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Does degree of asymmetry relate to performance? An investigation of word recognition and reading in consistent and mixed handers

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ABSTRACT

Is it advantageous to be strongly lateralized? The current study investigated this question by examining the relationship between visual field asymmetries for lexical tasks and reading performance in a sample of 200 young adults. Larger visual field asymmetries were associated with better reading performance, but this relationship was obtained primarily in those with strong and consistent hand preferences. Among mixed handers, variation in visual field asymmetry accounted for little or no variance in reading skill. In addition, correlations between visual field asymmetry and reading performance were observed for word recognition tasks, but not for tasks requiring controlled semantic retrieval. The results are consistent with the idea that consistent and mixed handers may represent differing neurobehavioral populations. Because greater lateralization was associated with better reading skill only for consistent handers, reduced behavioral asymmetry cannot be assumed to be a risk factor for reading dysfunction in the population as a whole.

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1. Introduction

Functional lateralization is an important organizing principle of the human brain. The left and right cortices have different specializations and each contributes to the performance of most cognitive tasks (Hellige, 1993). However, there appear to be individual differences in the extent to which the left and right hemispheres functionally specialize. Regardless of how lateralization is measured, some individuals show large behavioral asymmetries while others show much less or no evidence for asymmetrical functioning (Cowell & Hugdahl, 2000; Hellige, Bloch, & Taylor, 1988). Is it advantageous to be strongly lateralized? In other words, will better performance within a given domain be associated with stronger or weaker functional lateralization, or are variations in performance independent of lateralization altogether? It is important to investigate these possibilities within the normally functioning population, because it is frequently presumed that abnormal lateralization is associated with increased risk for disorders such as dyslexia, schizophrenia, and autism (Annett, 1997; Bradshaw & Sheppard, 2000; Eckert & Leonard, 2003; Green, Sergi, & Kern, 2003). Such positions implicitly assume that departures from “normal” lateralization are associated with performance deficits. How-

ever, it remains to be seen whether there are any costs to non-typical functional lateralization in the non-impaired population.

Boles, Barth, and Merrill (2008) have recently examined this issue by conducting a meta-analysis of a variety of lateralized performance measures. They observed that the absolute value of a person's asymmetry index for a given task was a better predictor of overall performance in that same task than an index that preserved the direction of asymmetry. This implies that it is the degree of task asymmetry that may confer an advantage/disadvantage for performance, rather than which hemisphere is a more efficient processor. Boles et al., 2008 further demonstrated that the asymmetry–performance relation varied by task. Some tasks were performed better by those with stronger task asymmetries (e.g., dichotic listening with syllables and words, judging spatial locations), and others were performed better by those with weaker task asymmetries (e.g., visual lexical tasks). The authors outlined a neurodevelopmental theory to account for these results. Briefly, individual differences in the rate of corpus callosum maturation, and the period during which various lateralized processes are established, contribute to the asymmetry–performance relation. Strong task asymmetries are associated with enhanced performance for processes that are acquired early (auditory linguistic processes), whereas weaker asymmetries predict enhanced performance for processes acquired somewhat later. For example, Boles et al. argue that visual lexical processes may lateralize between 8 and 11 years of age, and for such tasks weaker asymmetries should be associated with better performance (but

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see also Simos et al., 2002, for evidence of earlier lateralization). Boles et al., 2008 provide a more detailed explication of this theory.

This evidence implies that individual differences in hemispheric asymmetries may bear some relation to individual differences in various cognitive functions. However, we are far from having a complete picture of the nature and generalizability of this relationship because the tasks used to assess behavioral lateralization are often quite different from “real world” behaviors. For example, it is unclear whether the four divided visual field tasks that Boles et al. (2008) classified as “lexical” in fact measured visual lexical processes of the sort used in word recognition and reading. Their Naming task involved pronunciation of digit words (ONE through EIGHT), and the Visual Words task used the same 8 stimuli but required odd–even judgments. RT asymmetries were measured in these tasks. The other two tasks measured accuracy asymmetries. In the Typing task, 3-letter words from a set of 18 items were presented and participants responded by typing the presented word. The Visual Digits task was similar but the stimuli were strings of three digits. Previous factor analyses have shown that asymmetries for these tasks reflect a common underlying factor (Boles, 1996). However, one might question whether this factor represents processes used in more typical word reading tasks.¹ In all of these tasks stimuli from a very small set of items were repeatedly presented. The Naming task in particular could have been accomplished by recognizing a distinctive visual feature of the eight number words, and thus may not have required normal lexical access processes. Both typing tasks could have relied on letter/digit-keystroke associations without necessitating typical word recognition processes. The visual words task might require a type of semantic judgment, but the repeated presentation of a very small set of stimuli could engender strategies that would not generalize to other semantic tasks. Hence it is important to examine how asymmetry in tasks that are more commonly used to investigate lexical access and word reading relates to reading performance. To the extent that lexical task performance reflects processes used in reading, one should observe that task asymmetry predicts performance on standardized reading measures. We argue that using lateralized performance to predict actual reading behavior (rather than performance on experimental tasks) will increase the ecological validity of the findings, and facilitate comparisons with studies of reading-disabled populations.

