INTRODUCTION

Developmental dyslexia is defined as a specific disability in learning to read and to spell adequately despite at least normal intelligence, adequate instruction, socio-cultural opportunities, and the absence of sensory defects in vision and hearing. By this definition, instead of etiologically grounded criteria, the diagnosis rests upon a criterion of discrepancy between the reading performance expected from measures of general intelligence, and the observed reading performance—or, in other words, the discrepancy between how a child is expected to learn to read and how, in fact, she/he does. This definition is poorly descriptive because more than 100 years of scientific research have failed to provide a consistent account of the etiology of developmental dyslexia (Miles and Miles, 1999). Therefore, the diagnosis remains on the level of symptoms, instead of causing deficits.

One of the major symptoms of developmental dyslexia are reversal errors. Children confuse, for instance, letters which are horizontally or vertically symmetrical to each other or rotated (for example, p / q; b / d; p / d). These errors (static reversals) are normal in beginning readers (Hicks, 1981), but become very rare after developing reading practice. In dyslexics, however, they still occur even after years of reading experience. Orton (1925, 1928) postulated that these problems reflect the cardinal symptom of developmental dyslexia and that these confusion errors (‘strephosymbolia’) are caused by a faulty development of cerebral dominance and sub-optimal inter-hemispheric communication.
In the last decades, phonological skills were considered most relevant in explaining dyslexia (for example, Bradley and Bryant, 1978; Liberman et al., 1971). In this context, it was often argued that Orton wrongly believed that Dyslexics have a ‘perceptual deficit’ and actually see letters in a wrong orientation (Vellutino, 1977). However, as discussed at great length elsewhere (Corballis and Beale, 1993; Lachmann, 2002), Orton assumed reversals to be the result of labelling problems in memory, and not of problems in visual perception.

It is obvious that many of Orton’s particular assumptions, such as a serial order of processing steps in word processing, the existence of a separate word centre, and his assumption about the interhemiispheric communication are antiquated or simply wrong. However, as we will argue, his basic ideas may still be useful in understanding the origin of one group of symptoms of dyslexia, the orientation errors. There are a couple of alternative models which try to connect these ideas with more recent neurological theories (Corballis and Beale, 1993), and with more recent experimental results (Brendler and Lachmann, 2001; Lachmann and Geyer, 2003; Lachmann and van Leeuwen, in press). One is the multi-causal Functional Coordination Deficit (FCD) model (Lachmann, 2002). Within this model, reversal errors are explained as a result of a failure in suppressing symmetry generalization in reading.

Symmetry generalization, as a result of evolutionary and individual development, is a mechanism assumed to be learned as an infant to warrant behavioural advantages such as object constancy. In reading, however, this mechanism may be a hindrance, because graphemes are visual symbols, and as such they have to have a non-ambiguous relation to the respective phonological information they represent. It was argued that learning to read is comprised of learning to treat graphemes as symbols instead of objects. This skill is achieved very early, during the first stage of reading acquisition. A failure in the complete suppression of symmetrical information in the representation of visual symbols during reading produces ambiguous relations between visual and phonological information, and thus disturbs the functional coordination and may cause problems in learning to read. In this respect, reversal errors do not reflect a visual perceptual deficit (as announced by Vellutino, 1977) or an incomplete hemispheric dominance (as postulated Orton, 1925), and they do not reflect the one and only cardinal symptom of dyslexia. Instead, the FCD model assumes that this kind of problems occurs in a subgroup but not in all Dyslexics (Lachmann, 2002; Lachmann and Geyer, 2003).

In our own studies (Lachmann and van Leeuwen, 2004a; van Leeuwen and Lachmann, 2004) we have shown that objects (pseudo-letters and shapes) are perceived differently from letters even at a very early stage of information processing (early feature integration). In recognition tasks, using irrelevant form-congruent versus form-incongruent surroundings, letters evoked negative congruence effects on RTs, which contrasted to the positive congruence effects for objects (Lachmann and van Leeuwen, 2004a). In contrast to these very early effects, reversal errors are assumed to occur relatively late in information
processing, that is, they represent a representational deficit of grapheme–phoneme correspondence. This assumption indicates that reversals are not necessarily the result of problems in the processing of spatial information per se, neither for objects nor for symbols. They are rather an effect of a disability to represent symbols, such as graphemes, strictly viewpoint dependent. In particular, problems occur when different orientations have to be represented and performed distinctly to be connected unambiguously with distinct phoneme categories.

STUDIES ON REVERSAL ERRORS

In the last three decades, the relevance of reversal errors was questioned by those who believed them to merely be yet another illustration of phonological deficits (Bigsby, 1985). While dyslexics in general may have no problems in distinguishing non-letter objects, it was believed that the confusion of reversed letters was based on their phonological similarity (‘bee’, ‘dee’), and it was argued, as mentioned earlier, that dyslexics can ‘see’ (Vellutino, 1987) the distinction between ‘d’ and ‘b’ very well. However, as we have argued before, Orton never said they could not. He believed that the problem resides at a level of abstract labelling of the visual representation by a phonological code (Corballis and Beale, 1993; Lachmann and Geyer, 2003). In the following, we will introduce some of the classical studies that doubted the importance of reversal errors.

