Perception, 2009, volume 38, pages 1019 – 1034

doi:10.1068/p6313

Controlled but independent: Effects of mental rotation and developmental dyslexia in dual-task settings

Thomas Lachmann¶, Bettina Schumacher
Department of Psychology II, Faculty of Social Sciences, University of Kaiserslautern, E Schrödinger Strasse 57, 67663 Kaiserslautern, Germany (¶ also Laboratory for Perceptual Dynamics, Brain Science Institute RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan); e-mail: lachmann@rhrk.uni-kl.de

Cees van Leeuwen
Laboratory for Perceptual Dynamics, Brain Science Institute RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan

Received 21 October 2008, in revised form 7 January 2009; published online 18 June 2009

Abstract. In two experiments, we compared the performance of normal-reading ($n = 26$) and dyslexic children ($n = 22$) in discriminating letters from their mirrored images. In experiment 1, they were always presented in the upright orientation; in experiment 2, they were presented in different angular orientations (0°, 90°, 180°). In order to determine whether task and dyslexia affect reaction times in early or late stages of processing, a dual-task paradigm was adopted in which the primary task was tone discrimination. Stimulus onset asynchrony (SOA) between first and second task was systematically varied (50 ms versus 400 ms). In both experiments dyslexics were slower overall than controls. No effects of mirror-image letters were found. In experiment 2, mental-rotation effects were additive with SOA. In accordance with earlier findings we concluded that the mental-rotation effect involves central processing capacity. Mental-rotation effects were the same for normal-reading and dyslexic children; mental rotation is not impaired in dyslexia. Remarkably, SOA effects were larger in normal readers than in dyslexics. This result was explained by observing that dyslexics experience decision difficulties already on the first task. As a result, they do not benefit optimally from increased latencies between first and second tasks.

1 Developmental dyslexia

The present study combines two popular paradigms in the field of human perception and performance—mental rotation and dual tasking—in an effort to understand the deficits underlying developmental dyslexia. Developmental dyslexia has been documented in 5% – 13% of school-age children (American Psychiatric Association 1994). These figures differ considerably between countries and even regions (Shaywitz et al 1990; Schulte-Körne 2001; see Miles 1995 for a discussion). One reason for this variation may be the behavioural definition of the syndrome, a result of lacking consensus about its etiological basis. Several authors point to poor phonological skills as the main factor in developmental dyslexia (Brady and Shankweiler 1991; Rack and Olson 1993; Snowling 2001; Vellutino et al 2004; Steinbrink and Klatte 2008). Others believe that visual-information-processing deficits play an important role as well (Lovegrove et al 1980; Willows and Terepocki 1993; Slaghuis and Ryan 1999; Skottun 2001; Stein 2001; Stein et al 2001; Badian 2005; Becker et al 2005; Stanley and Hall 2005).

We believe that dyslexia is neither an exclusively phonological nor a visual deficiency but is based on deficient functional coordination between visual and auditory/phonological encodings (functional coordination deficit—FCD model, Lachmann 2002; Lachmann and van Leeuwen 2007a). The coordination deficit could arise at the cognitive level (Frith 2001), but may also result from various underlying deficits at the biological level. Different constellations of underlying causes may thus ultimately lead to a variety of partially overlapping, partially distinct effects at the behavioural level, ie various clusters of reading deficits (Lachmann 2002). This study concentrates on one of these symptoms in an effort to determine its possible causes.

A particularly prominent symptom of dyslexia is known as reversal errors, a tendency to reverse the order of letters within a word (eg was versus saw) and the orientation of single letters (eg b versus d). We recently proposed to explain these errors as a case of a disrupted visual – phonological coordination due to a suboptimal grapheme representation. This view was inspired by the pioneering research of Samuel Orton (1928), which nowadays is often misunderstood as a visual-deficit theory, and its more recent neurological interpretation (Corballis and Beale 1993). Our approach is based on the notion that normal visual processing is characterised by symmetry generalisation. Visual information processing, according to this view, involves a tendency to spontaneously generate mirror images, as well as other transformations of visual patterns, and to store them jointly with their original (Garner and Clement 1963). In many situations, symmetry generalisation facilitates perception of an object as identical under different orientations (Lachmann and Geissler 2002; Lachmann and van Leeuwen 2005). Thus, observers typically find it difficult to discriminate between mirror-image stimuli (Corballis and Beale 1970; Rentschler and Jüttner 2007).