Weems and Zaidel (2004) compared performance in lateralized lexical decision to vocabulary and reading comprehension subtests of the Nelson–Denny reading test (Brown, Fishco, & Hanna, 1993). They did not examine asymmetry scores or left–right differences, but observed that LVF lexical decision performance was positively correlated to vocabulary scores. However, since RVF lexical decision was also correlated with vocabulary scores (albeit to a lesser extent than LVF lexical decision), it is unclear how reading vocabulary might relate to the degree of lexical decision asymmetry.

A different approach to the asymmetry–performance issue comes from the research of Christman and colleagues. They have observed that degree of handedness (one indicator of functional lateralization) predicts performance on a variety of behavioral measures. In these studies participants with very strong hand preference asymmetries (consistent handers) differed from those with less consistent hand preferences (mixed handers). For example, mixed handers demonstrated enhanced episodic memory (Christman, Propper, & Dion, 2004; Propper, Christman, & Phaneuf, 2005) and risk perception (Christman, Jasper, Sontam, & Cooil, 2007), and were differentially affected by anchoring information during decision making (Jasper & Christman, 2005), relative to con-

sistent handers. These authors have argued that the handedness differences reflect the degree of hemispheric interaction, with mixed handers showing a greater reliance on hemispheric interaction during task performance. Although handedness is related to language lateralization (Knecht et al., 2000; Szaflarski et al., 2002), it is unclear whether the performance differences observed in these studies could be attributed to differing degrees of cerebral lateralization in mixed vs. consistent handers, as no language lateralization measures were included in their investigations. Because Christman and colleagues argue that strength of handedness is an important dimension of individual difference (e.g., Jasper & Christman, 2005; Propper et al., 2005), in the current study we also examined asymmetry–performance correlations separately for mixed and consistent handers.

Data from the Biological Substrates for Language project, which we report herein, allowed us to address these issues. Two hundred young adults, unselected for handedness, completed seven divided visual field lexical tasks (lexical decision, word naming, nonword naming, masked word recognition, semantic decision, category generation, verb generation). These tasks are standard psycholinguistic measures designed to assess various aspects of word recognition and lexical and semantic access. The tasks were selected to index a variety of lexical processes, including phonological encoding (nonword naming), rapid visual word perception (masked word recognition), semantic and lexical discrimination (semantic and lexical decision), and semantic generation (verb and category generation). Response requirements also varied across tasks, and included both vocal and manual responses, open-ended and forced-choice responses, and tasks with a single correct response and with multiple correct responses. In addition, each participant completed several subtests from a standardized reading battery, along with an IQ measure. This study allowed us to determine whether observed asymmetry across a variety of visual lexical tasks would predict reading skill as assessed by standardized (i.e., nonlateralized) reading measures.

We report data to address three questions. First, will degree of visual field asymmetry be a better predictor of reading performance than direction of asymmetry? This is an attempt to generalize the findings of Boles et al. (2008) using a different set of lateralized tasks and nonlateralized reading measures. Second, will weaker lexical task asymmetries be associated with better performance on typical reading tasks? Boles et al. (2008) observed a negative relation between asymmetry and performance on their visual lexical tasks, but we have questioned whether the tasks they used actually reflect lexical processes used in word recognition and reading. Third, will asymmetry–performance relations differ for consistent vs. mixed handers? If consistent handers rely more on within-hemisphere processors during task performance (Christman et al., 2004; Christman et al., 2007), then we might expect a tighter asymmetry–performance association among this group of individuals.

2. Method

2.1. Participants

One hundred male and 100 female university student volunteers participated, receiving \$100 payment for their participation (mean age = 21.6 y). All were native English speakers with normal or corrected-to-normal vision. An exhaustive analysis of possible sex differences in the lateralized tasks reported here obtained little evidence for sex differences in hemispheric asymmetry in the current sample (Chiarello et al., *in press*). Hence we report findings across the entire sample here.

To assess handedness, a five-item preference questionnaire was utilized (Bryden, 1982), which yields an index ranging from +1.00 (extreme right-handedness) to –1.00 (extreme left-handedness).

¹ Although Boles et al. (2008) did not explicitly claim that the visual lexical tasks reflected reading-related processes, the term “visual lexical” implies word recognition processes involved in reading, and it is important to determine whether cerebral asymmetries for experimental tasks can predict reading performance.

This questionnaire includes the five most reliable and valid items from the Edinburgh inventory (Bryden, 1977). Mean handedness score for our sample was +.71 (median = +.90). We considered consistent handers to be those who scored either -1.0 or $+1.0$ on the hand preference questionnaire.² These individuals ($N = 103$, 44 male) reported no use of the nondominant hand for any activity, and five of them were consistent left-handers.³ The remaining 97 (56 male) participants were considered to be mixed handers (handedness scores from $-.90$ to $+.90$, mean = $+0.49$). Among the mixed handers, 78% wrote with the right-hand. It should be noted that mixed handers are usually not ambidextrous and most have some degree of right-hand preference. The consistent and mixed handers did not differ in age (21.7 years vs. 21.5 years, respectively).

