

**Letter reversals in dyslexia: Is the case really closed?
A critical review and conclusions.**

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Summary

Reading is an automated desymbolization involving parallel operating subfunctions from which the major ones belong to the visual or the language comprehension domain, coordinated by guiding cognitive subfunctions. In this review, theories on dyslexia are subdivided according to what subfunction(s) is (are) primarily assumed to be impaired, according to the level of processing on which the deficit is assumed to be affective, and according to whether the theory is a mono- or multicausal one. The heterogeneity of theories and empirical results are explained by the inconsistency of methodological approaches, the differing definitions of dyslexia and shortcomings in the interpretation of experimental results attained after functional fragmentation of the reading process. Empirical studies on reversal errors are critically reviewed and re-interpreted on the basis of the Functional Coordination Deficit Model. Within this multicausal model, reversals are assumed to be a symptom of a deficit in the coordination of visual and phonological decoding in a subgroup of reading disabled children. It is argued that in order to learn to read it is important to treat graphemes as symbols instead of objects. Whereas in visual object recognition symmetrically related objects are learned to be represented by similar patterns of neural activity, in reading such a symmetry-generalization is a hindrance. A failure in suppression of visually symmetrical information in the representation of visual symbols produces ambiguous relations between visual and phonological information and disturbs the functional coordination and may cause problems in learning to read. It is emphasized that reversals do not reflect a visual deficit or an incomplete hemispheric dominance, and that they are not the one and only symptom of dyslexia.

Key words: reading, dyslexia, reversals, symmetry generalization, functional coordination deficit

Theories on reading disability

Systematic research on reading disability has a history of more than 100 years. However, there is still no consistency about the etiology of reading disability. In fact, theories on reading disability are very inconsistent and sometimes even contradicting. This may be due to the inconsistency in (1) the understanding of the reading process as such (cf., Rayner, 1993), (2) the point the phenomenon is viewed from, that is, symptomatically, etiologically, or from intervention/teaching (cf., Tonnessen, 1995) and (3) methodological approaches (cf., Lachmann, 2002).

To bring light into this heterogeneous field, it may be useful to classify models of reading disability according to various aspects.

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Reading (including silent reading) may be thought of as comprising two major processes: (1) *visual decoding* of the message presented in a written form, including configurational (feature) and orthographic (word form) analyses; and (2) *language comprehension* of this message, including phonological, semantic and syntactic decoding (Friederici & Lachmann, 2002; Lachmann, 2002). However, reading cannot be defined as simply the sum, but rather as an interaction of these two major components. Firstly, the visual processes involved in reading are not identical to those in visual object recognition. Instead, the visual subfunction has to be considered as a highly specialized, fast and accurate desymbolization of visual icons (e.g., van Leeuwen & Lachmann, 2002). The same holds for the phonological processing which cannot simply be seen as a higher stage of auditory processing (Mann & Liberman, 1983). As for instance argued by Liberman (1998), speech consists not of acoustic sounds, but rather of distinctly phonetic gestures of the articulatory organs. Secondly, it seems unquestionable that the subfunctions involved in reading do not operate in serial. Even though it may be clear that reading starts in fact with a visual analysis of the configuration of the written form of a message. However, immediately after the reading process is actuated, phonetic, semantic and syntactic hypotheses are generated - perhaps even before the visual representation is established, that is, top down and bottom up processes within and between the subfunctions are operating in parallel and are not independently from each other. This complex functional coordination is guided by (working- and long-term-) memory and attention processes (Friederici & Lachmann, 2002).

Consequently, reading may be defined as a highly automated desymbolization process which involves numerical parallel operating subfunctions from which the major ones can be attributed to the visual or the language comprehension domain and which have to be coordinated very quickly and accurately by guiding cognitive subfunctions. Accordingly, approaches to reading disability may be subdivided very grossly into those assuming *deficits in the visual domain* (Lyle & Goyen, 1968; Stanley & Hall, 1973; Stein, 2002), those assuming *language-based deficits* as causal factors for reading disability (Bradley & Bryant, 1983; Snowling, 2001), and those emphasizing the role of general or *guiding cognitive abilities* for functioning reading (Radach, Inhoff, & Heller, 2002; Starr, Kampe, Miller, & Rayner, 2002; Stein, Richardson, & Fowler, 2000; see Lachmann, Friederici & Witruk, 2002 for an overview). Even though the latter approaches investigate visual attention, eye movement control and stereo vision, these models have to be seen as distinct from pure visual approaches, because differences which were found between normal and disabled readers, e.g., in the pattern of saccades, the number of regressions and the location of the optimal viewing point, can also be explained in terms of differences in language processing (Everatt & Underwood, 1994; Friederici & Lachmann, 2002; Kennedy, 1987).

A further important aspect that differentiates between approaches to reading disability is that of an assumed monocausality versus multicausality underlying the reading disability. Numerous phonological processing deficit models are monocausally oriented (Snowling, 2001). In contrast, most model which assume visual processing deficits in disabled readers are multicausal ones (Becker, Lachmann & Elliott, 2001,

2002; Stein, 2002). Considering the reading process as a functional coordination process does imply the assumption of multicausality (Lachmann, 2002). There are numerous studies indicating that there are subgroups of disabled readers according to their underlying deficit (Ridder, Borsting, Cooper, NcNeel & Huang, 1997; see Watson & Willows, 1993 for review). Boder (1971), for instance, argues that there may be a dysphonetic subtype of dyslexics, showing deficits in grapheme-phoneme convention and phonological decoding, and thus especially in nonword reading; and a dyseidetic subtype, performing weakly in visuo-spatial perception and in the perception of letters and words as visual gestalts. These readers were, for instance, identified as to having no advantage in reading highly frequent words in comparison to normal reading individuals. Some disabled readers belong to a mixed group.