The classical study by Liberman et al. (1971) was one of the most influential early studies that explicitly questioned Orton’s theoretical approaches to reading disability (but see also Hildreth, 1934, as an example for earlier critique). The study of Liberman et al. (1971) was aimed directly at testing Orton’s (1925) theory of anomalous cerebral dominance as the universal cause for developmental dyslexia. In this context, the investigation concentrated on the analysis of the proportion of reversal errors to other reading errors (Orton’s secondary symptoms), especially of the relation between errors based on optical (reversals) and on linguistic properties (vowel and consonant errors), and of the relationship between reversals of sequence (kinetic reversals) and reversals of orientation (static reversals). The second graders of a primary school were asked to read a wordlist consisting of 60 monosyllabic words, including primer-level sight words, non-sight words, and words where reversals (both types) were possible versus words where reversals were not possible (for example get, was, bed, bet, not, pin), respectively. Those 18 students who performed within the lower third, measured by the rate of errors made while reading this word list, were defined as ‘poor readers’. The other 36 students were considered as control group of normal readers. In addition to the word list, all students had to perform the Gray Oral Reading Test and a matching task, where a given letter was to be matched to one out of a group of five, four of which were reversible. The results were analysed for the whole population, as well as for poor and normal readers separately.
Liberman and her colleagues found a significant correlation between the total performance in the reading test and the more artificial task of reading monosyllabic words in isolation. This may reflect a stage in reading development which is based on scanning syllables rather than larger chunks of text.

The main results the authors found were as follows. First, nearly all of the reversals were done by the poor reader group. Second, vertical b–d confusion (which they called horizontal transformation) occurred with as great a frequency (10.2 in average for both directions) as b–p confusion (11.4 in average for both directions), while both confusions obviously occurred more often than d–p confusion (1.1) as well as confusions of b, d, and p with g (0.9 in average for both directions). Furthermore, the authors found that for static reversals, the presence of equivalent shapes within the alphabet is important, and the reversibility of a letter is not by itself a sufficient condition for confusion. Another important finding was that normal as well as poor readers made less reversal errors than other reading errors (error percentages according to the opportunities of occurrence in poor readers: 6.3 kinetic reversals; 12.7 static reversals; 16.3 consonant confusion; 26.8 vowel confusion; error percentages according to the total number of errors in the same sequence: 10, 15, 32, 43). Within the group of poor readers, individual differences were larger and test–retest reliability was lower for reversals in comparison to vowel and consonant errors, indicating that reversals do not reflect a constant proportion of all errors as would be expected from assuming them to be cardinal symptoms. Finally, static and kinetic reversals in poor readers were found to be uncorrelated to each other, but both reversal types were correlated with other measures such as the reading test, but in a different way. These findings were counted as evidence for the importance of linguistic determinants in reading problems and against the theory of strephosymbolia as a consequence of hemispheric imbalance expressed by reversals. However, these results may be representative for the lower third of a regular second grade class only, but not for developmental dyslexics, not for strephosymbolics, and not even for poor readers. The results by Liberman and her colleagues are not sufficient to disprove Orton’s concept. The merit of their work does consist much more of a stronger emphasis on linguistic aspects in order to understand reading disability. Their publication is in fact a milestone in reading disability research, but it delivers no evidence against the significance of reversals.

In a follow-up study, published by Fisher et al. (1978), the performance of the poor reading students described by Liberman and her colleagues was compared to that of dyslexic children, defined by the discrepancy criterion (normal intelligence with a retardation of at least 18 months in Gray Reading Test performance), of the same age and intelligence. The authors showed that while both groups performed almost equally in the reading test, the dyslexic group (smaller data set) made significantly more errors in the Word List Test. However, these errors were relatively made in the same proportion as by the poor readers group (error percentages according to the opportunities of occurrence: 8.3 kinetic reversals, 11.4 static reversals, 32.9 consonant confusion, 40.3 vowel confusion),
underlining the importance of linguistic aspects. In contrast to the poor readers, the dyslexic children performed more consistently in their reversal errors, and both kinds were significantly correlated.

Lyle and Goyen (1968) presented letters and shapes tachistoscopically within different task settings in order to study the performance of disabled and normal reading primary school children of different age. The authors found disabled readers to perform worse than normal readers on all conditions. Interestingly, there was an Age (second versus third graders) x Group interaction in some of their conditions; the group effect was greater at the younger age level. A further question was whether or not the higher number of errors made by retarded readers could be characterized by reversal and rotation tendencies. The authors analysed static reversals (simultaneous and delayed condition), kinetic reversals (sequenced condition), and the remaining ‘miscellaneous’ errors separately. None of the analyses, however, revealed effects. For letters and shapes, the proportion between reversals and other errors did not differ between the groups. This was interpreted as evidence against Orton’s theory (1925) of reversals as the cardinal symptom of reading disability and as result of problems in binding visual and phonological information adequately (to speak in nowadays words). Instead, problems in the speed of visual decoding were assumed to the reason for reading problems, independent from phonological information possibly inherent to the stimulus. On the other hand, the results of a reading test applied by these authors showed indeed a higher number of reversals in disabled readers, and a higher proportion of reversals in relation to the total Error rate. Lyle and Goyen suggested problems in verbal labelling as one of the reasons for these phenomena. This, however, does not separate them from Orton (1925); what it is in contrast to Orton is the assumption about the underlying mechanism producing these problems. Lyle and Goyen argued that the speed of perceptual encoding may be a reason for problems in labelling, since it reduces the load of visual information in a given time unit.