When learning to read, symmetry generalisation is a hindrance. The well-known 'b'/'d' type of reversal errors is particularly illustrative, but the problem extends, for instance, to frequently occurring confusions of letter clusters. Early reading involves converting graphemes into phonemes on a one-to-one basis. Symmetry generalisation renders ambiguous the relationship between visual and phonological code, because it produces multiple visual representations, which compete for grapheme – phoneme binding. We, therefore, believe that suppression of symmetry generalisation with letters is part of learning to read.

While normal-reading adults have learned to suppress symmetry generalisation with letters, failure to do so may be a factor leading to developmental dyslexia. To determine whether dyslexics fail to suppress symmetry for linguistic materials, Lachmann and van Leeuwen (2007a) used a same – different task, in which two items differing only in rotation or reflection were to be judged as same. In this task, failure to suppress symmetry actually constitutes an advantage. Pairs of letters or dot-patterns were used, which were either symmetric or asymmetric in shape. Dyslexics performed faster in this task than normal-reading children, in particular, remarkably, with letters. This superior performance of dyslexics is due to their failure to differentiate between the visual processing of linguistic and nonlinguistic materials; they perform symmetry generalisation, not only with shapes but also with graphemes. Symmetry of dot-patterns facilitated performance in both dyslexics and normal-reading children; symmetry of letters facilitated performance in dyslexics but not in normal-reading children.

1.1 *Mental rotation and reading performance*

We will now consider the relationship between reading performance and mental rotation. Mental rotation tasks (Shepard and Metzler 1971; Cooper and Shepard 1973) involve visuo-spatial processing as well as matching a transformed image. In the classical paradigm by Cooper and Shepard (1973) participants report whether a letter, presented under a certain angle of rotation, is either normal or a mirror image. Reaction times typically increase linearly with rotation angle for adults (eg Heil et al 1999) and children (eg Jansen-Osmann and Heil 2007).

Regarding dyslexia, mental rotation tasks offer an opportunity to test predictions of the FCD hypothesis against those of the cerebellar-deficit hypothesis. The cerebellar-deficit hypothesis (Nicolson and Fawcett 1994; Fawcett and Nicolson 2001) associates dyslexia with deficits in automatisation and articulatory skill characteristic of cerebellar disfunction. The cerebellum has been found to be activated during mental rotation because of its role in motor functions and motor imagery (Calhoun et al 2001; see Jaskowski and Rusiak 2005 for a review). Given the involvement of the cerebellum in mental-rotation tasks, cerebellar dysfunction in dyslexic readers is likely to lead to impairment in the mental-rotation task. The cerebellar-deficit hypothesis, therefore, should lead us to expect a reduced mental-rotation rate in dyslexics as compared to normal readers. Such a deficit is expected to be present for different kinds of stimulus material (Jordan et al 2001); in particular, it is expected to be present in dyslexics for both letters and non-letter shapes.

According to the FCD hypothesis, the problems for dyslexics when reading result from their inability to achieve an unambiguous mapping between graphemic and phonemic representations. Thus, concerning the mental-rotation task, according to the FCD approach, dyslexics should have no problem in mental rotation but rather with ultimately deciding whether a letter is 'normal' or 'mirrored'. This means that a group difference between dyslexics and normal readers arises in a stage of processing after mental rotation. Moreover, the problem should be specific to graphemic material.

In Corballis et al (1985b), 12-year-old dyslexics and normal readers had to name letters that were presented in the left or right visual field. The letters were either normal letters or their mirror images over the vertical axis. These were presented at different angles of rotation. Corballis et al (1985b) found no differences in mean error rates and response times between the groups, no mental-rotation effect, and a preference for normal letters over mirror images (mirror effect) in both groups.

The absence of a mental-rotation effect, the mirror effect, and the absence of differences between normal readers and dyslexics could all be explained in terms of the FCD approach to dyslexia. Naming the letter does not require mental rotation but could be performed by using symmetry generalisation instead. Mirror effects could be the result of mapping familiar versus unfamiliar graphemic configurations to symmetry-invariant representations. According to Lachmann and van Leeuwen (2007a), dyslexics are not disadvantaged in this task, and may even show an advantage owing to their failure to suppress symmetry generalisation in letters. Interestingly, Corballis et al (1985b) found advantages for dyslexics in some letters, even amounting to 37 ms for the letter 'R'.