However, there is a striking number of papers reporting null-findings after testing the visual processing of disabled readers in comparison to normal readers, and therefore questioning the existence of a visual deficit subtype (Vellutino, 1987; see Miles & Miles, 1999 for a review). Why is it, however, that experimental research seems to fail to clearly answer the question of whether or not there is a visual deficit underlying the failure in adequately learning to read in at least a subgroup of the affected individuals? Sometimes, the results are even contradicting. From our point of view, the main reasons are methodological ones, some of which will be discussed in the following paragraphs and in section 3.3.

A first important point is the definition of dyslexia on which the sample creation depends on. Studies use quite different criteria for the definition of reading disability. The most common one is the so-called *discrepancy definition* which is based on a significant discrepancy between the reading performance as expected by measures of general intellectual ability and the reading performance as measured by a reading test. This - on the symptom principle (cf. Tonnessen, 1995) based definition - is often criticized, especially by those who define reading disability as caused (*causality principle*, cf. Tonnessen, 1995) by a purely phonological deficit (Miles, 1991; Siegel, 1998; Snowling, 1998, 2001; Toth & Siegel, 1994; Wimmer, Landerl, & Frith, 1999). However, even within those studies, which use the discrepancy definition, there is no consistency on how to state this discrepancy.

Furthermore, the school students participating in the studies are of differing ages, and sometimes the participants are adults. Therefore the results of studies sometimes cannot be compared. How should we know whether the deficit which caused the failure in learning to read has a stable quality over individual development; in older students the reading problem may be a secondary symptom and the underlying deficit is not significant any longer.

Another important point to be considered when comparing the experimental studies on reading disability is what was introduced by Lachmann (2002) as *functional fragmentation dilemma*. As argued earlier, reading requires the coordination of numerous subfunctions that have to be coordinated and which are to a high degree specialized. Therefore, fragmenting the reading process in experiments by testing one single subfunction (which is assumed to be impaired in the disabled readers) does not necessarily allow conclusions about the functioning within the context of reading. In particular, a study that investigates the ability of normal and disabled readers in

reproducing visual shapes that were shown to them before (e.g., Lyle & Goyen, 1968), does not necessarily reveal possible visual deficits as cause for the reading problems.

This is because

- (1) as mentioned earlier, the visual processing in reading is not identical to visual object recognition,
- (2) the null-finding in testing a subfunction does not confute the deficit of this function within the complex coordination process, and,
- (3) we even cannot be sure whether a found processing difference is a cause or a result of the reading problem,
- (4) when assuming multicausality it may not be expected that all participants show the deficit (e.g., Becker, Lachmann & Elliott, 2001),
- (5) subfunctions are complex processes by themselves and may be impaired on a certain level only.

The latter argument (5) will be analyzed in a bit more detail. When papers are arguing in favor or against a visual subtype in the defined population of disabled readers, the results may be revealed by quite differing methods, which all may test (to a certain degree – considering the limitations mentioned above) the visual subfunction, which, however, may test different *levels of processing*. There is a big difference between the hypothesis that disabled readers fail in generating a visual representation of the icons, versus the hypothesis that these readers have problems in operating with this visual representation or to keep the representation in working memory for a short period of time. The first group of studies are termed in the literature as to “low level (versus high level) deficits”, “perceptual (versus memory) deficits”, “early (versus late) deficits”. Unfortunately, the authors do not always define these concepts. We prefer to use the term *pre-representational* deficits.

An example for studies on pre-representational deficits are those testing the temporal integration of visual information (Stanley & Hall, 1973). The reason for a failure in this integration may be due to an abnormality in the coordination between the transient and the sustained pathway (Breitmeyer & Ganz, 1976; Livingstone & Hubel, 1987) in the lateral geniculate nucleus of the visual system in the brain (Lovegrove, Martin & Slaghuis, 1986; Stein, 2002; Galaburda, 2002). Under certain conditions (moving items, saccades), a failure of this coordination averts an adequate and fast setup of visual representations.

However, there are also studies which found a general temporal integration deficit (cf., Farmer & Klein, 1995), which is not only effective to the visual system, but also within the auditory modality (Kujala, 2001, 2002; Lachmann, Kujala, Berti & Schroeger, in preparation; Tallal, 1984). Thus, the same distinction between re-representational and representational deficits in visual processing holds for studies testing the phonological subfunction in reading. Tallal (1984), for instance, argues that deficits in phonological representations may be due to a general deficit in rapid processing of auditory information. In contrast, Snowling (2001) argues resolutely

against such an explanation and in favor of a higher level phonological deficit. However, the cause-and-effect paradox mentioned earlier also occurs within the distinction between early and late processes in terms of the question of whether late processing deficits, and finally reading by itself, is the effect of, or the cause for, early processing deficits (Hulme, 1988; Lachmann, 2002; Snowling, 2001).

Alone, the fact of correlation between measures of early or late processing and reading performance is not sufficient to decide this question. Very impressive in this respect, however, is the recent result of Kujala and her colleagues (Kujala, 2002; Kujala, Karma, Ceponiene, Belitz, Turkkila, Tervaniemi & Näätänen, 2001). The authors could show that non-linguistic, audio-visual training does lead to plastic neural changes in reading disabled children as measured by electrophysiological parameters. Most important is the result that, in fact, these changes led to a significant improvement of the reading performance of these children as compared to those disabled readers who did not receive this special training.

