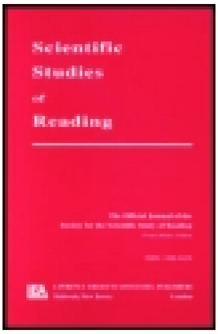

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Statistical Learning, Letter Reversals, and Reading

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Reversal errors play a prominent role in theories of reading disability. We examined reversal errors in the writing of letters by 5- to 6-year-old children. Of the 130 children, 92 had a history of difficulty in producing speech sounds, a risk factor for reading problems. Children were more likely to reverse letter forms that face left, such as <d> and <J>, than forms that face right, such as <b> and <C>. We propose that this asymmetry reflects statistical learning: Children implicitly learn that the right-facing pattern is more typical of Latin letters. The degree of asymmetry that a child showed was not related to the child's reading skill at Time 2, 2¾ years later. Although children who went on to become poorer readers made more errors in the letter writing task than children who went on to become better readers, they were no more likely to make reversal errors.

Early theories of reading development and disability treated reading as primarily a visual skill. Errors such as the writing of <d> as <b> or the reading of <was> as /s ɔ/ were thought to reflect problems in visual processing. Reversals of letter shape and sequence, indeed, were considered symptoms of dyslexia (Collette, 1979; Lyle, 1969; Orton, 1937). As the importance of linguistic skills for literacy development became clear (Ehri et al., 2001; Goswami, 2002; Vellutino, Fletcher, Snowling, & Scanlon, 2004), attention moved away from the visual and motor skills involved in letter perception and production. With a few exceptions (McBride-Chang et al., 2011; Puranik, Petscher, & Lonigan, 2012), recent studies of letter knowledge and its role in literacy development have focused on children's ability to link letter shapes with their names and sounds (e.g., Foulin, 2005; Levin, Shatil-Carmon, & Asif-Rave, 2006). In the present study, we return to the topic of letter production and left–right reversal errors. We examine these errors in a sample of children at risk for reading problems, viewing the errors not as indicators of incomplete cerebral dominance, as Orton (1937) did, but in light of recent discussions of statistical learning.

Statistical learning involves learning about the frequencies with which events occur and reoccur. It plays an important role in the learning of language (Romberg & Saffran, 2010),

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including the learning of written language. For example, children observe that <a> tends to be pronounced differently in English after <w> and <qu> than in other contexts (cf. *wasp, quad* vs. *clasp, bad*) and they observe that double letters occur in some positions of words but not in others (Pacton, Perruchet, Fayol, & Cleeremans, 2001; Treiman, Kessler, Zevin, Bick, & Davis, 2006; Wright & Ehri, 2007). Children learn about these and other patterns even when the patterns are not explicitly pointed out to them and even when the patterns are probabilistic rather than all or none. Knowledge of statistical patterns in turn influences the errors that children make. In one study, for example, 6-year-olds who learned the written form <LLES> as a spelling of /lɛs/ sometimes later spelled it as <LESS> (Wright & Ehri, 2007). Remembering that a doublet had occurred, but not remembering its position, children sometimes placed the doublet in the position that is more frequent in English—the end of the word—rather than in the less frequent initial position. An increasing body of research points to the importance of implicit statistical learning in learning about letter patterns in printed words and how these patterns link with units of language (e.g., Deacon, Conrad, & Pacton, 2008; Kessler, 2009).

In the present study, we examined the role of implicit statistical learning in another aspect of literacy acquisition: learning about and producing letters' shapes. Statistical learning principles have rarely been applied to the learning of letter shapes, but their applicability is suggested by the fact that, within a writing system, the shapes of symbols are not random or accidental. Rather, the shapes tend to share certain graphic properties (Treiman & Kessler, 2011; Watt, 1983). For example, most Hebrew letters are like < ד> and < ק> in having squarish shapes. They look quite different from symbols of Kannada such as < ಲ> and < ಔ>, with their characteristic curves. Because a script is not an arbitrary collection of graphic forms, children could use their statistical learning skills to learn about the patterns that characterize the symbols, even when the patterns are not explicitly pointed out. If so, children should be relatively good at producing symbols that follow the typical patterns of their script. They should perform less well on visually atypical symbols, sometimes changing them so that they conform better.

Letters of the Latin alphabet, the script that we study here, have been described as usually having their most informative visual features on the right and as appearing to face to the right (Brekle, 1994; Kolers, 1969). A number of Latin letters have a vertical or semivertical stem, what Brekle calls a *hasta*, and one or more appendages attached on its right. Brekle called the appendages the *coda*. For example, <b>, <P>, and <R> have the hasta–coda structure. Several letters, including <d> and <J>, deviate from this pattern in that they have the coda on the left of the hasta. Supporting the idea that children implicitly learn about the typical graphic pattern, typically developing children of around 5 years of age who are asked to print such letters as *d* and *j* sometimes produce forms such as < b> and < ᒑ>, respectively. Both left- and right-handed children appear to make more mirror-image reversals with left-facing letter forms such as these than with right-facing letters such as *f* and *k* (J.-P. Fischer, 2010, 2011; J.-P. Fischer & Tazouti, 2012; Simner, 1984; Treiman & Kessler, 2011). Children are rarely taught explicitly about the visual commonalities among the letter shapes, but these findings suggest that they pick them up implicitly. Thus, children who remember the shape of a letter but who forget its left–right orientation—something that is easy to do given that left–right orientation is irrelevant for most objects in the world (Kolinsky et al., 2011)—tend to produce the orientation that they have observed to be most common.