Grosser and Trzeciak (1981) studied the significance of reversal errors for reading disability by using a threshold and a masking paradigm in which the exposure time needed to name reversible (b, d, p, q) or non-reversible letters (w, x, u, o) correctly was used as a dependent variable. The performance of 29 disabled readers, aged between six and 14 years, and 15 normal readers of about the same age was compared. The authors found significant group effects for all conditions; disabled readers needed longer exposure times to name the letters correctly. However, there was no interaction between the group and the letter sets. In particular, all participants needed longer exposure times to name reversible letters; the proportion between reversible letters and non-reversible letters, however, was about the same in both groups. This result, coupled with the finding that normal reading younger children perform worse than the older ones, whereas such a correlation was not found within the group of reading disabled children, was interpreted as evidence for a disturbance of the development of visual perception in disabled readers. Within the scope of this chapter—the question whether or not reversals can be thought as characteristic for
dyslexia—Grosser and Trzeciak’s empirical findings led to the assumption that reversals have no relation to specific reading disability.

The naming speed of disoriented letters presented in the left or the right visual field of dyslexic and normal reading children (11 to 13 years old) was studied by Corballis et al. (1985b) in order to compare interhemispheric differences (Bradshaw et al., 1976) between the groups. According to Orton, both hemispheres initially store information, and problems in reading and writing can be attributed to an inadequate cerebral dominance. Therefore, Corballis and his colleagues (1985b) hypothesized that interhemispheric effects should be diminished or absent in disabled readers. However, no group effect for latency or error rate was found. As expected, they found a clear effect of speed of naming normal over backward letters (RT to normal letters = 797 ms, RT to backward letters = 908 ms). However, the interaction between visual field and letter orientation failed to reach significance as well as their interaction with the Group factor. Corballis et al. (1985b) concluded that such a pattern of results does not support the assumption that reading-disabled children show an abnormally high degree of left–right equivalence, as proposed by Orton’s (1925) original theory. In later study, Wolff and Melngailis (1996) found differences in accuracy between dyslexics and normal reading children for repeated naming of confusable letters.

Extending the work of Corballis et al. (1985a, 1985b), Rusiak et al. (submitted) investigated mental rotation of letters (Experiment 1) and of letters and shapes (Experiment 2) in normal readers and developmental dyslexics. Whereas the overall RTs were equal for shapes in both groups, for letters they were about 100 ms slower in dyslexics. For letters as well as for shapes, however, the same mental rotation effects were obtained between the groups. These results were interpreted as support for the symmetry generalization account, that is, the notion of developmental dyslexia as a deficit in functional coordination between graphemic and phonological letter representations. In contrast to the finding that dyslexics and controls did not differ in mental transformation skills, Rüsseler et al. (2005) found dyslexic readers impaired in mental rotation for letters as well as for shapes and pictures.

Another relevant study is that of Hicks (1981), who studied the failure in integrating visual and phonological information in four different groups of readers; beginning readers, skilled readers, retarded readers (that is, disabled readers according to the discrepancy definition but without showing typical dyslexia errors, for example left/right confusion), and dyslexic readers (that is, disabled readers according to the discrepancy definition showing typical dyslexia errors, for example left/right confusion or neurological defects). All groups, except that of beginning readers, were matched by age and intelligence, and all groups, except that of normal readers were matched by intelligence and literacy level. All participants had to perform a search task. A target had to be identified within a list of reversible (b, p, q, d) and non-reversible (g, h, k, l, t, y) letters. The target and the list were either presented visually or auditory. Consequently, there were four conditions, two testing
the intra-modality functions and two the inter-modality functions. The main results were as follows: normal readers made fewer errors than all of the non-fluent reading groups in all conditions. When a visually presented target item had to be identified within a visually presented list, most errors were made by beginning readers. When both the target and the list were presented auditory, most errors were made by dyslexics and retarded readers. In the inter-modality conditions most errors were made by dyslexics, whereas beginning and retarded readers performed about equally. All together, the results indicate two major conclusions. first, normal reading children perform better than all of the non-fluent reading children. Second, the underlying cause of reading problems may differ between beginning readers and disabled readers and between disabled readers depending on the pattern of their reading performance.