We argued that reading requires the coordination of parallel operating subfunctions. Moreover, this coordination process has to be extremely fast and accurate. From these simple and uncontested assumptions it appears logical that the reading process may be affected by any disturbance of the functional coordination. Thus, reading disability may be defined, as suggested in Lachmann (2002), as a Functional Coordination Deficit (FCD). The FCD-model is a multicausal one. It is argued that reading disability may be caused by a deficit - or better a difference in operating of either a single or a number of subfunctions - either on a low or a high level or both - in a way that the coordination process is disturbed. Moreover, even when all subfunctions operate optimally in isolation, reading may be affected when the coordination between two or more functions and the binding of information from different domains are impaired. According to this model, from the etiological and educational point of view there is not *one* reading disability, but rather a number of subtypes. These subtypes only have a failure in learning to read (and to write) at a level expected from the cognitive abilities and the reading performance of the average population in common.

Reversal errors in the context of the Functional Coordination Deficit model

Strophosymbolia

In most of the text books on reading disability, Samuel Orton is identified as the father of scientific dyslexia research. In fact, his 1925 publication "Word-blindness in school children" (Orton, 1925) is one of the most cited in the reading disability literature. His work dramatically influenced the interest and research on reading problems in school children. At his time, much was already known about neuropsychological failures in language and reading caused by damages in certain areas of the brain (see Lachmann, 2002, for review). The meritoriousness of Orton consists first at all in that he shifted attention to the *developmental* aspect of dysfunctions in the brain, and moreover in his statement that a faulty developed function may be compensated by special training (Orton, 1928, 1929).

However, his theory was still influenced by his neurological background. He knew about the specificity of the hemispheres and about separate levels (or types) of visual cortical brain functions (Brodmann, 1909). On this background, he interpreted the high frequency of left-handedness (-eyeness) within the group of reading disabled children and the typical reading and writing mistakes made by these students as result of a developmental disorder of the interhemispheric communication. He (Orton, 1925, 1928, 1929) identified three groups of such typical mistakes done by the students with reading problems:

- (1) Disabled readers show a significant difficulty in differentiating letters which are horizontally or vertically symmetrical to each other or rotated (*p* and *q*; *b* and *d*; *p* and *d*). These errors were called *static reversals*.
- (2) Disabled reader tend to confuse palindromic words (*was* and *saw*; *not* and *ton*) and to read partially from right to left resulting in a reverse of paired letters or even syllables within a word. These errors were called *kinetic reversal*.
- (3) Further more, these students demonstrate remarkable capability for mirror reading and writing, sometimes better than for reading in normal orientation.

These phenomena, without any visual deficit such as in visual recognition (Orton, 1928), were assumed to represent the cardinal symptoms of *strephosymbolia*, reflecting the whole graded series of developmental reading disability. The great variety of all other errors, which Orton (1925) also observed, were defined as a "secondary defect of the learning process resulting from a lack of practice in reading because of the obstacle in recognition interposed by the reversals" (1928). Orton even believed to have found an objective measure for reading disability in the number of reversals and in the ratio of the time from mirror reading to normal reading. By using this measures, he realized a striking difference in the percentage of strephosymbolic children in different school populations, which he counted as evidence for his hypothesis of the important role of teaching methods (multi-sensory training, sight reading plan, etc.) as an environmental factor.

Since Orton defines reversals as cardinal symptoms, the theory of strephosymbolia is actually the theory of the *genesis* of reversals. The theory postulated by Orton is based on neurological findings of those days. He assumed that reversals and mirror reading are the consequence of an abnormal cerebral dominance or a failure in establishing cerebral dominance. Orton (1925) postulated three levels within the visual cortex, based on both histological findings about distinct types of neurons in the visual field and neuropsychological evidence from focal brain damages (Brodmann, 1909; Hinshelwood, 1917). As an early *arrival platform* (after reflex centers), he assumes the area striata as the neurological basis for the first level, the *visual perceptive level*. From a bilateral destruction, but not from unilateral destruction of this area(s) a *cortical blindness* results in which there are no conscious visual processes, whereas the lower reflex phenomena remain unaffected. The occipital cortex which surrounds the arrival platform in both hemispheres (area occipitalis), he assumes to be related to the second level, the *visual recognitive level*. An extensive bilateral destruction results in a *mind-blindness*. There is retention of mere awareness of visual stimuli (first level), but there is a loss of their recognition (object memory). For the reading process the third level,

the *visual associative level* or *symbolic level*, is most interesting. According to Orton (1928), this functional level is not locatable, but includes temporal and parietal areas laying nearest to the visual recognitive field (prae-occipital area, occipito-temporal area, area angularis and parts of area parietalis superior, see Brodmann, 1909). With lesions in these areas, the awareness and the recognition of the meaning of visual objects or symbols remain intact, but there is a loss of the abstract or associative meaning of printed words (associative memory) and thus a difficulty in reading (acquired word-blindness). However, in this case, contrary to the first two levels, a unilateral damage in the dominant hemisphere (either left or right) is sufficient to produce the symptoms, whereas damage to these areas in the non-dominant hemisphere does not result in comparable clinical symptoms (Orton, 1928). This is similar to other disabilities resulting from a loss of a higher function after unilateral damages and points out the role of cerebral dominance in phylogenetic and ontogenetic development of higher processes (such as language).

