization, or neurostructural features.

Subtypes of College Student Readers

We have also considered whether variations in reading subskills are associated with alternate forms of brain organization. Although phonological encoding skill (the ability to make print-to-sound associations) is widely viewed as essential for reading acquisition, among college student readers text comprehension can be dissociated from this lower-level skill. Resilient readers are those with poor phonological encoding (word attack scores below 35th percentile), but normal-to-excellent passage comprehension (scores above 45th percentile). This group was compared to proficient readers (word attack and passage comprehension above 45th percentile) and poor readers (below 35th percentile on both subtests) – see Table 1.1. Behavioral

Table 1.1   Mean scores for proficient, resilient, and poor readers.

	Proficient (N = 22)	*Resilient (N = 21)*	*Poor (N = 12)*
Word attack percentile	62.3	20.2	20.8
Passage comprehension percentile	69.5	66.0	28.8
Semantic priming (ms)	+33	+74	+34
Planum temporale asymmetry (sd)	.152 (.169)	.143 (.307)	.210 (.286)

investigations of these groups indicated that both resilient and poor readers were equally impaired at phonological coding, even when the task did not require decoding print (auditory phoneme deletion; Welcome, Leonard, & Chiarello, ~~in press~~). Both groups also were less accurate than proficient readers in an orthographic choice task, implying that resilient readers are not relying on enhanced orthographic analysis as a compensatory strategy. However, we obtained evidence that resilient readers made greater use of word meaning relationships than either proficient or poor readers – resilient readers had significantly greater semantic priming than either of the other groups (see Table 1.1). Hence, resilient readers may achieve good reading comprehension, despite poor phonological decoding, by increased reliance on semantic context.

Manual measurements of planum temporale asymmetry and automated measurements of regional differences in cortical thickness were examined in the three reading subgroups (Welcome et al., ~~in press, submitted~~). Although these groups did not differ in mean asymmetry of planum temporale surface area, the resilient readers had significantly greater variability in planar asymmetry as compared to proficient readers (see Table 1.1), and poor readers showed a similar (albeit non-significant) trend. Follow-up analyses verified a greater percentage of resilient (23.8%) and poor readers (33.3%) having extreme planar surface area asymmetries (greater than two standard deviations from the mean) than proficient readers (4.5%), due mainly to increased variability in the right planum. Increased variability may suggest that buffering mechanisms that normally maintain an optimal trajectory of neural development are less efficient, permitting more extreme asymmetries to emerge.

In contrast to the manual measures, the automated measures suggested that, relative to proficient readers, both resilient and poor readers had reduced asymmetry of temporoparietal gray matter thickness (Welcome et al., ~~submitted~~). It remains for future research to determine whether the reduced or more variable asymmetry is the more robust finding. The automated and manual procedures are measuring different aspects of cortical asymmetry (cortical thickness vs. planar length, respectively). One possibility is that the groups have sulci of equivalent length, but differing depth, within this temporoparietal region. Because reading comprehension was normal for the resilient group, the reduced gray matter asymmetry appears to be

associated with deficient phonological decoding, rather than poor overall reading skill. In contrast, poor, but not proficient or resilient, readers had reduced volume of the right lateral inferior frontal region that was not associated with a reduction of gray matter. A reduction in either gyrification or white matter in the right frontal area could account for this result, which may be associated with poor text comprehension.

Taken together the data imply a dysregulation of asymmetry in the temporoparietal region for adult readers with poor phonological decoding skills. When poor decoding co-occurs with diminished reading comprehension, additional atypical features in the right inferior frontal area were observed. These data suggest that some fairly subtle differences in reading skills among college students can be associated with differences in brain morphology, particularly within the right hemisphere. Greater research emphasis on the neuroanatomical correlates of variations in specific dimensions of reading skill could reveal behavioral–anatomical associations that are obscured when more global comparisons between "normal" and a heterogeneous collection of dyslexic readers are made.

Reading-Lateralization Profiles Revealed by Cluster Analysis

A paradox arises when we attempt to understand *individual* differences by contrasting the behavior or neural functioning of *groups* of individuals, be they groups defined by subject characteristics such as sex or handedness, or behavioral traits such as reading subskills. On the one hand, the study of individual differences is motivated by a desire to understand what makes each of us unique, but on the other hand, we try to investigate this by grouping individuals in order to permit statistical assessments. Furthermore, the groups are formed based on investigators' a priori notions about what should be relevant dimensions of individual difference for brain organization (e.g., sex, intelligence, imagery ability, etc.). We have no way of knowing whether nature has deemed these to be the relevant dimensions for the organization of psychological functions in the brain, as opposed to a myriad of other possibilities (e.g, fertility, swimming ability, degree of extroversion, etc.). And because individual differences are inherently multidimensional, it may be that investigating specific combinations of traits holds the key to understanding variations in brain organization, rather than grouping individuals along single dimensions.