A more recent study is that of Patton et al. (2000). The authors investigated the rate of static and kinetic reversals in 201 children in a four-year longitudinal study from kindergarten to Grade 3. After three years, they found that there was no correlation between the two kinds of reversals, which may be interpreted as evidence against Orton’s (1925) theory of reversals. Furthermore, the rate of reversal errors in their study did not discriminate between children with and without problems in learning to read. Finally, reversals did not contribute to the prediction of the performance in a reading test. However, when the authors analysed the data of the fourth year of this longitudinal study (when children are in grade 3) kinetic reversals proved to be an excellent predictor for the performance in a reading test. Unfortunately, no interpretation of this effect was given.

Terepocki et al. (2002) used computer-based reversal detection tasks for numbers, letters, letter strings and words in order to compare 10-year-old normal readers and dyslexics in their performance accuracy. Dyslexics made more orientation errors than normal readers, whereas the two groups did not differ on attention control tasks. The authors suggested that the problems of dyslexics in discriminating similar looking items is due to poorly specified representations of letters. This interpretation is in some accordance with our view, as well as the assumption that such problems disrupt the process of learning to read and that, however, reversal errors are likely to disappear with reading experience, because alternative strategies become habitual in dyslexics. An interesting extension of Terepocki et al.’s work was published by Badian (2005). She argued that only a subgroup of dyslexics have problems in orthographic memory for the orientation of letters and numbers.

A study, often cited as evidence for the absence of a visual deficit in dyslexics was conducted by Bigsby (1985). She used a paradigm introduced by Posner and Mitchell (1967). These authors used a same-different task, in which participants were asked to decide whether two letters are the same or different. In one condition, a pair of letters had to be responded to as same only when the letters were physically identical (for example, B—B); in another condition, when they had the same name (‘value’) [a – A]; and in a third condition, only when they belonged to the same abstract category, such as vowels [a – e]. Posner and Mitchell (1967) found a temporal hierarchy of decision times
depending on the instruction which they interpreted as evidence for a theory of serial processing stages. According to this theory, at the lowest level, patterns are encoded in terms of their elementary physical characteristics (‘... the visual pattern ‘A’ is coded as a set of lines forming a unified but unfamiliar figure, which is not different from an infinite number of line combinations of similar complexity that are not letters’; Posner and Mitchell, 1967). If a decision cannot be made at this level, memory information has to be used. In a terminology characteristic of the time, memory information was taken to consist of ‘templates’, which are searched serially (cf., Sternberg, 1966). If no match is found, comparison operations proceed to the next stage of ‘conceptual’ processing, at which isolated concepts are used to tag the perceived objects. If comparison fails in this stage, semantic coding is used, which evokes rules and abstract categories to make identity decisions.

Following this logic, Bigsby (1985) argued that if dyslexics, as compared to normal reading children, show higher error rates and/or increased RTs for visual matches, then misperceptions would be present in dyslexics. In contrast, if the majority of errors and longer response latencies would occur for name matches, a linguistic dysfunction is to be assumed. Accordingly, in her experimental design, Bigsby differentiated between visual code pairs (lowercase letters, for example, ss versus rz) and a name code pairs (Dd versus Rs), whose letter elements were either reversible (bb) or not (Hs). For error rates, in case of the visual code pairs, no group effect and no effect of reversibility were found. Simple tests for the name code condition again showed no differences between disabled readers and normal reading children, but varieties between reversible and non-reversible letters were found (reversible >non-reversible). The results indicate that all of the conditions were easy for both groups. An analysis of reversibility confusion (the RT difference between reversible and corresponding non-reversible letter pairs) showed effects in all three groups for the name code pairs; dyslexic children showed more confusions than normal reading children; in particular, they had problems in differentiating lower and upper-case letters if they were reversible (for example P–q). In contrast, for the visual code pairs, no such group differences were found. Bigsby concluded from her findings that ‘Dyslexic children function well in the visual code and this code does not appear to be the locus of their reversible letter confusions’, and later she suggested that reversibility confusions seem ‘...to be mainly occurring somewhere during the translation from the visual code to either the name code or its referent, and to be more pernicious in dyslexic readers’.

Bigsby (1985) introduced reversal errors as to be introduced by Orton (1925) as misperceptions based on a visual deficit. By doing so, she lumped together Orton’s model with models of a visual perceptual deficit in dyslexics (Stanley and Hall, 1973). By citing studies which revealed null-findings between dyslexics and control in visual object recognition (Ellis, 1981), she argued that visual models of dyslexia may be wrong. However, from our point of view, neither the results cited by her nor her own data are sufficient to reject the importance of reversal errors. In fact, the data could even be used in advance of the Symmetry Generalization model to explain reversals. Her interpretation is that
reversals are an effect of a labelling deficit—this is exactly what symmetry generalization in letter perception would provoke. Even Orton's theory does not contradict her at all. Altogether, we actually should expect a faulty interaction between the verbal and the visual code only in her verbal condition.