In a follow-up experiment, Corballis et al (1985a) measured naming speed in dyslexics and normal readers for the letters 'b' versus 'd' presented in the normal upright position (identification task) or rotated in various angular orientations from 0° to 360° (mental-rotation task). In both tasks, dyslexics tended to be slower than normal readers, but the difference did not prove to be significant. For the mental-rotation task, mental-rotation effects were obtained both for normal readers and dyslexics, and no difference in mental-rotation rate was obtained between the groups. Normal readers showed an advantage for upright letters presented in the right hemifield. It was concluded that dyslexics are lacking in hemispheric specialisation. Recent research (Marsolek and Burgund 2008) suggests how this conclusion could be specified in accordance with FCD. These authors demonstrated that visual representations differ between both hemispheres. While representations in the left hemisphere are more abstract (eg rotation-independent), those in the right hemisphere are more detailed and specific. For dyslexics, however, failure to suppress symmetry generalisation may imply that these representations are less orientation-specific than for normal readers.

Rusiak et al (2007) extended the studies by Corballis et al (1985a, 1985b) investigating spatial processing in dyslexics by comparing mental rotation of letters (symbols) and shapes (objects) in dyslexics and normal readers. In a first experiment they used the paradigm by Cooper and Shepard (1973) and displayed isolated letters at different angles of rotation. The task was to decide whether the letter shown was normal or mirrored. The rate of mental rotation was found to be equal in both groups; dyslexics, however, were considerably slower overall. According to FCD this group difference should be restricted to letters. In order to test this hypothesis, in their second experiment Rusiak et al (2007) compared letters and non-letter stimuli in a successive same – different task. In this task one item is presented and has to be kept in memory after it has disappeared. A second item is presented after an interstimulus interval and has to be compared with the one shown earlier. Participants judged the sameness of either two letters or two shapes, irrespective of their angular orientation. This task resulted in a clear mental-rotation effect. Again, no differences in mental-rotation rate were found between controls and dyslexics in either the letter or the shape condition. Importantly, the effect was material-specific: the general delay in response was found in dyslexics only for letters. Both the independence of mental-rotation effects and group, as well as the material-dependence of the group effect favour the FCD hypothesis over the cerebellar-deficit hypothesis.

We might therefore consider the case against the cerebellar-deficit hypothesis closed. On the other hand, Rüsseler et al (2005) observed increased error rates in mental-rotation tests without time pressure in dyslexic children as compared to controls, for letters as well as for pictures and three-dimensional figures. The authors interpreted their results in favour of the cerebellar-deficit hypothesis. Moreover, Rusiak et al merely showed that slower response rates in dyslexics, as compared to normal readers, are independent of mental-rotation rate; they failed to identify them as belonging to controlled or automatic processing. Both the cerebellar-deficit hypothesis and the FCD hypothesis expect this effect to be due to enhanced controlled-processing load: in compensation for automatisation deficits according to the cerebellar hypothesis; because of a decision problem according to FCD model. In order to diagnose whether these effects belong to controlled, central, stages of processing, the present study included mental rotation in a dual-task paradigm.

1.2 *The psychological refractory period*

The dual-task paradigm can be used to determine whether an effect arises early (automatic, peripheral) versus late (controlled, central) in processing, on the basis of the logic of psychological refractoriness (Pashler 1984, 1994). In a dual-task paradigm, when two tasks are performed in rapid succession, performance is usually worse than when they are performed independently (Telford 1931; Welford 1952). Performance is degraded most when the stimulus onset asynchrony (SOA) between the first and second task is minimal. This result was attributed to a psychological refractory period in a central information processing bottleneck (Welford 1952; Pashler 1984; Pashler and Johnston 1989). The psychological-refractory period effect (PRP) is studied in a dual-task paradigm by systematically varying the lag in the onset of the stimuli (SOA) belonging to first and second task (see figure 1). This is done in combination with different levels of second-task difficulty (eg Schubert 1999; Schwarz and Ischebeck 2001; Lachmann and van Leeuwen 2007b). Instructions encourage participants to give full priority to the first task. This task involves a decision process (eg a choice-response task), but should otherwise be kept simple. Binary classification of tones is typically used (Pashler 1994). The decision process in the first task will occupy the central bottleneck, which means that processes of the second task that involve the central bottleneck will also be delayed until the bottleneck is cleared. With decreasing SOA this will result in increases in reaction time (RT) in the second task (see figure 1 for illustration). These increases, however, will be the same for all processes that involve the central bottleneck or occur after this stage. Thus, SOA-related variation in RT will be independent of these late processes. In a factorial design, this means that SOA and all factors affecting late processing components will have additive effects on RT of the second task. The decrease in SOA should be approximately equal to the increase in RT.