We have recently explored an alternate approach (cluster analysis) in which subject groups are discovered by identifying similarities in patterns across a set of behavioral measures (Chiarello et al., submitted). We can then examine whether the resulting "bottom-up" subject classifications are associated with distinct neurostructural characteristics. A subset of our behavioral variables was used in the cluster analysis to identify subgroups (clusters) with similar performance: word attack from the WRMT-R, and asymmetry scores for masked word recognition (RT [response time] and accuracy), verb generation (RT and accuracy), lexical decision (RT and accuracy), and nonword naming RT. All but 17 of our 200 participants were suc-

cessfully classified into one of four clusters (described below). The remaining 17 individuals were identified as multivariate "outliers"; these participants had behavioral profiles that did not resemble any of the clusters, and were not similar enough to each other to form their own cluster. After describing the four cluster groups, we will examine the behavioral and neuroanatomical findings from the outliers. Because these individuals have idiosyncratic behavioral features we suspect that they may have a less buffered type of neurodevelopment, resulting in atypical neuroanatomical characteristics.

The cluster analysis identified four distinct reading/VF lateralization profiles, and these differences across clusters generalized to reading and VF measures that were not included in the cluster analysis (Chiarello et al., submitted). Therefore we present the findings across all our measures to provide a more complete portrait of these groups (see Table 1.2) – note that the data are reported as z-scores. Because we obtain RVF/LH advantages for all the divided VF tasks (Chiarello et al., 2009b), a z-score of 0 for the VF measures indicates the typical RVF/LH advantage for that task; small negative z-scores indicate a reduced RVF/LH advantage and large negative z-scores a reversed asymmetry. The composite asymmetry score is the average of the z-scored asymmetries obtained in each task.

Cluster 1 (N = 61) consisted of individuals with the poorest reading skill, for our sample. Their VF asymmetries across all tasks were somewhat smaller than average. Cluster 2 individuals (N = 26) had superior reading skill and reduced or reversed asymmetry in our lexical tasks. Cluster 3 (N = 63) comprised persons with average reading skill and quite large LH advantages for the VF tasks. Finally, Cluster 4 represented a second group with very good reading skill, but their VF asymmetries

Table 1.2 Mean Z-scores, by cluster, for reading subtests and composite visual field asymmetry. F-tests indicate that there were significant differences across clusters for all behavioral indices.

	Cluster 1 (N = 61)	Cluster 2 (N = 26)	Cluster 3 (N = 63)	Cluster 4 (N = 33)	F(3,179)
Reading skill	Poorer	Good	Average	Good	
VF asymmetry	Low-to-average	Low	Large	Varies by task	
Reading subtests					
Word identification	−.535	.434	.037	.528	12.7[***]
Passage comprehension	−.382	.376	−.117	.362	6.3[**]
Word attack	−.748	.851	−.032	.600	34.9[***]
Composite VF asymmetry					
Accuracy	−.036	−.522	.275	−.111	18.4[***]
Response time	−.204	−.449	.217	.189	28.1[***]

**p < .001, ***p > .0001.

varied depending on the task. For example, individuals in this cluster had the highest asymmetries in masked word recognition, average asymmetries in lexical decision, and reduced asymmetries for nonword naming, and for verb generation accuracy. It is notable that the clusters did not vary significantly in sex or handedness, indicating that there is identifiable variance in reading and lateralization that is not captured by typical subject variables. Although the cluster analysis identified associations between reading skill and VF lateralization, the data do not support the view that weaker lateralization is associated with poor reading: the group with the least evidence for LH lateralization had very good reading ability, while the group with the largest LH advantages had average reading ability. The poorest readers in our sample did not demonstrate extreme asymmetries in either direction.

Somewhat to our surprise, cortical asymmetries for both anterior (pars triangularis, pars opercularis, anterior cingulate and midparacingulate sulci) and posterior (planum temporale, planum parietale, Heschl's gyrus) regions did not differ significantly by cluster. However, we did observe some differences for the callosal area measurements. First, the posterior body (and to a lesser extent the midbody) of the corpus callosum was larger for Cluster 1 (poor readers, low/average VF asymmetries) than for Cluster 4 (good readers, task-dependent VF asymmetries). Second, Cluster 2 individuals (good reading, reduced/reversed VF asymmetry) had much larger splenia than individuals from any other cluster (Chiarello et al., submitted).