Furthermore, a theoretical shortcoming may also be seen in her understanding of Posner and Mitchel’s (1967) model, whose approach she adopted for her study. The idea of distinct codes (physical and the name code) acting in serial stages of information processing, was rejected by Posner himself (1978; the serial stage approach ‘...is simply too restrictive to use as a complete description of the processes involved’, and ‘The temporal hierarchy ... does not imply that the processes involved at the different levels represent a strict series’, p. 35). With the beginning of the 1970s, serial models of information processing were found to be restricted to only some information processes. As a possible alternative, Posner considered a redundancy model in which all comparisons are made on the basis of a single memory code. This approach entails that comparison processes are facilitated by shared features between the items at different levels of abstraction. A second suggested alternative, the pathway activation model, states that each comparison reaches the highest possible level, but reaches this level the sooner the more lower-level features are being shared.

**SYMMETRY GENERALIZATION IN LETTER AND SHAPE RECOGNITION IN DEVELOPMENTAL DYSLEXIA**

One of our own experiments (Brendler and Lachmann, 2001) was conducted in order to test specific hypotheses that arise from the model of Symmetry Generalization, that is, the assumption that those reading disabled children who show more reversal errors in reading, as measured by a reading test (Zuericher Lesetest, ZLT, Grissemann, 2000), have problems in coordinating the visual and phonological subfunction due to an abnormal tendency of symmetry generalization in the representation of visual symbols, such as letters.

A *same–different* task was applied to test this hypothesis. Children with and without reading problems were asked to compare two stimuli, either two letters or two patterns, and to answer as fast and accurate as possible whether they are the same or different. Since symmetry generalization is assumed to operate in memory, the stimuli were presented successively, that is, one item in memory had to be compared with a visible one. The orientation of the stimuli was varied systematically, and thus in some pairs items were reflected or rotated version of each other. The task was varied between blocks. In the *categorical condition*, the orientation (rotation or reflection) had to be ignored, the children had to press *same* if letters or patterns had the same shape but of different orientation. In the physical condition, the children had to press *different* in these cases. The difference between these conditions is crucial, because in the physical condition, symmetrical relations between items must be suppressed in order to respond correct.
Experiment

The authors tested 66 children from Grades 3 and 4, half of which were diagnosed as dyslexics according to the discrepancy definition, and the others served as Controls. The authors used lexical versus non-lexical material (see Figure 23.1), and a physical versus a categorical instruction in a blocked design. The lexical material consisted of the letters ‘b, e, f, h, n, r’. As non-lexical material five-dot patterns were used (constructed on a $3 \times 3$ grid, leaving no row or column empty (Garner and Clement, 1963). Pairs of letters and pairs of patterns were shown successively. The items were presented in normal and in mirrored orientation. Therefore, a pair consisted of two items which were either identical in shape and orientation, identical in shape but not in orientation, or different in shape (for methodological details, see Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2004b, 2005a, 2005b).

**Figure 23.1**

Letter and shape stimuli used in different blocks in the experiment by Brendler and Lachmann (2001)

![Letter and shape stimuli](image)

In the *physical condition* the children had to respond to two items as to *same* only when they were physically identical, that is, the same in shape and orientation. Items of different orientation had to be judged as *different*—just as those items which are different in shape. In contrast, in the *categorical condition* the children were instructed to ignore the orientation of the stimuli. Items same in shape but different in orientation had to be responded as to *same* (Lachmann and van Leeuwen, 2005b). It is important to note that this *same–different* experiment differs from that of Bigsby (see above) in a rigorous way, we do not test any name categories (same responses are always required to the same stimulus) and in half of our pairs the stimuli have are transformationally related—not only vertically and independent on phonological similarities.

Main Results and Discussion

The main result was that disabled readers made more errors in discriminating stimuli under the *physical* condition relative to controls, whereas this effect was strongest when
letters had to be compared. In other words, children with problems in learning to read have special problems to give a different response when the same two letters were shown in different orientation. This was interpreted as evidence for symmetry generalization in the representation of visual symbols.

The results of the reading test (ZLT) exhibit a general overweight of the total number of reading errors within the disabled readers in contrast to normal readers. The children with reading disability had the greatest deficit in reading letters that were connected via left–right or vertical symmetry (for example reading ‘b’ instead of ‘d’). However, most important with respect to the Functional Coordination Deficit account is the fact that the authors found a significant correlation between the errors observed in the experiment and the reversal errors in the reading test. Those children who had more problems in discriminating orientationally related letters or patterns showed more reversal errors in text reading (see Figure 23.2). This result, however, was restricted to the b–d reversals. For other reversals the number of errors was too small, and an analysis could not be conducted. This is not less interesting for the symmetry generalization account; note that the errors in the experiment were made to all orientational axis.

![Figure 23.2](image)

**Relationship between ‘b–d’ reversals in word reading and errors in the same-different task with physical instruction and lexical material (taken from Brendler and Lachmann, 2001)**

The results were counted as evidence that difficulties in learning to read are related to difficulties in suppressing mirror-generalization in the representation of visual symbols, and thus to difficulties in the coordination of reading related subfunctions. Such difficulties are typical for beginning readers. In this respect, however, the questions remain whether reading disabled children have generally a greater tendency of symmetry generalization.
and therefore have more problems to suppress this mechanism in reading, or whether the degree of symmetry generalization is equal to that of normal readers, but there is a problem in learning to suppress this mechanism when confronted with visual symbols.