The first goal of the present study was to determine whether the finding of higher reversal rates for left-facing than right-facing letters (J.-P. Fischer, 2010, 2011; J.-P. Fischer & Tazouti, 2012;

Simner, 1984; Treiman & Kessler, 2011) would replicate in a new sample of children that is not limited to typically developing children. Replication is important given that the existing studies suggesting differences across letters have some limitations. In most of the studies (see Treiman & Kessler, 2011, for an exception), researchers did not consider whether the elevated reversal rate for a left-facing letter such as *j* might reflect the fact that this letter is relatively uncommon in English rather than the letter's orientation. In addition, the children in some previous studies (J.-P. Fischer, 2010, 2011; J.-P. Fischer & Tazouti, 2012) wrote only a subset of the reversible letters. Moreover, researchers defined the letter categories of interest in different ways. Treiman and Kessler (2011) limited their analyses to letters that have the hasta–coda structure described by Brekle (1994); J.-P. Fischer (2010, 2011; J.-P. Fischer & Tazouti, 2012) grouped letters such as <C>, which have the main concavity on the right, with letters such as <P>, which have a hasta and an appendage on the right, and Simner (1984) classified letters based on an earlier theory about the motor movements that children use when copying geometric shapes (Goodnow & Levine, 1973). Here we classified letters using data on whether language users perceive them as facing right or left. We asked whether previous findings about differences among letters in reversal errors hold up using this objective method of classifying letters.

If children tend to reverse left-facing letters more often than right-facing ones, our second research question was whether children differ in the degree of asymmetry that they show. A large degree of asymmetry may be a sign of good statistical learning ability, which according to some investigators is a domain-general ability that is linked to literacy skill (Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011; Pavlidou & Williams, 2010; Pavlidou, Williams, & Kelly, 2009; Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). For example, Vicari et al. (2003) had participants press a key whenever a green circle appeared on a screen. The green circle usually appeared after a red one, but participants were not explicitly told about the pattern. Children who had been diagnosed as dyslexic did not benefit from the sequential pattern to speed their responses, whereas normal readers seemed to do so. However, not all studies support the idea that children with reading difficulties have a general deficit in implicit statistical learning (Deroost et al., 2010; Menghini, Finzi, & Benassi, 2010; Roodenrys & Dunn, 2008; Waber et al., 2003). Moreover, some researchers (Jiménez-Fernández et al., 2011) have raised questions about some of the laboratory tasks that have been used to assess implicit learning, including the sequence learning task used by Vicari et al. (2003) and others. Arciuli and Torkildsen (2012) recently called on researchers to investigate statistical learning using naturalistic tasks and stimuli. We responded to this call by examining left–right reversal errors in writing letters of the alphabet to dictation.

Our third research question concerned the overall rate of reversal errors and other errors in young children's letter production and its relationship to the children's later reading skill. Children's knowledge of the alphabet at the time that reading instruction begins, including their ability to write individual letters to dictation, is one of the more powerful predictors of later reading skill (e.g., Leppanen, Aunola, Niemi, & Nurmi, 2008). More controversial is whether reversal errors, in particular, are linked to literacy performance. Many early researchers, as mentioned earlier, saw the tendency to reverse letters as a characteristic of a child rather than as a tendency that may vary across letters in a given child, and they suggested that the tendency to reverse letters is a marker of dyslexia (Collette, 1979; Lyle, 1969; Orton, 1937; see Kaufman, 1980, for a review of the early work on this topic). Some more recent studies continue to support the idea that children with reading difficulties make more reversal errors than typical children (Brooks, Berninger, & Abbott, 2011; Terepocki, Kruk, & Willows, 2002). Other researchers have questioned the widespread idea that reversal errors are a marker of reading problems, however (F. W. Fischer, Liberman, & Shankweiler, 1978; Liberman, Shankweiler, Orlando, Harris, & Berti, 1971; Simner, 1982). According to these latter studies, reversal errors may be rather common even in young children who will go on to become good readers.

To address our three questions, we carried out new analyses of data that were collected from 130 children who participated in a longitudinal study of reading development that was conducted at the University of Denver (Peterson, Pennington, Shriberg, & Boada, 2009; Raitano, Pennington, Tunick, Boada, & Shriberg, 2004). We analyzed the children's performance in a letter writing task at Time 1, when the children had a mean age of 5 years 8 months. We asked how letter writing performance at Time 1 related to literacy skill on a battery of standardized tests at Time 2, when the children had a mean age of 8 years 4 months. Ninety-two of the children were originally recruited for the study because they had a history of speech sound disorder (SSD), or a difficulty in producing developmentally appropriate speech sounds. Of these, 20 also had broader problems with language, meeting criteria for the diagnosis of language impairment (LI). The remaining 38 children were recruited as a control group. Childhood SSD and LI have been shown to be risk factors for the development of reading problems (e.g., Pennington & Bishop, 2009), and they are typically evident before children are exposed to formal literacy instruction. Indeed, children in the SSD group in the present sample showed significantly poorer literacy skills at Time 2 than children in the control group, especially if they also had LI (Peterson et al., 2009). Although not all children with SSD or LI go on to become poor readers, studying a sample that includes a number of such children gives us the opportunity to examine children with a range of reading outcomes.