2.2. Materials

Three subtests of the Woodcock Reading Mastery Test – Revised (Woodcock, 1998) were administered. Word Attack requires pronunciation of increasing difficult pseudowords, Word Identification requires reading aloud words of increasing difficulty, and Passage Comprehension involves reading texts and producing a sentence completion appropriate for each text. The reading assessments are untimed. Percentile ranks for each subtest were used in the data analyses.

Experimental stimuli consisted of 3–6 letter concrete nouns and/or pronounceable nonwords, presented in uppercase 20 point Helvetica font. Nonwords were created by replacing a letter of a concrete noun, with each letter position replaced equally often. Additional details about the stimuli are described in Chiarello et al. (in press). Unique stimuli were used in each task, and stimuli were never repeated within a task. Stimuli appeared in black on a white background.

2.3. Apparatus and procedure

Each participant was tested across five test sessions. In the first session participants completed the handedness questionnaire, the WASI IQ measure (Wechsler, 1999), and the three Woodcock reading subtests (Woodcock, 1998). The seven experimental tasks were administered across four subsequent testing sessions, in the following order:

Lexical decision: 90 word and 90 nonword trials, keypress discrimination response, 125 ms exposure. Participants were asked to determine whether or not each stimulus was an English word.

Word naming: 90 trials, pronounce word, 125 ms exposure. Participants were asked to read each word aloud.

Category generation: 82 trials, produce exemplar of stimulus noun category, 155 ms exposure. Participants were shown a category name (e.g., FRUIT) and were asked to produce a member of that category. A novel category name was provided on each trial.

Nonword naming: 90 trials, pronounce nonword, 150 ms exposure. Participants were asked to pronounce an orthographically legal nonword string.

Masked word recognition: 100 trials, recognize word preceded and followed by 60 ms pattern mask (@##@#), two-alternative

forced-choice key press response, 30 ms exposure. After viewing the masked stimulus, participants were shown the stimulus and a distractor word and asked to select which one was the stimulus. Distractors differed from the stimulus word in only one letter. Response choices were presented centrally, one above the other, with the stimulus shown in the upper and lower position equally often.

Verb generation: 100 trials, pronounce verb associated with stimulus noun, 150 ms exposure. Participants were shown a noun (e.g., PEN), and were asked to respond with a verb that described what the object did or was used for.

Semantic decision: 120 trials, keypress response, 120 ms exposure. Participants were shown a noun and asked to determine whether it represented a naturally occurring or a manmade object.

On average, each session was separated by four days.

Experimental stimuli were presented on an Apple Studio Display M7649 monitor, and Psyscope programming software was used to control experimental events and record responses (Cohen, MacWhinney, Flatt, & Provost, 1993). Stimuli were randomly presented to the left or right visual field (LVF, RVF), 1.8 degrees eccentric from a central fixation “+”. At the onset of each trial, the fixation marker appeared for 600–805 ms and flickered just prior to the onset of the stimulus. Participants were instructed to maintain central fixation and respond as quickly and accurately as possible. Keypress responses were made bimanually using the computer keyboard, with the index and middle fingers of each hand. Vocal responses were registered by a Sony ECM-MS907 microphone, with responses entered into the computer by the experimenter. Each task was prefaced by 30–48 practice trials.

2.4. Asymmetry measures

In order to determine whether there are relationships between asymmetry and performance, it is important to utilize an asymmetry measure that does not itself vary with experimental task performance level. Various asymmetry indices have been proposed to attempt to “control for” overall performance (e.g., Birkett, 1977; Bryden & Sprott, 1981). These typically involve some type of ratio, with a left–right difference score as the numerator, and combined left–right scores as the denominator. Differences in asymmetry scores could then be due to either changes in the numerator (left–right differences) or the denominator (overall performance). To avoid this ambiguity, we utilized a multiple regression approach in which each individual's overall mean reaction time or accuracy was partialled out from their left–right difference score. The resulting signed residual difference score reflects each individual's direction and degree of task asymmetry, independent of their overall performance. Asymmetry scores were computed in this fashion separately for each task, for both reaction time (RT) and accuracy (percent correct). The Appendix describes how the residual difference scores are calculated, and contains an illustration of the variation in these asymmetries for the accuracy measure in the word naming task. Positive residual scores indicate larger RVF/LH advantages, while negative residuals indicate smaller or reduced asymmetries (a residual score near 0 represents the average asymmetry, i.e., a small RVF advantage for our tasks). To examine the absolute value of asymmetry, the absolute value of the left–right difference was used in a similar regression. On this measure, positive residuals indicate greater visual field differences, and negative residuals smaller or no visual field asymmetries, regardless of direction.

In addition to considering asymmetry scores for each individual task, we also created a composite visual lexical asymmetry score (see Chiarello, Kacinik, Manowitz, Otto, & Leonard, 2004; Chiarello et al., in press for use of composite asymmetry scores). For such composites, values for each task are first z-scored (to normalize RT and accuracy variations across tasks) and then averaged over

² This procedure departs somewhat from that used by Chrisman and colleagues who utilize a median split approach with the 10-item Edinburgh handedness inventory (EHI). With only five items on the modified Bryden scale that we adopted, there is a higher probability of receiving the maximal score (either $+1.0$ or -1.0), than with the 10-item EHI. Hence we obtained nearly equal-sized handedness groups by contrasting those with the most extreme handedness scores to all others. Our group cut-offs were intended to yield groups comparable to those used by Christman, despite the fact that we used a shorter inventory.