Mental Rotation of Letters in Developmental Dyslexia

Mental rotation is a task which requires visuo-spatial processing of images in mind. Usually, people are asked to decide whether two items, presented either simultaneously or in succession, are the same or different regardless of their orientation. The first study on mental rotation was published by Shepard and Metzler (1971). They showed that the RT increased linearly with the three-dimensionally angular difference of the objects presented, suggesting that the shown image is rotated in the individuals’ minds just as they would physically manipulate the object. The mental rotation effect has been replicated in many studies irrespective of the type of stimuli used in these experiments and even for other tasks than a same–different task (Cohen et al., 1996; Harris et al., 2000; Jordan et al., 2001; Kosslyn et al., 1998). Cooper and Shepard (1975), for instance, displayed isolated letters of different orientation, and the task was to decide whether the letter was shown in normal or mirrored parity. Ruthruff et al. (1995) used a mental rotation task within a dual-task setting and concluded that this operation requires central capacity.

Mental Rotation Studied in Dyslexics

Mental rotation studied in dyslexics was subject of some experimental studies (Corballis et al., 1985b; Karadi et al., 2001; Rusiak et al., 2003; Rusiak et al., submitted), some of which were already described earlier in this chapter. In the second study, Karadi et al. (2001) used pictures of right and left hands as stimuli. They were presented at angle of 0°, 50°, 90° and 180° clockwise from the normal upright. The participants’ task was to decide whether a left or a right hand was shown on the screen and to press the corresponding key. The results indicated that dyslexics perform this task with a higher speed but with lower accuracy. Moreover mental rotation occurred in non-dyslexics, but not in dyslexic children. The authors interpreted the results in terms of a dysfunction of the parietal cortex. They concluded that dyslexics have general problems in the processing of spatial information (and thus in mental rotation tasks), which may result in a variety of reading and writing difficulties. From our point of view, a deficit in spatial information processing may be one possible problem in Dyslexics, but it is unlikely to produce reversal errors.

In one of our own studies (Rusiak et al., 2003) we asked 15 dyslexic and 14 non-dyslexic teenagers to take part in a classical mental rotation experiment. The participants’ IQs were estimated with the Wechsler Adult Intelligence Scales. Moreover, a reading test using
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chain-words and the chain-sentences (Ober, 1998) was performed. The task and the main results are described in the following paragraphs in some more detail.

The Experiment

The stimuli were black letters: R, F, G, e, k and the exact mirror-images of those letters. They were presented against a white background in the centre of a computer monitor. The letters were displayed in different angular orientations: 0º, 45º, 90º, 135º, 180º, 225º, 270º, and 315º clockwise from the normal upright. The participants' heads were fixated. The participants were instructed to look at the fixation cross and to decide whether the subsequent stimulus was a normal or mirrored letter regardless of its orientation by pressing corresponding keys. All participants were asked to perform the task as quickly and as accurately as possible.

Main Results and Discussion

To statistically evaluate the results of mental rotation an ANOVA was performed for RTs and Error rate with one between-subject (group) and one within-subject factor (rotation angle). For RT, a significant group main effect was found; dyslexics were slower than normal readers, and for both groups, RT and Error rate increased significantly with increasing angle of rotation from the upright orientation. This finding reflects a typical mental rotation effect (Cooper and Shepard, 1975). Dyslexics needed 300 ms more to decide whether the letter presented was normal or mirrored. However, as can be seen in Figure 23.3, the slope is the same in both groups, that is, the effect is additive with rotation angle between the groups. The null finding of an interaction between the factors confirmed the interpretation that dyslexics show no difference in the operation of mental rotation. Instead, the reason for the dramatically increase in RT is either before or after the mental operation under investigation. The analysis of accuracy rate revealed no difference between the groups (see Figure 23.4).

According to the Symmetry Generalization model, which assumes that orientation errors in dyslexics occur from a failure in suppressing symmetry generalization in the representation of graphemes, the difference in RT between the groups may be caused by a decision problem, that is, after the mental rotation process has been completed. In simple words, after the Dyslexics have finished the rotation process, they still have a problem to decide whether the letter (the grapheme) is in normal orientation or mirrored because to decide this requires a mapping between the input and the representation of the grapheme in memory. This problem produces higher decision times and more errors which, of course, are then independent from the degree of rotation.
The present results are somehow in opposite to what was obtained by Karadi and coworkers (2001). This, however, is expected by the Symmetry Generalization model, because they used non-linguistic stimuli. Also the null-finding of group differences in the study of Corballis and colleagues (1985a) is actually in good accordance with our model. Dyslexics who make a lot of reversal errors and fail in the present task may not have a problem in naming the letter but in differentiating the normal from the mirrored, because both versions represent the grapheme; whereas in non-dyslexics, only the normal letter is connected with the phoneme representation (but not the mirrored).