As the lesion studies suggest, within the first two levels, the hemispheres “work in union to produce a single conscious impression” (Orton, 1929), whereas the association with sounds and abstract meanings (associative level) - required for reading - is realized by the dominant hemisphere only. Orton’s interest, however, not only refers to what happens in the associative fields of the dominant hemisphere, but also to what happens in the cells of the symmetrical counterpart. These cells are assumed to be stimulated similarly by the incoming stimuli, and are also supposed to form a mnemonic record or engram. Orton assumed this engram to be a mirrored (antitropic) version of the one in the dominant hemisphere, because of the oppositely orientated nerve cells. Thus, in reading, the orientation of letters and words becomes relevant at the associative level. A mirrored word or letter might even be related to a different concept or sound association (as for p/q). Since the linkage between the levels must be simultaneous or quickly successive and strongly concordant, it is crucial to completely suppress the mirrored record to make a fast and correct association with sounds or abstract meanings. In this respect, learning to read means learning to suppress memory patterns in the associative fields of the non-dominant hemisphere. Otherwise confusion leads to mistakes and/or a delay in reading, as well as in writing because of failing recognition of correct associations (see above). According to this point of view, teaching to read must use a multi-sensory, more phonetic approach instead of a “look and say” method (Gillingham & Stillman, 1969).

Modification of Orton’s concept

The theory of Orton is based on the neurological knowledge of the first quarter of the 20th century and from today’s perspective has numerous limitations. One important shortcoming is the assumed strong monocausality postulated by Orton. As it was found later, there are many other mistakes which cannot simply be considered as secondary symptoms. Strongly related to this shortcoming is that of the assumed strong serial order of the levels and the assumption of the visual-associative level as the highest of the so-called *visual word center*. This may be one reason why Orton’s theory is often cited as a visual deficit theory even though it is the coordination (to use FCD

terminology) between the visual and the phonological subfunction which Orton assumes to be impaired. Furthermore, the theory of Orton is very restrictive. He assumes that the neural representation of an engram in one hemisphere is exactly the mirror counterpart of the one in the other hemisphere and that reversals are the consequence of missing dominance of the hemisphere which is representing the original orientation. However, there is evidence against such an assumption (for review see Corballis & Beale, 1993 or Lachmann, 2002).

In the last decades a lot of evidence was found (Achim & Corballis, 1977; Beale et al., 1972; Corballis & Beale, 1970, 1993; Cummings, 1970; Herbert & Humphrey, 1996; Noonan & Axelrod, 1992; Saarinen & Levi, 2000; Sperry, 1962) that in fact many callosal and commissural fibers connect homotopic mirror-image points of both hemispheres. Thus, just as Orton (1925) suggested, it seems reasonable to look at both hemispheres and their interaction. However, the theory needs a significant modification in order to cover nowadays neurological knowledge. Such a modification was for instance suggested by Corballis and his colleagues (Corballis & Beale, 1993; Corballis, Macadie, Crotty, & Beale, 1985). In contrast to Orton, the authors argued that a visual representation of a shown object, such as a letter or a word, is recorded adequately, that is, in normal orientation in each hemisphere. They postulate a *mirror-image generalization* as a result of the interhemispheric communication. Thus, mirror-image representations do not occur with the initial laying down of traces as supposed by Orton (1925), but with the transference of traces from one hemisphere to the other. In so far, mirror-image generalization describes an effect of memory formation and not of perception.

Transferring this concept into the Functional Coordination Deficit framework, reversal errors in reading are explainable - beyond Orton's (1925) theory - as occurring during the coordination process in reading (Lachmann, 2002). This process includes the storage and retrieval of visual bottom-up information which is assumed to be represented symmetrically in the cortex, while the phonological representations are organized asymmetrically. This induces confusion because different phonological codes ("bee" vs. "dee") might be appropriated to the same visual representation (b = d) in memory. Thus, in correspondence with Orton (1925), reversals are assumed to be an effect of labeling. However, in contrast to him, within the FCD approach they are seen as a memory effect. This, especially, explains reversals in writing directly.

According to this approach, an important factor in learning to read is the suppression of mirror-image information (of graphemes), or better, their connection to the phonological label. This can be ensured by a hemispheric dominance and a shift of magnitude of the representation between the hemispheres, such as a stronger visual record in one hemisphere, which leads to a stronger reversion in the other. Still, both orientations do represent the stimulus shown, but there will be a stronger connection between the label and that part of the representation which reflects the configuration in its original (physical) orientation.

We may assume that hemispheric asymmetry is not only a phylogenetic (evolutionary) but also an ontogenetic (developmental) stage (Lachmann, 2002). An impairment in the development of hemispheric dominance or of the pattern of interhemispheric communication in general, results in a deterioration of the

coordination process. In that case, the FCD predicts either a need for more time and/or a higher probability of reversals in reading and writing because bottom-up information cannot be used adequately.