³ Analyses reported below were also conducted dropping the five consistent left-handers. Since none of the findings were altered, we report data for all consistent handers as one group.

tasks. Composite measures are more reliable than any single assessment (Rosenthal, 2005), and the composite score can be used to determine whether a general measure of visual lexical asymmetry (combined across several tasks) varies with standardized reading test performance. We computed a composite lexical asymmetry score for each participant as follows. For each task, a left–right difference score was calculated and transformed into a z-score. Next the average of these z-scores across the 7 tasks was calculated, resulting in a composite difference score. A composite residual difference score, analogous to the residual difference score for each task (see Appendix A), was then computed by using multiple regression to partial out composite average performance from the composite difference score. This produces a composite asymmetry index from which the effects of overall performance level are removed. Like the residuals for each task, positive composite asymmetry scores indicate larger RVF/LH advantages and negative composite scores indicate smaller or reversed visual field differences. To examine the absolute value of asymmetry combined across tasks, a similar procedure was used, except that the absolute values of the left–right differences were used in creating the composite score.

3. Results

Preliminary analyses of variance on the mean RT and percent correct scores for each task verified that the expected RVF/left hemisphere advantage was observed for all tasks for accuracy, and for all tasks except for nonword naming for RT (as described in Chiarello et al., *in press*). All subsequent analyses were based on the residual difference scores as described above. We first report findings across the entire sample, and then examine consistent and mixed handers separately.

3.1. Sample-wide findings

The individuals in our sample had a mean verbal IQ of 108.7 ($sd = 11.0$, range 78–143) and a mean performance IQ of 108.8 ($sd = 11.4$, range 76–138) (Wechsler, 1999). Means of percentile scores for the reading tests were as follows: Word Attack ($M = 48.0$, $sd = 21.4$, range 5–98), Word Identification ($M = 49.7$, $sd = 16.8$, range 5–98), Passage Comprehension ($M = 65.4$, $sd = 23.8$, range 8–99.7). Although mean IQs were somewhat above average, performance on the reading subtests was quite variable in this sample.

The first set of correlations was conducted to determine whether the degree of task asymmetry, independent of direction, (absolute value of asymmetry) showed a stronger relationship with performance than a task asymmetry measure that preserved direction (signed asymmetry). To examine this, we correlated performance on the standardized measures with the composite lexical asymmetry scores, separately for accuracy and RT – see Table 1. As can be seen, there was not much difference in the correlation coefficients for signed vs. absolute value of asymmetry, although the correlations were nominally greater for the absolute value for all verbal tasks except word identification. To simplify the presentation of our results, all further analyses reported here will use the absolute values of the visual field asymmetries. Very similar results were obtained using signed asymmetries.

As Table 1 indicates, greater evidence for asymmetry–performance relationships was obtained with accuracy, than with RT, asymmetry scores. For accuracy, the degree of asymmetry was positively related to verbal IQ, and to the reading subtests. That is, those with greater accuracy asymmetries performed better on most psychometric measures. For RT, the associations with performance were observed less consistently. However, a greater degree of RT asymmetry was weakly associated with higher scores on

Table 1

Correlation of composite lexical asymmetry scores (signed and absolute value) with performance measures – significant correlations in bold.*

Performance measure	Accuracy		Reaction time	
	Signed asymmetry	Absolute value asymmetry	Signed asymmetry	Absolute value asymmetry
Performance IQ	.078	.057	.103	.132
Verbal IQ	.152	.182	.116	.130
Word Attack	.141	.148	.104	.173
Word Identification	.171	.123	.093	.083
Passage Comprehension	.146	.168	.173	.175

* $p < .05$.

Word Attack and Passage Comprehension. For both response measures, however, the significant correlations were quite small in magnitude. Nevertheless, the findings are consistent with the idea that a greater degree of lexical task asymmetry is associated with better verbal and reading performance.

We next examined asymmetry–performance relations for each of our divided visual field (DVF) tasks separately. Tables 2 (accuracy) and 3 (RT) display these data. Reliable positive correlations were observed between each verbal performance measure and accuracy asymmetry for one or more of the word recognition DVF tasks (lexical decision, word naming, nonword naming, masked word recognition). However, there was no relation between performance and accuracy asymmetry for the semantic DVF tasks (semantic decision, category and verb generation). The findings for RT asymmetry were mainly driven by the masked word recognition task – greater RT asymmetry for this task was associated with better performance on all IQ and reading subtests. As was observed for accuracy asymmetry, no correlations were observed for the three semantic tasks. However, in general, all significant correlations between task asymmetries and the IQ and reading measures were positive, indicating that larger visual lexical asymmetries were associated with better performance.

3.2. Consistent vs. mixed handers

Consistent and mixed handers did not differ in performance IQ (107.6 vs. 110.0, $p > .10$), Word Attack (48.0 vs. 47.9, $t < 1$), Word Identification (48.7 vs. 50.8, $t < 1$), or Passage Comprehension (62.7 vs. 67.4, $p > .15$). However, consistent handers had somewhat lower verbal IQs (107.1) as compared to mixed handers (110.5), $t(198) = 2.18$, $p < .05$.