Of course, this interpretation is not exclusive. It could also be argued that this particular group of Dyslexics tested here has a problem in encoding the stimuli or in other processing stages prior mental rotation. Therefore, a number of other studies are planed to test this interpretation directly and indirectly. A direct way could be to use electrophysiological methods. Heil and Rolke (2002) introduced a method in which Event Related Potentials (ERP) can be used to localize mental rotation in space and time. If the deficit is indeed located after mental rotation, there should be no difference in this ERP component.
between the groups. However, if the relevant peak will appear in Dyslexics later than in Non-Dyslexics it could be concluded that the deficit is located before the process of mental rotation.

**Figure 23.4**

Accuracy rate (%) as a function of angle of rotation in the dyslexic and normal reader group (taken from Rusiak, Lachmann, and Jaskowski, 2003)

An indirect way has already been delivered with the results of Brendler and Lachmann (2001), described before and of a more recent study (Lachmann and van Leeuwen, forthcoming). In these studies, the authors showed that dyslexics have indeed problems in suppressing symmetry in the representation of graphemes, indicated by increased response latencies and error rates for the physical and categorical match under the physical instruction, but not under the categorical instruction, as well as by the fact that the difficulty is especially prominent for letters. Since for both instructions the same stimuli and procedure were used, but a group effect was found for the physical instructions only, it was concluded that the problem of dyslexics in the mental rotation task may not be
caused by an early processing deficit. Instead the interpretation of a decision deficit was supported.

GENERAL DISCUSSION

On the basis of the studies reviewed, the question about the significance of reversal errors for explaining the nature of reading disability cannot clearly be answered, because, at the first glance, the results seem to be very heterogeneous. However, spoken in simple words, the reason for the heterogeneity of the results is the heterogeneity of the studies, that is, different methodological approaches were applied and therefore the results are not comparable. We reviewed a number of reversal studies. Some of these studies investigate the relation between reading and the processing of reversible visual shapes (Goins, 1958; Lyle and Goyen, 1968). Using non-verbal material, however, they may have tested hypotheses of certain deficits in the visual subfunction as to be responsible for the problems in learning to read. In itself, this is absolutely legitimate. However, such studies can neither be used to test the theory of Orton (1925) nor any other theory that assumes reversals to result from a failure in coordinating visual and phonological subfunctions. In fact, from some reversal models (Corballis and Beale, 1993; Lachmann, 2002; Orton, 1925), a null-finding in these studies would even be expected.

Yet, studies using verbal material may also differ significantly, as for in the instance of the degree of functional fragmentation (Lachmann, 2002). Whereas Orton (1925) analysed the writing performance of disabled readers and a reading test measures the reading performance per se, experimental studies test the performance of normal versus disabled readers on an experimental task which requires only (a) certain subfunction(s) of the reading process (functional fragmentation). In some experiments, reversible and not reversible letters are presented in the context of words (Lyle, 1969; Seidenberg et al., 1985), and in others in the context of non-words (Seidenberg et al., 1985), which may affect subgroups of disabled readers quite differently (for example, Boder, 1973a, 1973b). The involved cognitive functions in both conditions, however, may differ from those functions involved when isolated letters are presented (Brendler and Lachmann, 2001; Corballis et al., 1985a; Liberman et al., 1971).

Experimental studies on reversal errors do not only differ in the used material, but also in the procedure. For instance, presenting reversible shapes or letters very briefly, followed by a mask (Grosser and Trzeciak, 1981) to measure the recognition threshold, may test the pre-representational processing (albeit not exclusively), whereas presenting one of the items for a sufficient time to create a representation may test a different kind of processing.

The required response must be considered as well. The response can be speeded or not and may require naming, reproducing, recalling or simply recognizing; the response may
require the manipulation of the representation (as in our mental rotation experiment), or not, and the decision may be based on the same, or a higher (categorical) level of processing (for example, Bigsby, 1985; cf., Posner and Mitchell, 1967). Furthermore, the modality of the input and the response may differ, verbal material may be presented visually or auditorily, and the response may be visual or auditory as well (Fuchs and Lachmann, 2003; Hicks, 1981).

Thus, the material and the procedure should be chosen carefully depending on the hypothesis. Unfortunately, some review articles and introduction sections put all reversal studies together, and conclude undifferentially that the majority of them show that reversals do not play an exceeding role in the Error rate of reading disabled children. Moreover, some articles characterize reversal studies as testing the visual deficit theory, and conclude on the basis of some null-findings that visual problems are generally unlikely to be present in disabled readers (for example, Bigsby, 1985; Vellutino and Scanlon, 1998).

A further problem in comparing studies on reversal errors is the definition of reversals. Some experimenters only consider static reversals (for example, Brendler and Lachmann, 2001), while others are especially interested in testing the relation between static and kinetic reversals (Liberman et al., 1971; Patton et al., 2000). But even within the two kinds of reversals, there is no consistency about what to be counted as a reversal. Lyle and Goyen (1968), for instance, assume their sequential condition (see above) as measuring mechanisms equivalent to those responsible for kinetic reversals in writing and reading. Grosser and Trzeciak (1981), for instance, define ‘u’ as a non-reversible letter; but since they used ‘b’ and ‘q’ as reversible letters, they should have considered ‘u’ as reversible to ‘n’ (even though ‘n’ was not presented). In Liberman et al. (1971) the letter ‘g’ counted as reversible, which is questionable.