METHOD

Participants

Table 1 provides information about the participants, which consisted of the 130 children (80 boys, 50 girls) from the longitudinal study described in Raitano et al. (2004) and Peterson et al. (2009), who had complete data on the measures included in the present analyses at both Time 1 and Time 2. At Time 1, as Table 1 shows, the children had completed an average of .35 months of kindergarten schooling. At Time 2, the children were on average in the 8 month of second grade. Children in the United States are usually taught informally about letter shapes at home and in preschool, receiving more formal training when they enter kindergarten. Children in the SSD group were recruited through public and private schools in the Denver area and through newspaper and radio advertisements. All the children in this group had a history of speech difficulties according to parent report. In addition, they had a history of speech therapy for articulation problems or a score at or below the 30th percentile on a standardized articulation test at T1. Although only one of the latter two criteria was required for inclusion in the study, the large majority of children in the SSD group met both. Participants were considered to have LI as well if at T1 they scored at the 10th percentile or lower on any of the four components (expressive language, receptive language, semantics, and syntax) of the Test of Language Development, Primary (Newcomer & Hammill, 1997). The remaining 38 children were recruited as a control group. These children

TABLE 1
Mean Values on Time 1 and Time 2 Measures for SSD and Control Groups

Measure	*SSD*[a]	*Control*[b]
Time 1		
Age in months	67.98 (7.52)	67.47 (5.20)
Years and months in school, starting from kindergarten entry	.39 (.47)	.25 (.43)
Proportion correct in letter production task	.63 (.48)	.81 (.39)
Proportion reversals in letter production task, pooling over all letters judged to face either left or right	.15 (.36)	.13 (.33)
Proportion reversals of left-facing letters	.57 (.50)	.53 (.50)
Proportion reversals of right-facing letters	.05 (.21)	.04 (.20)
Time 2		
Age in months	99.85 (7.97)	99.11 (5.83)
Years and months in school, starting from kindergarten entry	2.85 (.72)	2.79 (.56)
Average standardized score on literacy measures	98.79 (12.81)	112.45 (14.87)

Note. Standard deviations are in parentheses. SSD = speech sound disorder.
[a]$n = 92$. [b]$n = 38$.

were recruited from the same school districts as children identified as having SSD, through newspaper advertisements, and through the University of Denver developmental participant pool. The children in the control group were chosen to be similar in age, gender, and ethnicity to the children in the SSD group. Of the 130 participants, 85% were Caucasian, 8% were African American, and 5% were Asian. The parents of the remaining children identified the children as members of other groups or declined to provide information about ethnic background. Further details about the battery of tests administered at each time point may be found in Raitano et al. (2004) and Peterson et al. (2009).

Procedures and Measures

The measures of interest here are the Time 1 letter writing task and the Time 2 literacy measures. In the Time 1 writing task, the examiner said the name of each letter of the alphabet and asked the child to write the letter. The letters were presented in a predetermined random order. The children wrote the letters on unlined paper, and the examiner did not specify where to place the letters and whether the child should use uppercase or lowercase forms. Both were used, although uppercase forms were more common. At Time 2, single-word reading accuracy, single-word spelling accuracy, and reading comprehension were assessed using the Basic Reading, Spelling, and Reading Comprehension subtests of the Wechsler Individual Achievement Test (Wechsler, 1992). Accuracy and fluency in the reading of connected text were assessed using the Gray Oral Reading Test–Third Edition (Wiederholdt & Bryant, 1992). We report the average standardized score on the four measures in order to maximize reliability, as did Peterson et al. (2009). Table 1 shows information about the performance of the SSD and control groups on the letter writing and literacy measures.

To classify letters as facing right or left, we used ratings from 33 students at Washington University in Louis. The students were asked to imagine each individual uppercase and lowercase letter, to determine whether it faced left, faced right, or was neutral, and to circle the corresponding answer on an answer sheet. Three different random orders of the 52 uppercase and lowercase letters were prepared, and each was presented to a different group of students. The letter forms for which the most popular response was "left" and that were counted as left-facing in our analyses were as follows (the figure in parentheses after each letter is the proportion of "left" answers): lowercase *a* (.85), *d* (.94), *g* (1.00), *j* (.97), *q* (.88), *y* (.91), and *z* (.66) and uppercase *j* (.97) and *z* (.55). The letter forms for which the most popular response was "right" were as follows (the figure in parentheses after each letter is the proportion of "right" answers): lowercase *b* (.91), *c* (.94), *e* (.94), *f* (1.00), *h* (.88), *k* (1.00), *n* (.58), *p* (.94), *r* (1.00), and *s* (.73) and uppercase *b* (.94), *c* (1.00), *d* (.85), *e* (.97), *f* (1.00), *g* (.91), *k* (.94), *l* (.91), *p* (.97), *q* (.52), *r* (1.00), and *s* (.78). In the remaining cases, the most popular answer was that the letter form was neutral.