Symmetry-Generalization in memory

There is a question that remains with the model of mirror-image generalization: How can non-vertically symmetrical reversals be explained? Experiments on symmetry detection have shown that the relative advantage of vertical symmetry in comparison to symmetries at other orientations disappears when the pattern is presented away from the fixation point (e.g. Bornstein & Krinsky, 1985; Herbert & Humphrey, 1996; Wenderoth, 1995). This finding substantiates the original callosal hypothesis, but it also suggests that there are additional mechanisms (not specifically explained by the cited authors) for detecting non-vertical symmetry, as well as for detecting vertical symmetry away from the point of fixation. Palmer & Hemenway (1980), for instance, have shown that there is not only an advantage for vertical symmetry, but also, albeit a smaller one, for horizontal symmetry, relative to diagonal symmetries. Lachmann (2000; pp. 188-193) could confirm such effects for a recognition task. The participants of his study had to judge two successively presented dot-patterns (as used by Garner & Clement, 1963) as *same* not only when they were identical (repetition) but also when they were symmetrical to another (transformationally related by rotation in multiples of 90° or reflection on any axis, producing vertical, horizontal, and oblique symmetrical pattern pairs), and as *different* otherwise. The reaction times (RT) found for *same* responses followed a linear function; performance was fastest for identical patterns, followed by vertically, horizontally, and lastly diagonally symmetrical patterns. In some cases (patterns with imaginary straight lines), there was no RT difference at all between identical patterns and patterns that were vertically symmetrical to each other, whereas the RT for other symmetries still followed the linear trend.

There is theoretical and experimental support for the argument that the visual representation of a stimulus configuration in memory is to a certain extent invariant against any reflection (e.g. Lachmann & Geissler, 1999; 2002; Lachmann & van Leeuwen, 2002a, b, c). In this respect, Lachmann (2002) introduced the term *Symmetry Generalization* with the understanding of *Mirror-Image Generalization* as a special mechanism which prevails in the evolutionary stage of a vertically symmetrical organization of the nervous system. Admittedly, he does not have a physiological model - such as the callosal transfer for vertical symmetry - to explain an overall symmetry generalization. Instead, Lachmann (2002) suggested that a memory unit (engram), represented by a neuronal *cell-assembly* (Hebb, 1949) which is activated by a perceived object, consists of neurons, the majority of which are identical to those of the assembly, which would have been activated by a symmetrical version of that particular object. Such an overlap of assemblies, may be a result of their frequently synchronized activation, and thus depend on the behavioral relevance of the orientation of the symmetry.

Bornstein and his colleagues (1981, 1985), for instance, showed that four month old infants have no preference for symmetry at all, but process vertically symmetrical stimuli faster than others, whereas 12 month old infants prefer vertical symmetry to horizontal symmetry and asymmetry. This pattern of results, as well as results mentioned earlier, suggest that the special role of vertical symmetry might indeed be a consequence of the symmetrical organization of the cortex (or vice versa) and interhemispheric communication (callosal transfer), which leads to a faster performance but not to a preference of vertical symmetry in newborns. However, the advantages of other symmetries and the preference of vertical symmetry in older infants could be explained as a learning effect, the graded character of which results as a consequence of behavioral relevance. Regarding the hypothesis that the evolution of the nervous system can be described as a progression from spherical to radial to bilateral symmetry and finally to asymmetry and considering that this progression reflects in some respect also the individual (ontogenetic) development, Lachmann (2002) assumes a genetically based predisposition for learning symmetry generalization and its graded orientation preference.

Reversals as effect of Symmetry-Generalization in reading

Symmetry generalization warrants a significant advantage for visual processing of objects (and scenes) and consequently for behavior, not only of humans, but also of higher animals. Thus, it is strongly related to the architecture of the nervous system and its evolution. However, language (and thus reading) seems to be unique for humans (Bierwisch, 1999; Chomsky, 1959) and related to a specific tendency towards the development of asymmetrical functions in the human cortex. As we outlined already, visual processes in reading (as well as the auditory processing in spoken language) are not identical to visual (or auditory) object recognition. The meaning of letters, words, sentences, numbers, punctuation marks, etc. is coded abstractly, and have no direct behavioral relevance. What we perceive within a text are symbols. Consequently, both the evolutionary and individual development of language, and thus of reading, imply symbolic representation (in addition to associative learning, Chomsky, 1959; see also Byrne, 1995; Deacon, 2000; Friederici & Lachmann, 2002; Klix, 1985; Lachmann, 2002). The processing of letters (or words) as visual icons requires the internal representation of rules which guarantee its desymbolization, and thus making the icon into a symbol. A Japanese character means nothing to a German, and thus is not a symbol to her/him, as long as she/he has not learned its correspondence to a certain sound or meaning. In other words, whereas symmetry generalization is beneficial to vision directly related to behavior, it may be detrimental for vision as part of a symbolic processing such as reading, especially if symmetrical counterparts of visual symbols are related to different sounds or meanings.

However, there is no separate visual system for reading. Generally, the evolutionary as well as the individual development is mostly characterized by a differentiation and specialization of pre-existing functions. Lachmann (2002) argued that a part of the visual differentiation required for reading is the suppression of

symmetry-generalized representations of visual icons in working memory as a precondition of an automated desymbolization process. The development of this visual differentiation has to take place in the early non-alphabetic phases of reading acquisition (before letters function as symbols: e.g., Ehri's, 1999, pre-alphabetic & partial alphabetic phase) and is accompanied by typical mistakes, including reversals, made by children learning to read. Therefore, not a dysfunction of the visual system, rather than an incomplete functional specification or its developmental delay hinders the fast desymbolization process (Lachmann, 2002). Consequently, reading as a process of coordination of parallel operating functions and fast integration of non-ambiguous information will be impaired. This explains not only reversals but also other errors reflecting a general deterioration of the coordination process.