We considered whether the handedness groups differed in lexical task asymmetry by comparing the composite asymmetry scores across groups. There were no group differences when signed asymmetry was examined for either accuracy ($t < 1$), or RT ($t < 1$). However, for the absolute value asymmetry measure, group differences approached significance. Consistent handers had somewhat larger asymmetries than mixed handers for both accuracy (.065 vs. $-.070$, $t(198) = 1.83$, $p < .07$), and RT (.058 vs. $-.062$, $t(198) = 1.94$, $p < .06$).⁴ This may imply that consistent handers have more extreme asymmetries, regardless of direction, than mixed handers, rather than larger left hemisphere asymmetries on average. To explore this, Fig. 1A and B, respectively, display the distributions of signed and absolute value composite accuracy asymmetry scores by handedness group. For signed asymmetries (Fig. 1A), consistent handers are overrepresented, relative to mixed handers, at both ends

⁴ Because the composite asymmetry measures are z-scores, a score of 0 indicates the average asymmetry, rather than lack of asymmetry. Hence the mixed handers had reduced, but not usually reversed asymmetries.

Table 2

Correlations of within-task accuracy asymmetry scores (absolute values) with task performance and IQ and reading subtests – significant correlations shown in bold.

	Lexical decision	Word naming	Nonword naming	Masked word recogn	Semantic decision	Category generation	Verb generation
Perform IQ	.117	–.038	–.040	.076	.038	.012	.044
Verbal IQ	.217**	.045	.046	.149*	.121	–.032	.124
Word Attack	.107	.114	.158*	.120	–.085	.004	.126
Word Identification	.159*	.153*	.061	.024	.027	–.038	.065
Passage Comprehension	.156*	.142*	.085	.025	.102	.015	.090

* $p < .05$.** $p < .01$.**Table 3**

Correlations of within-task RT asymmetry scores (absolute values) with task performance and IQ and reading subtests – significant correlations shown in bold.

	Lexical decision	Word naming	Nonword naming	Masked word recogn	Semantic decision	Category generation	Verb generation
Perform IQ	.027	–.046	.086	.242**	.093	–.036	.042
Verbal IQ	.101	.035	.127	.193**	.041	–.002	–.095
Word Attack	.041	–.048	.115	.273**	.063	–.025	.115
Word Identification	.089	–.013	.045	.249**	–.023	.024	–.114
Passage Comprehension	.117	.029	.165*	.267**	.055	–.029	–.063

* $p < .05$.** $p < .01$.

of the distribution. However, a comparison of means across groups does not show a difference because the greater frequency of both large positive and negative scores offset each other. However, as

Fig. 1. Distribution of residual VF difference scores (composite accuracy measure) for signed (1A) and absolute value (1B) measures for mixed and consistent handers. For signed asymmetry scores, near zero residual represents a moderate RVF advantage; negative residuals indicate minimal RVF advantages or no or LVF advantages (as the residual becomes more negative). For absolute value asymmetry scores, a zero residual indicates a moderate VF difference (independent of direction), negative residuals indicate small or no VF asymmetry, and positive residuals indicate increasingly larger VF differences (independent of direction).

Fig. 1B shows, the absolute value asymmetry score documents a group difference in strength of asymmetry independent of direction.

To examine whether asymmetry–performance relations differed for consistent and mixed handers, we computed correlations separately for these two groups. Sex was entered as a variable in the multiple regressions because the handedness groups were not balanced by sex – there were somewhat more females among consistent handers, and somewhat more males among mixed handers, as has been found previously (Christman et al., 2007). For these analyses, residual difference scores were calculated partialling out average performance and dummy coding sex. The findings reported here, then, eliminate any contribution of sex to the reported correlations.⁵

Table 4 displays the correlations of the composite accuracy and RT asymmetry scores with our performance measures, by handedness group. Although both handedness groups showed positive correlations, the coefficients were significant only for the consistent handers, for both RT and accuracy. For this group, greater lexical accuracy asymmetry was associated with higher verbal IQs, and better performance on all reading subtests; greater lexical RT asymmetry was associated with higher verbal and performance IQs, and with higher word attack and passage comprehension.

Individual lexical task correlations are given in Tables 5 (accuracy) and 6 (RT) by handedness group, and the significant correlations are shown graphically in Fig. 2A (consistent handers) and B (mixed handers). In all cases, reliable correlations between task asymmetry scores and reading performance were positive, indicating that greater task asymmetry was associated with better reading and verbal performance. For the most part, the consistent handers showed the same patterns of asymmetry–performance relations as those previously described for the entire sample. Many fewer significant correlations were observed for the mixed handers. As shown in Fig. 2A, consistent handers demonstrated reliable asymmetry–performance correlations for each word recognition lexical task (lexical decision, word and nonword naming, and masked word recognition) with one or more of the reading measures. Visual field asymmetries in most of these tasks, along with

⁵ We also examined the asymmetry–performance correlations among consistent and mixed handers without partialling out sex. The findings were very similar to those reported here, suggesting that differences between handedness groups are not attributable to sex differences.

Table 4

Correlation of composite lexical asymmetry scores (absolute value) with several performance measures for consistent vs. mixed handers – significant correlations in bold.