RESULTS

To score the children's productions, we developed a set of detailed guidelines about shape. For example, *p* was scored as having the correct shape if there was circular appendage at the top or near the top of a vertical stem but as incorrect if the appendage was in the middle. A reversed letter form was defined as a mirror image of the correct shape. A second judge who scored 10% of the data agreed on 99% of the primary judge's decisions about letter correctness and reversals. Both judges were blind to the child's group membership and reading outcome.

For each letter form that was classified as facing either left or right, we calculated the proportion of mirror-image productions relative to the total number of productions that had the correct general shape. For letters such as *c*, which have the same shape in uppercase and lowercase, we did not attempt to distinguish between the two cases. Thus we calculated the proportion of reversed productions like <ɔ>, regardless of their size, relative to the total number of <ɔ> and <c> productions. For letters such as *l*, which have different shapes in uppercase and lowercase, we considered the two cases separately. For example, the proportion of reversal errors for uppercase *l* was the proportion of <⅃> productions relative to the total number of productions of <⅃> and <L>, that is, the proportion of reversed productions relative to the number of productions with the correct general shape. Instances in which children produced *l* in lowercase, which does not face either left or right, were not included in the reversal analyses. Table 1 shows the proportion of reversals, calculated as previously described, pooling over all letter forms that were classified as facing either left or right. It also shows the results separately for left-facing and right-facing forms, revealing a much higher reversal rate for left-facing forms.

We ran a mixed-model analysis on those productions that had the correct general shape, using data from all children at the trial level. (One child who produced no forms with the correct general shape could not be included in this analysis.) Mixed-model analyses are well suited to examining the characteristics of both letters and children that influence performance. We used the software package lme4 (Bates, Maechler, & Bolker, 2011), selecting a generalized mixed-effects model with a logit link function because the dependent variable, whether a letter was reversed on a particular trial, was binary. We first fit a model to predict whether the letter was reversed using children and letter forms as random variables and child age in months at Time 1, whether the letter faced right or left, and average literacy performance at Time 2 as fixed variables. Literacy performance at Time 2 was treated as a continuous variable, as was child age at Time 1. We centered the continuous variables before running the analyses. This first analysis showed a significant effect of child age at Time 1 ($\beta = -.065$, $SE = .020$, $p < .001$). This outcome reflects the fact that children who were older when tested at Time 1 showed a lower proportion of reversals than children who were younger. Whether a letter faced right or faced left was strongly associated with reversals ($\beta = 3.67$, $SE = .41$, $p < .001$). For those children for whom a reversal rate could be calculated for both left-facing and right-facing forms (some children did not produce any letters with the correct general shape in one or both categories), 86 children made more reversals on left-facing than right-facing forms, 8 showed the opposite pattern, and 17 were tied. This result suggests an affirmative answer to our first research question—whether children are more likely to reverse left-facing than right-facing letters. Literacy performance at Time 2 did not contribute significantly to the model, however ($\beta = -.01$, $SE = .01$, $p = .16$). That is, given that a child produced a form with the correct general shape, whether the child used the correct left–right orientation was not significantly related to the child's later literacy skills. When we added the frequency of the letter form in English words to the analysis (using data on the frequency of uppercase and lowercase letters from Jones & Mewhort, 2004, and log transforming the frequencies in order to make the distribution more normal), the fit of the model did not improve significantly ($p = .35$).

To address our second research question—whether children with poorer reading skills at Time 2 showed the same asymmetry in reversal errors as children with better reading skills at Time 2—we fit another model to predict whether a letter was reversed. This model included, in addition to Time 2 literacy performance and whether the letter faced left or right, the interaction between these variables. This model did not account for significantly more variance than the model that did not include the interaction ($p = .72$). This outcome indicates that children who became poor readers demonstrated a similar degree of asymmetry in their reversal errors as children who became average or good readers. The results presented so far thus show that neither the rate of reversal errors nor the degree of asymmetry of the reversal errors was significantly related to reading outcome. To illustrate this latter point, the 28 children who had an average standardized score of 90 or lower on the Time 2 literacy measures had a reversal proportion of .59 on left-facing letters and .06 on right-facing letters. The 102 children who had an average standardized score of higher than 90 showed very similar results, with a reversal proportion of .55 on left-facing letters and .04 on right-facing letters.

We carried out an additional analysis to determine whether, after other factors were taken into account, the rate of reversal errors varied as a function of whether a child had a history of SSD. To do this, we compared a model that included the two effects shown to be significant so far—age at Time 1, and whether the letter faced left or right—to a model that included the contrast between the SSD and control groups. The more complex model did not explain significantly more variance than the simpler model ($p = .72$). That is, given that a child produced a letter form with the correct general shape, mirror-image reversals were not significantly more common for children with a history of SSD than control group children once other factors were statistically equated. We also obtained null results ($p = .88$) when we classified children as having a history of only SSD, both SSD and LI, or neither.