Experimental research on letter reversals

Classical studies

The paper by Liberman, Shankweiler & Orlando (1971) may be deemed to as one of the most influential early studies which explicitly questioned Orton's theoretical approaches to reading disability (but see also Hildreth, 1934, as an example for earlier critique) and precluded a "phonological turnaround" (Lachmann, 2002). Liberman et al. investigated reversal errors in their numeral relation to other errors made by 54 second graders of normal intelligence when confronted with a printed word or letter. The question was whether poor readers, which were defined as the lower third in performing to read a word list (N=18) as measured by their total number of errors, show a different pattern of result and a different relation of errors as the remaining students which were counted as normal readers (good readers).

A 60-real-word monosyllables list was presented twice to each of the students. These items were either primer-level sight words, non-sight words or word forming reversals. The reading performance was analyzed separately for (1) kinetic reversals (e. g., *form* was read as *from*), (2) static reversals (e.g., b-d), (3) vowel errors (e.g., *trep* was read instead of *trap*) and (4) consonant errors (*pig* for *pik*). From the authors' point of view, in doing so, optic aspects can directly be compared with linguistic aspects in poor readers. Furthermore, a comparison between static and kinetic reversals may be enlightening, because Orton's theory of an abnormal cerebral dominance underlying the reading difficulty predicts equal occurrence or at least a systematic relationship between the two kinds of reversal errors. Additionally, the students had to match a single letters presented tachistoscopically to one of a set of five from which four were reversible. With the latter test only reversal errors were measured.

Liberman and colleagues found that almost all reversal errors were made by the group of poor readers. So far, the result is consistent with Orton. However, they found that reversals represent only a small proportion of the total number of errors made by the poor readers (25%). Almost half of the errors were made on vowel substitutions (43%), the rest of the errors were consonant omissions, additions and substitutions. That is, what Orton (1925, 1928) calls secondary symptoms occur to a much higher

degree than his cardinal symptoms, even when vowel or consonant constitutions were not counted as such when the misread letters were reversible.

An analysis of the individual results revealed a high degree of variance in the error rate within the poor readers group which was interpreted as evidence that reversals do not form a constant proportion of all errors in this group. Furthermore, there was no correlation at all between the two kinds of reversal errors, which was counted as direct evidence against Orton's theory.

Another classical study to be mentioned is that of Lyle and Goyen (1968). The authors tested whether reading disabled second and third graders perform worse than fluent readers on a task in which one out of 15 tachistoscopically presented simple line patterns, word-like line patterns, or isolated letters, respectively, had to be recognized within a sample of five choices presented either simultaneously, or with a delay. In a further condition the sample consisted of nine items, three of which, presented in sequence, were targets to be recognized in their correct order. The authors found disabled readers to perform worse than the averaged readers on all nine conditions. Interestingly, there was a significant Age (second versus third graders) x Group (disabled versus normal readers) interaction in five conditions, the only one of which that concerned letters was the sequential condition. In all of these five conditions the differences between both groups were 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 in their proportion to the total number of errors.

The authors analyzed static reversals (simultaneous and delayed condition), kinetic reversals (sequenced condition), and the remaining "miscellaneous" errors of the children, separately. None of the analyses, however, revealed significance. That is, for all types of material, shapes and letters, the proportion between reversal and other errors did not differ between the groups. Thus, the finding that disabled readers perform worse than averaged readers in all conditions but with no difference in the proportion of the errors was interpreted as the result of a generalized visual perceptual deficit. The fact that the group difference is greater in the younger children was interpreted as evidence for their developmental lag theory. In this, the authors dissent strictly from 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, the reason for the poorer performance is assumed to be due to problems in the speed of visual decoding, that is independent from phonological information possibly inherent to the stimulus. On the other hand, the results of a reading test applied by the authors show indeed a higher number of reversals in disabled readers and a higher proportion of reversals in relation to the total error rate. Lyle & Goyen suggested problems in verbal labeling as one of the reasons for these phenomena. This, however, does not separate them from Orton (1925); what does is the underlying mechanism assumed to produce these problems. Lyle & Goyen argue that the speed of perceptual encoding may also be a reason for problems in labeling, since it reduces the load of visual information in a given time unit.

In summary, the results endorse the importance of reversal errors in reading disability. After functional fragmentation, however, it was shown that a confusion on rotated or mirrored shapes or letters does not occur in a higher proportion in disabled readers.

Studies in the last decades

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 differences between the two groups in all conditions. Disabled readers needed longer exposure times to name the letters correctly. However, there was no interaction found between the group and the letter sets. In detail, all participants needed longer exposure time to name reversible letters, the proportion between reversible letters and nonreversible 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 his 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 ability of disabled readers to identify disoriented letters was investigated in the study of Corballis, Macadie, Crotty and Beale (1985). The children were timed as they named disoriented letters in the left or the right visual field. The letters were "F", "G" and "R", in upper-case and were normal in half of the trials and backwards in the other trials. The children were aged from 11 to 13 years. Half of them were disabled readers according to the discrepancy definition. At first, the authors wanted to find out whether normal letters would be named more rapidly than backward ones. Previous studies (Corballis, Zbrodoff, Shetzer & Butler, 1978; White, 1980) showed that adults categorize and identify normal oriented characters faster than backward ones. A further point of interest, more related to Orton's (1925) concept of strephosymbolia, was to test for interhemispheric differences in the relative times to name normal over backward letters. According to Orton, both hemispheres initially store information and problems in reading and writing are attributable to an inadequate cerebral dominance (or a failure in establishing cerebral dominance). Therefore, Corballis and his colleagues (1985) hypothesized that interhemispheric effects should be diminished or even absent in disabled readers. Bradshaw, Bradley and Patterson (1976) did indeed find evidence for an interhemispheric difference in the relative dominance of normal and reversed representations within the context of the lowercase letters "e", "h", "k", "r" and their symmetrical counterparts. Right-handed participants showed a right visual-field advantage in RT to discriminate normally