In the previous section, we argued that experiments on reading have to test certain component sub-functions of reading. Thus, in studies on reversal errors the experimenter aims on testing functions which are assumed to produce reversal confusion. When the performance in the used task proved to be significantly different in students with reading disability and normal reading students, it is concluded that the tested function is responsible for reversal confusion and problems in learning to read. Consequently, not only does the selection of sub-functions have to be tested, but the definition of the reading disability group is also crucial. We already introduced the discrepancy definition of reading disability and the problems related to that definition. We mentioned that there is a critical discussion going on about this definition. Consequently, not all experimenters use it (for example, Liberman et al., 1971), and those who do are not uniform about the criterions for a discrepancy. Hicks (1981), for instance, differentiated between retarded readers and dyslexics as two different groups. The retarded readers are defined as having a reading retardation of 2.1 years from chronological age. Most studies, however, would define this group as dyslexics. The dyslexic group in Hicks’ study was defined as having 1.5 years retardation in reading and showing typical patterns of errors in reading and
writing. Of course, this may influence the experimental results and their interpretation.

There is also inconsistency about the terms used to describe the samples. The terms poor readers, dyslexics, disabled readers, retarded readers, stereosymbolics, and so on, are either used synonymously or to distinguish between different groups. As a consequence, the same term may be used in different studies; the definition, however, may differ. Lyle and Goyen (1968), for instance, used the term reading retarded children, just as Hicks (1981) did, but in contrast to her, Lyle and Goyen defined retarded readers as showing a reading retardation of nine months in Grade 2 and 18 months in Grade 3. In Corballis et al. (1985a, 1985b), as a further example, the term disabled readers was used and two years retardation in reading was required to meet the criterion.

The discrepancy criterion depends not only on reading performance, but also on measures of the general cognitive abilities. Whereas, for instance, Lyle and Goyen define an IQ value of at least 90 to meet the criterion, most authors just report the average of the samples, and in Grosser and Trzeciak we learn nothing about the IQ of the students at all. Not only the discrepancy definition, but the age of the children the sample consists of may also differ between studies. Whereas the children in Corballis et al. (1985b) were 12 years old, Patton et al. (2000), and Lyle and Goyen (1968) asked younger children (Grades 1–3) to participate in their experiments. The participants in the experiments of Grosser and Trzeciak (1981) were aged between seven and 14 years, and the authors revealed a strong correlation between age and performance, but only in normal reading students. From this result, we may expect greater differences in samples of higher average age, but the results in Lyle and Goyen suggest bigger differences at younger age level. In any case, the age is a crucial factor; as in all developmental disorders, the older the person, the less sure we can be that what we have measured reflects the primary or a secondary lag.

A problem arises when reading disabled children receive a special training, as for instance those in Brendler and Lachmann (2001). In some German Federal States a diagnostic procedure takes place in Grade 2, and those diagnosed as dyslexics attend the Grade 3 level over two years instead of one in order to have the chance for an extensive training in reading and writing. This results in methodological problems for researchers: testing the reading disabled children means that the controls are either younger or have a higher grade level, which may be important for the interpretation of reading tests. Moreover, children who attended already the two-year dyslexia training program may show more similar performance than Controls in reading, including reversal errors, while their underlying deficit may still exist.

**SUBGROUPS**

Last but not least, we shall emphasize the importance of subgroups of dyslexics (Becker et al., 2005; Boder, 1970, 1973; Flynn and Deering, 1989). The FCD model is a multi-causal
Developmental dyslexia is not a homogenous syndrome. Children differ in their reading problems (Boder, 1973b), and it was shown that different deficits are responsible for these problems. For instance, Lachmann et al. (2005) studied auditory processing in 8–11-year-old children with developmental dyslexia by means of event-related brain potentials. Cortical sound discrimination was evaluated by analysing the mismatch negativity (Näätänen, 1992; Schröger, 1997) to syllable and tone changes. The analysis of the data obtained from two dyslexic subgroups, Dyslexics-1 being impaired in non-word reading (or both non-word and frequent word reading) and Dyslexics-2 in frequent word reading but not in non-word reading, revealed that the mismatch negativity was specifically diminished in the latter group, whereas it was normal-like in Dyslexics-1. These results showed that different diagnostic subgroups of dyslexics have different patterns of auditory processing deficits as suggested by sound-discrimination impairment specific to one of the groups. We may assume that reversal errors are a symptom of Dyslexics-1, those with problems in grapheme-to-phoneme conversion (cf. Lachmann et al., 2005).

REFERENCES


Hicks, C. 1981. ‘Reversal Errors in Reading and Their Relationship to Inter- and Intra-modality Functioning’. Educational Psychology, 1: 67–79.