By contrast, processes prior to the central-bottleneck stage of the second task may overlap with the bottleneck stage of the first task. With decreasing SOA, these processes will increasingly be buried in the overlap. As a result, in a factorial design we should

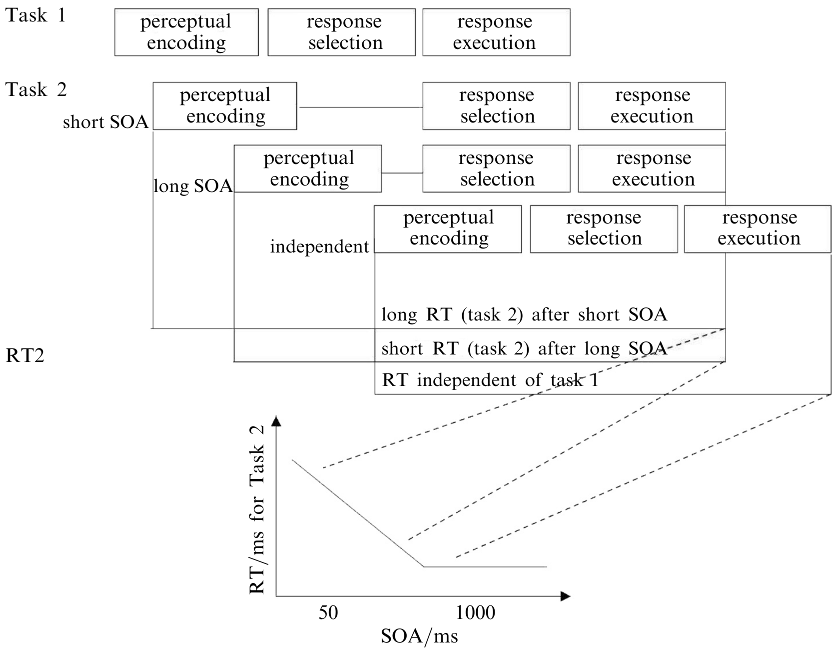

Figure 1. The structural-bottleneck model used to explain the PRP effect in dual-task settings (Pashler 1984). Response selection in task 1, because of its central processing character, cannot be performed simultaneously with that of task 2. When SOA between task 1 (first row) and task 2 (second row) is small, the decision stage of task 2 has to wait for completion of that of task 1; reaction times of the second task (RT2) are therefore at a maximum (lower half of the figure). With increasing SOA (third row), the waiting time is reduced, resulting in a decrease in RT for task 2. With further increase in SOA (fourth row), the tasks become independent and no further decrease in RT2 occurs.

observe a sub-additive interaction with decreasing SOA and factors of task difficulty affecting early processes. The presence or absence of an interaction with decreasing SOA can be used to determine whether an effect arises in an early or late stage of processing.

With respect to the central bottleneck, the debate is still on whether limited capacity resources are allocated to either task in an all-or-none fashion, as assumed in the structural model (Welford 1952; Pashler 1984, 1989), or whether capacity sharing between tasks is allowed (Navon and Miller 2002; Tombu and Jolicoeur 2002). According to the first model, we should expect no influence of second task variables or the SOA between first and second task on the response to the first task. If resources are shared in a graded fashion between tasks, however, we may expect such effects. Complex processing requirements for the second task and/or short SOA could then increase the RTs of the first task as well.

2 Experiments

We tested the difference between normal-reading and dyslexic children in a mental-rotation task, and whether this difference occurs in an early, automatic, or in a late controlled, decision stage of processing. According to the dual-task paradigm, an effect of second-task difficulty that is additive with decreasing SOA belongs to a late, controlled, stage of processing. If, therefore, a task is easy for one group and difficult for another, such that it leads to a group effect on RT, this effect should be additive with decreasing SOA if the difficulty of the task arises in a late stage of processing. This constitutes our first hypothesis according to FCD.