oriented letters and nearly all of these (27 of 32) either a reversal or a reduction of this effect when mirror-image letters were presented. The remaining participants indicated a left visual-field advantage for normal letters and a reversal of this effect when mirror-image letters were displayed (13/16). However, the overall interaction between visual fields and left-right orientations was not significant. The results of Corballis, Macadie, Crotty and Beale (1985) indicate no differences on individual error rates and RT between reading-disabled children and normal readers. The only point of difference was a significant interaction between the group and letter variable, that is, disabled readers responded most slowly in naming the letter "G". Moreover, the effect of normal over backward letters was clearly significant (RT to normal letters=797 ms, RT to backward ones=908 ms). The interaction between visual field and letter orientation failed to reach significance. Corballis et al. (1985) concluded that such a pattern of results does not support the fact that reading-disabled children show an abnormally high degree of left-right equivalence, as proposed by Orton's (1925) original theory.

An investigation more related to the theoretical assumptions of the FCD model about the cause of reversal errors, that is, a failure in integrating visual and phonological information, comes from Hicks (1981). She investigated 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, e.g. left/right confusion), and dyslexic readers (that is, disabled readers according to the discrepancy definition showing typical dyslexia errors, e.g. left/right confusion or neurological defects). All groups, except that of beginning readers, were matched by age and intelligence. All groups, except that of normal readers were matched by intelligence and literacy level. All participants had to perform what the author called a search task. A target had to be identified within a list of lines containing ten reversible (b, p, q, d) and nonreversible (g, h, k, l, t, y) letters each. The target and the list were either presented visually or auditory, respectively. 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 less 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 the same. All together the results indicate two major conclusions. Firstly, normal reading children perform better than all of the non fluent reading children. Secondly, 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, Yarbrough & Thursby (2000). The authors investigated the rate of static and kinetic reversals in 201 children in a four year longitudinal study from kindergarten to grade three. 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 analyzed the data of the fourth year of this longitudinal study (that is, when children are in grade three) kinetic reversals proved to be an excellent predictor for the performance in a reading test. Unfortunately, no interpretation of this effect was given.

A last study to be reviewed here is that of Lachmann, Brendler & Geyer (in preparation, cf., Brendler & Lachmann, 2001). Normal and disabled readers were tested on their performance in responding to mirror-oriented stimuli within a *same-different* task procedure. Within the FCD model (Lachmann, 2002) the authors assume that those reading disabled children who make more reversal errors, as measured by a reading test (Zuercher Lesetest, Grisseemann, 2000), have problems in coordinating the visual and phonological subfunction. The resulting failure in binding visual and phonological information is assumed to be due to an abnormal tendency of symmetry generalization in the representation of visual symbols such as letters.

The authors tested 66 undergraduate students from Grade 3 and 4, half of which were diagnosed as dyslexics according to the discrepancy definition, and the others served as controls. In a blocked design, the authors used lexical versus nonlexical material and a physical versus a categorical instruction. The lexical material consisted of the letters 'b, e, f, h, n, r'. As nonlexical material 5-dot patterns were used (constructed on a 3x3 grid, leaving no row or column empty, cf., Garner & Clement, 1963). Pairs of letters and pairs of patterns were shown consecutively, that is, an item in memory had to be compared with an item shown on the screen. 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.

In the *'physical condition'* the children had to respond to two items as to *same* only when they were physically identical, that is, same in shape and orientation. Items of different orientation had to be judged as *different* just as those items which differ in shape. In contrast, in the *'categorical condition'* the children were instructed to ignore orientation. Items same in shape but different in orientation had to be responded as to *same*.

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 two letters in different orientation were shown. 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 (e.g. reading 'b' instead of 'd'). However, most important with respect to the FCD model is that the authors found a significant correlation between the errors observed in the experiment and the reversal errors in the reading test. In other words, those children which had more problems in

discriminating orientationally related letters or patterns showed more reversal errors in text reading. This was 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 question remains of whether reading disabled children have generally a greater tendency of symmetry generalization and therefore 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. The fact that the difference between normal and disabled readers was found for lexical and for non-lexical material, but that the difference is greater in letter than in pattern comparison suggests that there are again subgroups.

About the heterogeneity of empirical findings

On the basis of the studies reviewed so far, the question about the role of reversal errors for explaining the nature of reading disability cannot clearly be answered. 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. Some most important differences in the methodological approach may now shortly be outlined.

Some studies on reversal errors investigate the relation between reading and the processing of reversible visual shapes (Goins, 1958; Lyle & Goyen, 1968). Using nonverbal material, however, may test hypotheses of certain deficits in the visual subfunction as to be responsible for the problems in learning to read. 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, 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) analyzed 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, Mark, Bruck, Fornarolo & Backman, 1985), and in others in the context of nonwords (Seidenberg et al., 1985), which may affect subgroups of disabled readers quite differently (e.g., Boder, 1971, 1973). The involved cognitive functions in both conditions, however, may differ from those functions involved when isolated letters are presented (Brendler & Lachmann, 2001; Liberman et al., 1971; Corballis et al., 1985).