Our third research question was whether children's tendency to produce reversal errors and other types of errors at Time 1 was related to their reading performance at Time 2. Results already presented suggest that the rate of reversed productions at Time 1 was not related to reading outcomes, and we carried out an additional analysis to ask whether the overall error rate at Time 1 was related to reading outcomes. For this analysis, we scored a child's response to a letter as correct if it was an appropriate uppercase or lowercase shape with the proper orientation and as incorrect if it was not. Table 1 shows the results for the SSD and control groups. We carried out a mixed model analysis using children and letters as random effects and child age in months at Time 1 and average literacy performance at Time 2 as fixed variables. As before, these predictor variables were treated as continuous. We found a significant effect of child age at Time 1, such that children who were older at Time 1 had more correct responses on the letter production task than children who were younger ($\beta = .19$, $SE = .02$, $p < .001$). We also found a significant effect of literacy performance at Time 2, such that children who were better readers at Time 2 had more correct responses on the Time 1 letter production task than children who were poorer readers, controlling for age at Time 1 ($\beta = .07$, $SE = .01$, $p < .001$). The main effect of literacy performance may be illustrated by comparing the proportion of correctly written letters for children who had an average standardized score of 90 or lower on the Time 2 literacy measure and children who had an average standardized score above 90. The proportion of correctly written letters was much lower for the former group (.47) than the latter group (.74). When we added the frequency of a letter to the model (using the summed frequency of the upper- and lowercase forms from Jones & Mewhort, 2004, log transformed in order to improve the distribution), the fit improved significantly ($p < .001$). Correct productions were more common for letters that occur often in English words than for letters that occur less often ($\beta = .61$, $SD = .15$, $p < .001$).

In a final analysis of correct responses, we compared a model that included age at Time 1, literacy performance at Time 2, and letter frequency to a model that also considered the child's Time 1 group membership. When children were classified into the two groups of SSD and control, there was a trend for children with SSD to make more letter production errors at Time 1 than expected on the basis of the other factors. However, the more complex model did not account for significantly more variance than the simpler model ($p = .06$). When the children were classified into the three groups of SSD only, SSD and LI, or neither, the more complex model again did not account for significantly more variance than the simpler model ($p = .59$).

DISCUSSION

Linguistic knowledge, including phonological awareness, is crucial for learning to read and spell (Ehri et al., 2001; Goswami, 2002; Vellutino et al., 2004). Learning about the shapes of letters and how to produce them accurately and efficiently, although relatively little studied in recent years, is important too. This is not an easy task because the letter shapes within a script often differ from one another in small details and because left–right orientation—something that is not important for most objects in the natural world—is sometimes critical. Here we asked whether the implicit statistical learning that is involved in learning about links between letters and linguistic units (Deacon et al., 2008; Kessler, 2009) is involved in learning about and producing letters' shapes and whether children vary from one another in this ability.

Statistical learning involves learning about the regularities in the world and using those regularities to help remember the past and predict the future. There are recurring patterns in the shapes of the Latin letters, just as there are in other aspects of the world. One such pattern is that many Latin letter shapes face right, as with <b>, <C>, and <R>. Fewer letters have the opposite orientation. Children who have learned about this difference can use the orientation that they know to be most common when they fail to remember the left–right orientation of a specific form. Thus, a child who has forgotten the orientation of *j* may conclude that it is more likely to face right than left, producing < ᒑ >. This approach causes errors on left-facing letters like *j*, but it yields correct responses on the many letters that face right.

Since the time of Orton (1937), researchers have considered the tendency to reverse letters to be a characteristic of children rather than of letters. Thus, most of the large body of work on reversal errors has studied differences among children. However, there is some evidence that the rate of reversal errors differs for left-facing and right-facing letters, even within the same child (J.-P. Fischer, 2010, 2011; J.-P. Fischer & Tazouti, 2012; Simner, 1984; Treiman & Kessler, 2011). These latter studies have some limitations, which we attempted to overcome here. We used objective data to classify letters as facing right or left, and we statistically controlled for differences in the frequency with which letters occur in English words. Also, to better isolate errors that reflect lack of knowledge of left–right orientation, we calculated the rate of reversals out of all productions with the correct general shape rather than out of all productions. Even with these added controls, differences in reversal errors between left- and right-facing letters were robust. The answer to our first research question—that of whether children make more reversal errors on left-facing letters than on right-facing ones—is therefore affirmative.

Having found that reversal errors are asymmetric, our second research question was whether the degree of asymmetry that a child shows in his or her reversal errors is related to the child's later reading ability. Such a relationship is expected according to the theory that there exists a general statistical learning ability that is linked to reading ability (Arciuli & Simpson, 2012; Jiménez-Fernández et al., 2011; Pavlidou et al., 2009; Pavlidou & Williams, 2010; Vicari et al., 2005; Vicari et al, 2003). We did not find a relationship of this sort. When tested at 5 to 6 years of age, children who would vary in their reading ability 2 years and 8 months later did not differ reliably in the degree of asymmetry that they showed in their reversal errors.