Performance measure	Accuracy asymmetry		Reaction time asymmetry	
	Consistent handers	Mixed handers	Consistent handers	Mixed handers
Performance IQ	.157	.007	.202*	.074
Verbal IQ	.290**	.178	.258**	.034
Word Attack	.237*	.127	.246*	.126
Word Identification	.211*	.108	.109	.126
Passage Comprehension	.237*	.186	.254*	.113

* $p < .05$.** $p < .01$.**Table 5**

Correlation of accuracy asymmetry scores (absolute value) with performance measures by handedness group – significant correlations shown in bold.

	Lexical decision	Word naming	Nonword naming	Masked word recognition	Semantic decision	Category generation	Verb generation
<i>Performance IQ</i>							
Consistent handers	.156	.055	–.039	.110	.040	.152	.134
Mixed handers	.111	–.182	–.031	.062	.077	–.156	–.012
<i>Verbal IQ</i>							
Consistent handers	.300**	.199*	–.012	.160	.202*	–.025	.180
Mixed handers	.150	–.159	.134	.154	.029	–.042	.112
<i>Word Attack</i>							
Consistent handers	.193	.150	.175	.112	–.068	.096	.092
Mixed handers	.028	.026	.143	.137	.079	–.122	.174
<i>Word Identification</i>							
Consistent handers	.223*	.223*	–.008	.099	.108	–.042	.091
Mixed handers	.113	–.017	.174	–.058	–.036	–.068	.064
<i>Passage Comprehension</i>							
Consistent handers	.143	.274**	.068	.097	.186	–.008	.104
Mixed handers	.201*	–.060	.118	–.048	.025	.031	.116

* $p < .05$.** $p < .01$.**Table 6**

Correlation of reaction time asymmetry scores (absolute value) with performance measures by handedness group – significant correlations shown in bold.

	Lexical decision	Word naming	Nonword naming	Masked word recognition	Semantic decision	Category generation	Verb generation
<i>Performance IQ</i>							
Consistent handers	.058	.015	.156	.298**	.120	.013	.024
Mixed handers	–.017	–.107	.055	.182	.126	–.088	.108
<i>Verbal IQ</i>							
Consistent handers	.142	.134	.192	.234*	.200	.005	–.148
Mixed handers	.082	–.068	.069	.148	–.129	–.005	.019
<i>Word Attack</i>							
Consistent handers	.026	.033	.118	.338**	.173	.033	.035
Mixed handers	.025	–.134	.145	.197	–.016	–.096	.218*
<i>Word Identification</i>							
Consistent handers	.149	–.019	.065	.299**	.041	–.050	–.191
Mixed handers	–.026	–.021	.080	.174	–.027	.106	.028
<i>Passage Comprehension</i>							
Consistent handers	.102	.126	.312**	.279**	.180	–.036	–.147
Mixed handers	.128	–.076	–.012	.249*	–.049	–.024	.079

* $p < .05$.** $p < .01$.

semantic decision, also predicted verbal IQ. In contrast, among mixed handers (Fig. 2B), there was no relation between lexical asymmetries and performance for either IQ or Word Identification. Lexical decision accuracy asymmetry, and masked word recognition RT asymmetry did predict Passage Comprehension in this group, and an association was also observed between verb generation RT asymmetry and Word Attack. However, comparison of Fig. 2A and B demonstrates that task-wise asymmetry–performance correlations were much more numerous for those with consistent handedness. This implies that the relationship between reading and VF task asymmetry is more robust among consistent

handers, generalizing across several VF tasks and reading measures. In contrast, among mixed handers, associations between VF task asymmetry and reading are more sporadic.

Could the handedness differences we document here be attributable the fact that most left-handers are in the mixed-handed group? In other words, are the findings for mixed handers really due to a weaker expression of handedness, regardless of direction of preference? We do not have adequate numbers of left-handers to compare mixed vs. consistent hand preference for this group. However, we did recompute our composite task asymmetry–performance correlations for right-handers only, contrasting those

Fig. 2. Associations between asymmetry scores for individual DVF tasks and reading/IQ subtests for consistent (2A) and mixed (2B) handers. Only significant correlations are shown.

with consistent right-hand preference ($N = 98$) to those with weaker right-hand preference (i.e., scores from +0.1 to +.90, $N = 76$). These data are given in Table 7, and confirm that, even among right-handed individuals, strength of hand preference moderates the visual field asymmetry-reading performance relationship. Significant asymmetry-performance correlations were obtained only for consistent right-handers, and not for mixed right-handers.

4. Discussion

The current investigation examined whether asymmetry of visual word processing is related to performance on reading and IQ tests. In other words, is enhanced or reduced visual field asymmetry associated with better reading skill? In a sample of 200 young adults, we obtained some evidence for an association between lexical asymmetry and reading performance: larger asymmetry scores were positively, albeit weakly, correlated with reading scores.

Before discussing these results in greater detail, we should acknowledge some limitations of this study. First, our sample, although large, was restricted to college students. No doubt a greater range of reading ability is present in the general population, and we cannot speculate about the extent to which our results might be generalizable to older, or to less educated, groups. Second, our lateralized tasks all measured various aspects of single word processing. This is an important component of reading skill, but other factors such as verbal working memory and text processing also contribute to reading performance, and we did not assess lateralization for such processes. Finally, the divided visual technique is an indirect measure of functional lateralization. Measures of brain activity such as MEG and fMRI will be needed to corroborate our findings. Nevertheless, the data reported here represent the beginnings of an empirical foundation (along with the findings of Boles et al., 2008) for a more comprehensive view of the costs and benefits of cerebral lateralization for cognitive performance.