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 and followed by a mask (Grosser & 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 also be considered. 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 (e.g., mental rotation), or not, and the decision may be based on the same, or a higher (categorical) level of processing (e.g., Bigsby, 1985; cf., Posner & Mitchel, 1963). Furthermore, the modality of the input and the response may differ, verbal material may be presented visually or auditively and the response may be visual or auditive as well (Hicks, 1981; Lachmann & Fuchs, in preparation).

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 problem are generally unlikely to be present in disabled readers (e.g., Vellutino & Scanlon, 1998).

A further problem in comparing studies on reversal errors is the definition of reversals. Some experimenters only consider static reversals (Brendler & Lachmann, 2001; Lachmann & Fuchs, in preparation), while some are especially interested in testing the relation between static and kinetic reversals (Lieberman, 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 & 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 & Trzeciak (1981), for instance, define "u" as a nonreversible 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.

We argued that functional fragmentation is the principle of experimental reading disability research, that is, the experimenter is testing certain subfunctions 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 the selection of subfunctions to be tested, but also the definition of the reading disability group is crucial. We already introduced the discrepancy definition of reading disability, and we mentioned that there is a critical discussion about this definition. Consequently, not all experimenters use this definition (e.g., Liberman, et al., 1971) and those who are using it are not uniform about the criteria 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*, *strophosymbolics* 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 & Goyen (1968), for instance, used the term *reading retarded children*, just as Hicks (1981) did, but in contrast to her, Lyle & Goyen defined retarded readers as showing a reading retardation of nine month in grade 2 and 18 month in grade 3. In Corballis, Macadie, Crotty and Beale (1985), 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 & Goyen define an IQ value of at least 90 to meet the criterion, most authors just display the average of the samples, and in Grosser & Trzeciak we learn nothing about the IQ of the students at all. Not only the discrepancy definition, but also the age of the children the sample consists of may differ between studies. Whereas the children in Corballis, Macadie & Beale (1986) were 12 years old, Patton et al. (2000), Lachmann et al. (in preparation), and Lyle & Goyen (1968) asked younger children (grade 1-3) to participate in their experiments. The participants in the experiments of Grosser & Trzeciak (1981) were aged are between 7 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 & 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 & Lachmann (2001; Lachmann et al., in preparation). In the German Federal State of Saxony, for instance, a diagnostic procedure takes place in grade 2 and those who will be diagnosed as dyslexics will attend the grade 3 in two years instead of one in order to have the chance for an extensive training in reading and writing. In our view, this seem like an excellent solution to the problem which in fact shows a high success rate in overcoming the reading problems in many dyslexics. However, 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, when testing children which attended already the 2-year dyslexia training, they may show more similar performance than normals in reading, including reversal errors, while the underlying deficit may still exist.

Reinterpretation of old findings

With the background of the arguments outlined in 3.3, the classical study of Liberman et al. (1971) will be revisited. Liberman et al. (1971), tested whether those students who make more errors when reading a word list (not dyslexics) have a higher proportion of reversal errors, and if so, whether in these students, that is, the lower third of performance in the word list test, the proportion of errors is constant. The null-finding in this respect was interpreted as evidence against Orton (1925). However, Orton defined the group of reading disabled children according to what we would call today the discrepancy definition and not as a part of the normal distribution in reading performance of the total population. This is important, because according to Orton, reversal errors are the cardinal symptom of strephosymbolia (dyslexia). The rate of reversal errors is assumed to be a measure for the degree of this developmental disorder but it is not assumed to reflect the reading performance in the normal population. Thus, the results of Liberman et al. is not sufficient to decide about Orton's hypothesis; in fact, it is not sure that even a single strephosymbolic child (or dyslexic child) was in the sample of poor readers in their study at all.

Furthermore, the study of Liberman et al. (1971) was very often cited and over-generalized not only as evidence for the importance of linguistic aspects, which may be entitled, but also as evidence against the significance of reversal errors in general. In fact, the study even certifies the importance of reversal errors, and some poor readers were indeed identified who reversed to an extensive degree.

Some of the shortcomings of the Liberman et al. study were corrected in the follow-up study by Fisher, Liberman & Shankweiler (1978). There, the performance of the poor reading students described in Liberman et al. was compared to that of dyslexic children, as defined by a reading retardation of at least 18 months despite same age, educational background, and normal intelligence. The authors could show that, whereas both groups performed almost equally in the reading test, the dyslexic group made significantly more errors in the word list. These errors were made in relatively the same proportion as by the poor readers (emphasizing the importance of linguistic aspects for the error rate). However, in contrast to the poor readers, dyslexic children performed more consistently in their reversal errors and kinetic and static reversal error were significantly correlated.

Summary and conclusions

In summary, all studies reviewed here tested quite different samples of disabled readers, used different material and methods, and tested different functions, and may therefore not be compared without restriction. It was argued that testing a single function (functional fragmentation) may not necessarily be meaningful in order to conclude on a complex multi-functional process such as reading.

Within the multicausal FCD model, reversal errors are assumed to be one possible symptom of a deficit in the coordination of visual and phonological decoding in a subgroup of reading disabled children. It was argued that in order to learn to read it is important to treat graphemes as symbols instead of objects. In visual object recognition symmetrically related objects are learned to be represented by similar patterns of neural activity. However, this process of symmetry-generalization is a hindrance in reading. A failure in suppression of visually symmetrical information in the representation of visual symbols produces ambiguous relations between visual and phonological information in memory and disturbs the functional coordination. This may cause problems in learning to read.

However, it is important to note again that within the FCD model reversals do not reflect a visual deficit or an incomplete hemispheric dominance, and that they are not assumed to be the one and only symptom of dyslexia.

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