Our third research question was whether the rates of reversal errors and errors in general at Time 1 were related to reading ability at Time 2. We found a strong relationship between letter production errors in general at 5 to 6 years of age and later reading ability, in line with previous findings (e.g., Leppanen et al., 2008; Simner, 1982). However, we did not find such a relationship for reversal errors. This outcome speaks against the widespread view that reversals in the production of individual letters are a good predictor of future reading problems (Brooks et al., 2011; Collette, 1979; Kaufman, 1980; Lyle, 1969; Orton, 1937; Terepocki et al., 2002). Simner (1982) also spoke against this view based on data suggesting that kindergartners' tendency to reverse letters when writing them from memory did not correlate significantly with teachers' ratings of their reading skill in first grade. Because we used objective tests to measure reading ability, our findings are more conclusive. Educators and clinicians, therefore, should not assume that reversal errors in writing are indicative of dyslexia.

Although our study goes beyond previous work in a number of ways, it has some limitations. We examined reversal errors only in the writing of individual letters, each child wrote each letter only once, and reversal errors were not tracked longitudinally. In future work, it would be valuable to have each child write each upper- and lowercase letter multiple times, to examine reversal errors in the writing and reading of words as well, and to examine how reversal errors change as children develop. We did find that children who were older at Time 1 made fewer reversal errors than children who were younger, but our data do not show whether this reflects age per se or additional time in school. Future studies could attempt to tease apart these influences. Tasks in which children make judgments about pseudo-letters also could be developed to tap children's knowledge about the patterns in letter shapes. We did not find significant differences as a function of whether a child entered the study with a history of SSD and/or LI or as a member of the control group, once other factors had been taken into account, but the numbers of children in the control group and the group with LI were rather small. Future studies making comparisons across these groups would benefit from larger sample sizes.

Although additional work is needed, our findings suggest that children with and without SSD who will go on to become poor readers show adequate statistical learning in an important reading-related task: learning about the patterns that characterize the shapes of Latin letters. Poor readers, including those with a history of SSD, are poor at learning mappings between visual symbols, including letters' shapes, and phonological codes, including letters' names and sounds (Treiman, Pennington, Shriberg, & Boada, 2008; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). However, they do not appear to be worse than other children at learning about certain patterns pertaining to the shapes themselves. By 5 to 6 years of age, even children who will go on to become poor readers have implicitly learned that letters of the Latin alphabet are more likely to face right than left. This knowledge reveals itself in their reversal errors.

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REFERENCES

Arciuli, J., & Simpson, I. C. (2012). Statistical learning is related to reading ability in children and adults. *Cognitive Science*, *36*, 286–304. doi:10.1111/j.1551-6709.2011.01200.x

Arciuli, J., & Torkildsen, J. (2012). Advancing our understanding of the link between statistical learning and language acquisition: The need for longitudinal data. *Frontiers in Psychology*, *3*. doi:10.3389/fpsyg.2012.00324

Banai, K., & Yifat, R. (2012). Anchoring in 4-to 6-year-old children relates to predictors of reading. *Journal of Experimental Child Psychology*, *112*, 403–416. doi:10.1016/j.jecp.2012.04.008

Bates, D., Maechler, M., & Bolker, B. (2011). lme4: Linear mixed-effects models using S4 classes. Retrieved from http://cran.r-project.org/package=lme4

Brekle, H. E. (1994). *Die Antiqualinie von ca.-1500 bis ca.+ 1500: Untersuchungen zur Morphogenese des westlichen Alphabets auf kognitivistischer Basis [*The Aniqua lineage from circa -1500 to circa 1500: Research on the morphogenesis of the western alphabet on a cognitive basis]. Münster, Germany: Nodus.

Brooks, A., Berninger, V. W., & Abbott, R. D. (2011). Letter naming and letter writing reversals in children with dyslexia: Momentary inefficiency in the phonological and orthographic loops of working memory. *Developmental Neuropsychology*, *36*, 847–868. doi:10.1080/87565641.2011.606401

Collette, M. A. (1979). Dyslexia and classic pathognomic signs. *Perceptual and Motor Skills*, *48*, 1055–1062. doi:10.2466/pms.1979.48.3c.1055

Deacon, S. H., Conrad, N., & Pacton, S. (2008). A statistical learning perspective on children's learning about graphotactic and morphological regularities in spelling. *Canadian Psychology*, *49*, 118–124. doi:10.1037/0708-5591.49.2.118

Deroost, N., Zeischka, P., Cooman, D., Bouassa, S., Depessemier, P., & Soetens, E. (2010). Intact first-and second-order implicit sequence learning in secondary-school-aged children with developmental dyslexia. *Journal of Clinical and Experimental Neuropsychology*, *32*, 561–572. doi:10.1080/13803390903313556

Ehri, L. C., Nunes, S. R., Willows, D. M., Schuster, B. V., Yaghoub-Zadeh, Z., & Shanahan, T. (2001). Phonemic awareness instruction helps children learn to read: Evidence from the National Reading Panel's meta-analysis. *Reading Research Quarterly*, *36*, 250–287. doi:10.1598/RRQ.36.3.2

Fischer, F. W., Liberman, I. Y., & Shankweiler, D. (1978). Reading reversals and developmental dyslexia: A further study. *Cortex*, *14*, 496–510.