The techniques we used did not provide any evidence for an association between VF/reading profiles and cortical asymmetry. Additional techniques such as voxel based morphometry or diffusion tensor imaging and/or alternate behavioral measures may be needed to identify correlates of variation in cortical asymmetry. However, the data indicate an association between the size of posterior callosal regions and VF asymmetry for the skilled-reader clusters: reduced VF asymmetry associated with enlarged splenia (Cluster 2) and larger, although variable, VF asymmetry associated with reduced callosal posterior body (Cluster 4). The corpus callosum, and especially the splenium, has a protracted period of maturation extending well into adulthood (Giedd et al., 1999; Muetzel et al., 2008). We suggest that the most proficient readers will have accumulated greater reading experience during this extended maturation period, increasing the probability of experience-dependent sculpting of callosal organization relevant to reading processes. If this is the case, then skilled readers could continue to "fine tune" the relationship between hemispheric specialization for reading and interhemispheric channels, resulting in associations between lateralization and callosal area that are not found in less skilled readers.

To summarize, distinct behavioral/lateralization profiles were revealed by the cluster analysis, and a few neuroanatomical correlates were noted. The findings become more interesting when we consider the data for the outliers, those individuals whose behavioral data (for measures used to identify clusters) was dissimilar to any of the identified clusters. In what way was their data unusual, and are any atypical neuroanatomical features observed for these individuals? Although the outliers,

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by definition, do not resemble each other on the variables used in the cluster analysis, a consideration of their behavior across all our measures revealed some intriguing observations.

Statistical analyses consisted of comparisons between the outliers and the remainder of the sample considered as one group (see Chiarello et al., ~~submitted~~, for details). Although the outliers' performance on the WRMT-R word level tests (word identification, word attack) was unremarkable, they had extremely high scores on passage comprehension ($z = .526$) relative to the rest of the sample ($z = -.049$). In other words, in contrast to any of the clusters (see Table 1.2), their reading comprehension dissociated from lower-level reading skills. The outliers also had higher IQs than the rest of the sample. With respect to our VF tasks, analysis of the composite task asymmetries revealed that the outliers had greater RVF/LH advantages ($z = .249$ vs. $.024$), at least for reaction time. Most remarkable, however, was the finding that the outliers had much more extreme variations in asymmetry across tasks, relative to the individuals with more normative behavioral profiles. This was indicated by a standard deviation measure of the consistency of their asymmetries across tasks (for previous use of this measure see Chiarello, Kacinik, Manowitz, Otto, & Leonard, 2004; Chiarello et al., 2009b): outliers $z = 1.43$ vs. clusters $z = .851$, $p < .0001$, indicating much more extreme variations in asymmetry scores across tasks for the outliers.

The outliers were also less likely to have leftward asymmetry of the planum temporale, and their mean asymmetry did not differ from zero (Chiarello et al., ~~submitted~~). In contrast, the clustered individuals as a group, and every individual cluster, had leftward planar asymmetries that significantly differed from zero. The absence of asymmetry for the outliers was due to significantly larger right plana for the outliers, relative to the rest of the sample; left planum size did not differ. The outliers also differed significantly from the rest of the sample in that they were less likely to have the typical rightward asymmetry of the anterior cingulate sulcus. In this case, the absence of asymmetry was due to larger left anterior cingulate for the outliers; the right cingulate did not differ from the rest of the sample. Thus, the reduced asymmetry for these two cortical areas among outliers was due to increased size of the typically smaller hemisphere (RH for the planum temporale, LH for the anterior cingulate), resulting in greater symmetry for these typically asymmetrical structures. However, there were no differences in any of our corpus callosum measurements when we compared the outliers to the clustered individuals.

We note, in the behavioral data obtained from the outliers, some dissociations between measures that co-vary for the remainder of the sample: between word-level and text-level reading skill, and between VF asymmetries across various tasks. This may be why these individuals were statistically identified as outliers. This may suggest a less well-regulated type developmental trajectory with less buffering from random influences, which could result in unusual (although not necessarily harmful[3]) behavioral features. It is interesting that the atypical behavioral profiles found for the outliers co-occurred with some atypical neuroanatomical features, specifically reduced asymmetry in the planum temporale and anterior cingulate

sulcus. Because the reduced asymmetry was due to increased size of the (normally smaller) right planum and left anterior cingulate, we cannot localize the unusual neuroanatomical findings to a single hemisphere or brain region. Rather, it appears that the unusual behavioral profiles were associated with alterations across multiple regions of the cortex, which is consistent with the dysregulation view.