In addressing the issue of the relationship between asymmetry and performance, we felt it was important to utilize measures of task asymmetry that do not themselves potentially vary with performance. Because overall performance (combination of LVF and RVF scores) enters into the calculation of various asymmetry indices (Birkett, 1977; Bryden & Sprott, 1981), we utilized a multiple regression approach to statistically remove the effects of overall performance from the left-right difference scores. Thus we can be certain that any asymmetry-performance associations that we observe are not due to variations in the asymmetry index that might be linked to overall performance levels. This should be kept in mind when comparing our findings to others that have used more standard asymmetry indices.

One objective of this study was to examine whether there were stronger asymmetry-performance correlations when one considered only the degree of lateralization (absolute value of left-right differences) rather than direction plus degree (signed left-right difference). For the most part, there was little difference between these measures, implying that preserving the direction of visual field asymmetry does not provide much explanatory value over and above degree of asymmetry. However, we did not replicate the observation of Boles et al. (2008) that asymmetry-performance correlations are stronger for the absolute value of asymmetry scores. It is possible that this is due to the fact that our language tasks yielded RVF advantages for most participants, whereas the selection of tasks used by Boles et al. (2008) produced visual field asymmetries that included LVF and RVF advantages. We did observe a trend for consistent handers to have greater lexical lateralization for the absolute value, but not for signed, asymmetry. Examination of this data indicated that consistent handers had more extreme lexical task asymmetries than mixed handers, but not more leftward asymmetries on average. This could imply that individuals with a very strong hand preference also tend to have very strong hemisphere asymmetries for language, inviting the speculation that there may be stronger links between handedness and hemispheric specialization for language when degree, rather than direction, of asymmetry is exam-

Table 7

Correlation of composite lexical asymmetry scores (absolute value) with several performance measures for consistent vs. mixed right-handers – significant correlations in bold.

Performance measure	Accuracy asymmetry		Reaction time asymmetry	
	Consistent right-handers	Mixed right-handers	Consistent right-handers	Mixed right-handers
Performance IQ	.165	-.122	.178	.086
Verbal IQ	.287**	.134	.245**	.048
Word Attack	.246*	.031	.234*	.178
Word Identification	.203*	-.038	.085	.121
Passage Comprehension	.249*	.007	.256**	.043

* $p < .05$.

** $p < .01$.

ined. At a minimum, future studies of individual differences in lateralization should examine degree of asymmetry, independent of direction, since it has been argued by some that lateralization may provide a selective advantage regardless of which hemisphere may be more dominant (Hopkins & Cantalupo, 2008).

In our entire sample there was a small, but reliable association between composite visual lexical asymmetry and reading performance such that those with greater visual field asymmetries tended to have higher reading scores. An analysis of individual tasks revealed that this association was mainly due to the contribution of the word recognition tasks. Visual field asymmetry for tasks that require controlled semantic retrieval (semantic decision, verb and category generation) was unrelated to reading performance. This suggests that it is hemisphere asymmetry for lower level, more basic reading processes (e.g., lexical access, phonological encoding) that is predictive of enhanced reading skill. Because these processes are acquired early in the process of learning to read, our findings may imply that stronger lateralization during early reading development promotes the eventual development of skilled adult reading. However, longitudinal studies will be needed to support such a conjecture.

It is also interesting that for RT, visual field asymmetry scores for the masked word recognition task were the most strongly associated with both reading and verbal and performance IQ measures. Stimuli in this task were severely data-limited (30 ms exposure, pre- and post-stimulus masks), and thus place a premium on the ability to rapidly extract visual information for word recognition. It appears that individuals whose processing time under these conditions is most asymmetrical also perform best on measures of reading and cognitive ability. Correlational data do not allow us to ascertain cause and effect here, but perhaps a lack of interhemispheric competition early in the process of word recognition is associated with better cognitive skill in a variety of domains.

Our findings of positive asymmetry–performance correlations differ from those of Boles et al. (2008) who found negative associations for their visual lexical tasks. We noted earlier that the visual lexical tasks employed by Boles et al. (2008) may not be assessing the same word recognition processes that are normally used in reading. Another difference is that we examined the relationship between visual lexical asymmetries and standardized reading measures, whereas Boles et al. (2008) correlated visual asymmetries with overall performance within the same DVF tasks.⁶ However, these investigators did observe positive asymmetry–performance correlations for recognition of dichotic syllables and words, so it is possible that the reading performance advantages for increased lexical asymmetry that we observed here can be extended to some other linguistic tasks.