Fischer, J.-P. (2010). Vers une levée du mystère des écritures en miroir (des lettres majuscules) chez l'enfant: Une hypothèse nouvelle [Toward a solution to the mystery of mirror writing (of upper-case letters) in children: A new hypothesis]. *Enfance*, *2010*, 371–386. doi:10.4074/S0013754510004015

Fischer, J.-P. (2011). Mirror writing of digits and (capital) letters in the typically developing child. *Cortex*, *47*, 759–762. doi:10.1016/j.cortex.2011.01.010

Fischer, J.-P., & Tazouti, Y. (2012). Unraveling the mystery of mirror writing in typically developing children. *Journal of Educational Psychology*, *104*, 193–205. doi:10.1037/a0025735

Foulin, J. (2005). Why is letter-name knowledge such a good predictor of learning to read? *Reading and Writing: An Interdisciplinary Journal*, *18*, 129–155. doi:10.1007/s11145-004-5892-2

Goodnow, J. J., & Levine, R. A. (1973). "The grammar of action": Sequence and syntax in children's copying. *Cognitive Psychology*, *4*, 82–98. doi:10.1016/0010-0285(73)90005-4

Goswami, U. (2002). Phonology, reading development, and dyslexia: A cross-linguistic perspective. *Annals of Dyslexia*, *52*, 141–163. doi:10.1007/s11881-002-0010-0

Jiménez-Fernández, G., Vaquero, J. M. M., Jiménez, L., & Defior, S. (2011). Dyslexic children show deficits in implicit sequence learning, but not in explicit sequence learning or contextual cueing. *Annals of Dyslexia*, *61*, 85–110. doi:10.1007/s11881-010-0048-3

Jones, M. N., & Mewhort, D. J. K. (2004). Case-sensitive letter and bigram frequency counts from large-scale English corpora. *Behavior Research Methods, Instruments, & Computers*, *36*, 388–396.

Kaufman, N. L. (1980). Review of research on reversal errors. *Perceptual and Motor Skills*, *41*, 55–79. doi:10.2466/pms.1980.51.1.55

Kessler, B. (2009). Statistical learning of conditional orthographic correspondences. *Writing Systems Research*, *1*, 19–34. doi:10.1093/wsr/wsp004

Kolers, P. A. (1969). Clues to a letter's recognition: Implications for the design of characters. *Journal of Typographic Research*, *3*, 145–168.

Kolinsky, R., Verhaeghe, A., Fernandes, T., Mengarda, E. J., Grimm-Cabral, L., & Morais, J. (2011). Enantiomorphy through the looking glass: Literacy effects on mirror-image discrimination. *Journal of Experimental Psychology: General*, *140*, 210–238. doi:10.1037/a0022168

Leppanen, U., Aunola, K., Niemi, P., & Nurmi, J.-E. (2008). Letter knowledge predicts Grade 4 reading fluency and reading comprehension. *Learning and Instruction*, *18*, 548–564. doi:10.1016/j.learninstruc.2007.11.004

Levin, I., Shatil-Carmon, S., & Asif-Rave, O. (2006). Learning of letter names and sounds and their contribution to word recognition. *Journal of Experimental Child Psychology*, *93*, 139–165. doi:10.1016/j.jecp.2005.08.002

Liberman, I. Y., Shankweiler, D., Orlando, C., Harris, K. S., & Berti, F. B. (1971). Letter confusions and reversals of sequence in the beginning reader: Implications for Orton's theory of developmental dyslexia. *Cortex*, *7*, 127–142.

Lyle, J. G. (1969). Reading retardation and reversal tendency: A factorial study. *Child Development*, *40*, 833–843. doi:10.2307/1127192

McBride-Chang, C., Zhou, Y., Cho, J.-R., Aram, D., Levin, I., & Tolchinsky, L. (2011). Visual spatial skill: A consequence of learning to read? *Journal of Experimental Child Psychology*, *109*, 256–262.

Menghini, D., Finzi, A., & Benassi, M. (2010). Different underlying neurocognitive deficits in developmental dyslexia: A comparative study. *Neuropsychologia*, *48*, 863–872. doi:10.1016/j.neuropsychologia.2009.11.003

Newcomer, P. L., & Hammill, D. D. (1997). *Test of language development, primary: Third edition*. Austin, TX: ProEd.

Orton, S. T. (1937). *Reading, writing, and speech problems in children*. New York, NY: Norton.