To summarize, the cluster analysis revealed several distinct profiles of reading skill and visual lateralization that would not have been evident from more standard ways of grouping individuals a priori. The clusters were not differentiated on the basis of sex or handedness, nor on any particular behavioral trait. Rather, they represent behavioral subtypes differentiated by their within-group similarity across multiple behavioral measures. But some individuals in our sample did not "fit" into any cluster, indicating more idiosyncratic profiles of reading and visual lateralization. Some neuroanatomical differences were associated with individual clusters and with the outliers. This suggests that some anatomical–behavioral correlations may be obscured when we rely on a priori ideas about how to categorize individuals.

Conclusions and an Alternate View of Individual Differences

The study of the neural correlates of individual differences is still at a very early stage of development. Nevertheless, although our project is ongoing, we can offer some preliminary conclusions. First, easily measured grouping variables such as sex and handedness at best only account for a very small amount of the variance in brain lateralization and reading ability. Second, even when subject groups are similar behaviorally and anatomically, the association between behavior and brain can differ. That is, neural and behavioral variation can map onto each other in different ways within different subgroups of persons. This suggests that there is more than one way in which the human brain can support cognitive functions such as reading. Third, novel multivariate statistical approaches can reveal profiles of individual variation that may not be observable when the investigator determines a priori what the appropriate subgroups should be. Finally, it is just as important to investigate those individuals who cannot be classified into definable subtypes, as those who can. Such outliers can potentially inform us about the costs and benefits of atypical developmental outcomes.

Our findings on anatomical and behavioral variability in healthy young adults have implications for the search for neurological substrates of disorders such as autism, dyslexia, and schizophrenia. Given the variability that is characteristic of such healthy "control" populations, simple comparisons of control and clinically identified groups that rely on group averaging may not yield the sort of insights we seek. Greater attention to the relation of individual behavioral and anatomical profiles is essential if we are to understand the ways in which various disorders depart from the normal range.

Because individuals can differ from each other in a multitude of ways, no single approach to the study of human variation can explain even a fraction of this diver-

sity. For example, although the cluster analysis described above identified some interesting differences between subgroups, no doubt a different grouping of the same individuals would have resulted had we examined a different set of measures. We make no claim that our analysis is any more valid than other ways to carve up the individual difference "space." If we think of each individual as a single point in a multidimensional space, where each dimension represents one facet of variation, then there can be a nearly infinite number of empirically valid subgroups within this space. Hence it may be a fruitless quest to attempt to understand the mapping between behavioral and neural variation by identifying a small number of relevant dimensions, be they subject characteristics such as sex or handedness, or information processing differences such as Phoenician versus Chinese reading styles (e.g., Bowey, 2008).

We propose a kaleidoscope metaphor as an appropriate approach to the study of individual differences and their neural correlates. A kaleidoscope consists of a tube containing a set of colored beads and internal mirrors. When looking through a kaleidoscope a range of different patterns can be seen by rotating the tube that adjusts the mirrors. Although the patterns change, the elements (beads) out of which the patterns are formed do not. Similarly, different subgroups (patterns) can be revealed when the same individuals are examined in different ways. This implies that even small adjustments in our analytical lens (i.e., variations in variables and statistical methods) can reveal a succession of patterns latent in the population under study, each of which is a "true" reflection of the associations underlying individual variation. As investigators, then, it will behoove us to continually vary our analytical lenses in order to better understand the many ways in which individuals are similar and different.

Notes

1 Variations due to sex or handedness are often considered, but this can only go so far in understanding *individual* differences. Subdividing groups by sex or handedness does not generally have a substantial effect on the range of individual variation. A large range of variation is still evident when examining groups such as right-handed females.
2 Note that although there appears to be slightly more learning disabled individuals with reversed asymmetry, this is actually due to a less peaked distribution overall.
3 In general, greater "openness" to random genetic and environmental influences should have both positive and negative outcomes, since random factors are not biased in any direction (see Belsky & Pluess, 2009, for a similar hypothesis). Yet in our sample, the "outliers" seemed to have somewhat superior intellectual skill. We hypothesize that unregulated individuals with net negative outcomes would be unlikely to attend college, and hence not represented in our sample. A larger, community-based sample would be needed to confirm this conjecture.

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