We have already noted that the asymmetry–performance correlations across our entire sample were quite modest. Examination of these correlations by handedness group revealed that this was partly due to differences between consistent and mixed handers. Significant asymmetry–performance correlations for the composite lexical asymmetry measures were only observed among consistent handers, and these correlations were larger than those observed for the entire sample. Consideration of visual field asymmetries for individual tasks also revealed many more task asymmetry–performance correlations for consistent, than for mixed, handers (Fig. 2A and B). Thus our finding that increased visual field

asymmetry is associated with better reading performance applies mainly to those individuals with a strong phenotypic expression of handedness. Variation in asymmetry among mixed handers accounts for little or no variance in reading and cognitive performance in this group. It is interesting that we have previously reported that in mixed, but not consistent, handers brain volume predicts performance in nonlateralized measures of reading and word recognition (Chiarello, Welcome, Towler, Otto, & Leonard, 2008). These findings imply that brain-behavior relationships vary depending on strength of handedness, and no single relationship will characterize the entire population.

Our data imply that when handedness is strongly expressed, there is a coupling between extent of functional asymmetry (as indexed by DVF measures of word processing) and performance on “real world” reading tasks. Perhaps for this group of strongly handed individuals, consistency between strong lateralization for handedness and for language represents a more optimal type of brain organization that provides better support for the development of reading skill.

One can only speculate about why asymmetry–performance correlations are not reliably observed in mixed handers. If mixed handers have smaller or more inconsistent behavioral asymmetries, relative to consistent handers, then they may rely more on both hemispheres for many cognitive functions. Furthermore, if Christman et al. (2004), Christman et al. (2007) are correct that mixed handers rely more on interhemispheric communication than consistent handers, then it may be that variations in reading performance in mixed handers depend more on variations in the efficiency of hemispheric communication, than on varying degrees of lateral asymmetry. This could be examined using experimental paradigms that compare within and across hemisphere processing of task-relevant information (Belger & Banich, 1998).

Even among the consistent handers, degree of lateralization explains only a small amount of the variance in reading skill. Clearly many other factors contribute to reading skill as well (e.g., educational quality, general language ability, availability of printed material in the home, etc.), and such variables may explain a greater proportion of the variance in reading ability. If degree of lateralization only accounts for a small amount of variance in reading skill for unimpaired readers, this could help explain why attempts to relate dyslexia to altered lateralization have yielded inconsistent results (Beaton, 2004; Rutherford, 2006). However, although one should be careful not to over-interpret the current findings, they do suggest that degree of lateralization is one contributor to reading skill, at least for individuals with strongly expressed handedness.

Furthermore, it is acknowledged that there is no universally accepted way to categorize handedness differences. In this investigation we considered whether consistent and mixed handers might represent distinctive neurobehavioral subgroups, despite the fact that hand preference scales yield a continuous (albeit non-normal) distribution of scores. Many other investigators compare left- and right-handers, without regard to degree of handedness, using various cut-off scores to determine group membership. Our categorization of handedness groups follows that of Christman and colleagues who distinguish between those with extreme hand preferences and those with weaker hand preference and/or some use of the nondominant hand. Witelson and colleagues compare consistent right-handers to those with less consistent hand use, but they employ a somewhat looser criterion for consistency for right-handedness (Witelson, Beresh, & Kigar, 2006; Witelson & Goldsmith, 1991) – consistent right-handers have no reported preference for left hand, but could indicate no hand preference for one or more items. Such individuals would be considered mixed handers according to our criteria. A sample larger than that reported here, with larger numbers of left-hand-

⁶ There are other methodological differences between the studies. We employed unilateral stimulus presentation; Boles et al. (2008) used bilateral stimuli. We have distinguished between consistent and mixed handers, while Boles et al. tested right handers only. Because the majority of mixed handers have a right hand preference to varying degrees, it can be assumed that the group tested by Boles et al. (2008) included both consistent and mixed handers. In addition, Boles et al. (2008) computed asymmetry indices, whereas the current study adopted a multiple regression approach.

ers, would be needed to compare asymmetry–performance correlations across different ways of categorizing handedness. However, we did show that our differing results for consistent vs. mixed handers could be observed both for the right-handers in our sample, and for our entire sample that was unselected for handedness. This implies that consistency of hand preference is an important dimension of individual difference, even within the right-handed population.

To summarize, the current study documents a positive association between degree of visual lexical asymmetry and performance on standardized reading measures. This association was primarily attributable to those with a strong expression of handedness. The results are consistent with the idea that consistent and mixed handers may represent different neurobehavioral populations. Because greater lateralization was associated with better reading only for consistent handers, reduced asymmetry cannot be assumed to be a risk factor for reading dysfunction in the population as a whole. We suggest that strength of handedness be considered in future investigations of individual differences in asymmetry and performance.

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Appendix A

Scatterplot illustrating calculation of residual VF difference scores (for accuracy asymmetry in the word naming task). Each point represents the difference in R/L percent correct as a function of the average percent correct. The distance of each point from the regression line is the residual difference score – this reflects the VF difference when the effects of overall performance are removed. The regression line has a negative slope because those with greater accuracy cannot have large raw difference scores. Points above the line represent positive residuals – asymmetry scores greater than predicted. Points below the line represent negative residuals – asymmetry scores lower than predicted. Residuals near zero indicate scores close to the predicted value. In this case, zero represents a moderate RVF advantage (see Fig. A1).

Fig. A1. Scatterplot of scores used to calculate residual asymmetry measure for the word naming task. See Appendix text for more detailed explanation.

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