Pacton, S., Perruchet, P., Fayol, M., & Cleeremans, A. (2001). Implicit learning out of the lab: The case of orthographic regularities. *Journal of Experimental Psychology: General*, *130*, 401–426. doi:10.1037//0096-3445.130.3.401

Pavlidou, E. V., & Williams, J. M. (2010). Developmental dyslexia and implicit learning: Evidence from an AGL transfer study. *Procedia Social and Behavioral Sciences*, *2*, 3289–3296. doi:10.1016/j.sbspro.2010.03.503

Pavlidou, E. V., Williams, J. M., & Kelly, L. M. (2009). Artificial grammar learning in primary school children with and without developmental dyslexia. *Annals of Dyslexia*, *59*, 55–77. doi:10.1007/s11881-009-0023-z

Pennington, B. F., & Bishop, D. V. M. (2009). Relations among speech, language, and reading disorders. *Annual Review of Psychology*, *60*, 283–306. doi:10.1146/annurev.psych.60.110707.163548

Peterson, R. L., Pennington, B. F., Shriberg, L. D., & Boada, R. (2009). What influences literacy outcome in children with speech sound disorder? *Journal of Speech, Language, and Hearing Research*, *52*, 1175–1188. doi:10.1044/1092-4388(2009/08-0024)

Puranik, C. S., Petscher, Y., & Lonigan, C. J. (2012). Dimensionality and reliability of letter writing in 3- to 5-year-old preschool children. *Learning and Individual Differences*, *28*, 133–141.

Raitano, N. A., Pennington, B. F., Tunick, R. A., Boada, R., & Shriberg, L. D. (2004). Pre-literacy skills of subgroups of children with speech sound disorders. *Journal of Child Psychology and Psychiatry*, *45*, 821–835. doi:10.1111/j.1469-7610.2004.00375.x

Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. *Wiley Interdisciplinary Reviews: Cognitive Science*, *1*, 906–914. doi:10.1002/wcs.78

Roodenrys, S., & Dunn, N. (2008). Unimpaired implicit learning in children with developmental dyslexia. *Dyslexia*, *14*, 1–15. doi:10.1002/dys.340

Simner, M. L. (1982). Printing errors in kindergarten and the prediction of academic performance. *Journal of Learning Disabilities*, *15*, 155–159. doi:10.1177/002221948201500306

Simner, M. L. (1984). The grammar of action and reversal errors in children's printing. *Developmental Psychology*, *20*, 136–142. doi:10.1037//0012-1649.20.1.136

Terepocki, M., Kruk, R. S., & Willows, D. M. (2002). The incidence and nature of letter orientation errors in reading disability. *Journal of Learning Disabilities*, *35*, 214–233. doi:10.1177/002221940203500304

Treiman, R., & Kessler, B. (2011). Similarities among the shapes of writing and their effects on learning. *Written Language and Literacy*, *14*, 39–57. doi:10.1075/wll.14.1.03tre

Treiman, R., Kessler, B., Zevin, J. D., Bick, S., & Davis, M. (2006). Influence of consonantal context on the reading of vowels: Evidence from children. *Journal of Experimental Child Psychology*, *93*, 1–24. doi:10.1016/j.jecp.2005.06.008

Treiman, R., Pennington, B. F., Shriberg, L. D., & Boada, R. (2008). Which children benefit from letter names in learning letter sounds? *Cognition*, *106*, 1322–1338. doi:10.1016/j.cognition.2007.06.006

Vellutino, F. R., Fletcher, J. M., Snowling, M. L., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, *45*, 2–40.

Vicari, S., Finzi, A., Menghini, D., Marotta, L., Baldi, S., & Petrosini, L. (2005). Do children with developmental dyslexia have an implicit learning deficit? *Journal of Neurology, Neurosurgery & Psychiatry*, *76*, 1392–1397. doi:10.1136/jnnp.2004.061093

Vicari, S., Marotta, L., Menghini, D., Molinari, M., & Petrosini, L. (2003). Implicit learning deficit in children with developmental dyslexia. *Neuropsychologia*, *41*, 108–114.

Waber, D. P., Marcus, D. J., Forbes, P. W., Bellinger, D. C., Weiler, M. D., Srensen, L. G., & Curran, T. (2003). Motor sequence learning and reading ability: Is poor reading associated with sequencing deficits? *Journal of Experimental Child Psychology*, *84*, 338–354. doi:10.1016/S0022-0965(03)00030-4

Watt, W. C. (1983). Grade der Systemhaftigkeit: Zur Homogenität der Alphabetschrift [Degrees of systematicity: On the homogeneity of the alphabet script.]. *Zeitschrift für Semiotik*, *5*, 371–379.

Wechsler, D. (1992). *Wechsler Individual Achievement Test*. San Antonio, TX: The Psychological Corporation.

Wiederholdt, J., & Bryant, B. (1992). *Gray Oral Reading Test–Third Edition*. Odessa, FL: Psychological Assessment Resources.

Wright, D.-M., & Ehri, L. C. (2007). Beginners remember orthography when they learn to read words: The case of doubled letters. *Applied Psycholinguistics*, *28*, 115–133. doi:10.1017/S0142716407070063

Ziegler, J. C., Pech-Georgel, C., Dufau, S., & Grainger, J. (2010). Rapid processing of letters, digits and symbols: What purely visual-attentional deficit in developmental dyslexia? *Developmental Science*, *13*, F8–F14. doi:10.1111/j.1467-7687.2010.00983.x