However, applying the dual-task paradigm in this way is tricky. Usually in the dual-task paradigm, a task difficulty variable for the second task is chosen so that it affects processing of the second task alone. This cannot be guaranteed for group differences. It is possible that the group that finds the second task more difficult than the other group also has more difficulties with the first task. In this case we may expect a group difference also on the first task, leading to a delay in the start of central processing in the second task. Thus, we will observe a positive correlation between RT of the first and second task. Paradoxically, if this is the case, we might even find an interaction of the group effect with decreasing SOA, even though the group effect belongs to a late stage of processing. This is because the benefit of larger SOAs diminishes if the first task is more difficult. Such a correlation, in combination with an under-additive interaction of SOA and group, constitutes our second, alternative, hypothesis in accordance with FCD.

The second task in experiment 1 requires only a decision about the orientation of a letter, normal versus mirrored. The second task of experiment 2 is a mental-rotation task. The third hypothesis in this study is that the mental-rotation effect occurs late, ie after the central-processing bottleneck. Ruthruff et al (1995) used a mental-rotation task within a dual-task setting. They obtained additive effects of rotation and SOA on RT and concluded that mental rotation requires central capacity. Van Selst and Jolicoeur (1994), in contrast, found an interaction (even though only at 10% significance level) between mental rotation and SOA and concluded that at least parts of the mental-rotation process occur prior to the bottleneck. The FCD approach, as such, is not committed to either hypothesis. However, it is hypothesised that visuo-spatial processes should not differentiate normal-reading children from dyslexics; for both groups the location of mental-rotation processes with respect to the bottleneck should be the same. We will test this hypothesis in experiment 2.

If our results confirm that the mental-rotation effect and the difference between normal readers and dyslexics in the mental-rotation task both belong to the controlled stage of processing, a condition is fulfilled for testing between the FCD and the cerebellar-deficit hypotheses. The first predicts both effects to be independent, as dyslexics have no specific difficulties in mental rotation (fourth hypothesis). The second predicts super-additive interaction, because dyslexics will increasingly require additional resources, the larger the angle of rotation (fifth hypothesis).

3 Experiment 1

3.1 *Method*

3.1.1 *Participants.* A total of forty-eight children participated in this study; twenty-two children diagnosed with developmental dyslexia (seven female) and twenty-six normally reading children (seventeen female). The children were recruited from three primary schools in Leipzig. All had normal or corrected-to-normal vision and normal hearing. There were no significant differences between the groups in age, grade, or non-verbal intelligence (see table 1). Each child received a 5 euro gift coupon for a toy store and small give-aways for participation. The children, their parents, and teachers and the federal office of education gave their agreement to this study.

In accordance with Saxony state law, every schoolchild is given a screening test for developmental dyslexia in Grade 2 (at an average age of 7.5 years). Children who score positive on the screening undergo a week of intensive testing by a team consisting of one educational psychologist, two specialist teachers for dyslexic children, and one specialist for language disorders. This examination uses a test battery (Weigt 1980), which includes reading and spelling tests for both contextualised and isolated letters and words, phoneme segmentation, visual recognition, phonological and visual differentiation (Breuer and Weuffen 1995), as well as a number of test lessons.

Table 1. Test scores and ages for normal-reading children and developmental dyslexics.

Variable	Normal-reading children, *M*(SD)	Developmental dyslexics, *M*(SD)
Number of participants	26	22
Age	115.2 (7)	115.3 (6.4) ns
IQ	106.9 (13.4)	95.8 (16.9) ns
FWR time/s	17.3 (3.9)	66.4 (39.1)*
NWR time/s	41.3 (10.1)	109.9 (51.9)*

Note. IQ, average of individual intelligence quotients according to German norms of the Standard Progressive Matrices Test; FWR time, reading time for the frequent word reading test of the Salzburger Lese- und Rechtschreibtest (SLRT; Landerl et al 1997); NWR time, reading time for the non-word reading test of the SLRT (Landerl et al 1997). * Significant difference between the groups (see text).

Furthermore, physical development and sensory functioning are tested by an ophthalmologist and an otolaryngologist.

Children diagnosed as dyslexic are brought together from different schools within a district, to join a special 2-year training program, such as is offered by the current schools. During this period, children in this program follow the normal Grade 3 curriculum, which is spread over a period of 2 years in order for specialised teachers to provide training in basic reading and writing skills. After completion of the training program, the children return to their original school to join Grade 4.

All participating children had thus previously been screened for dyslexia; dyslexic participants from the special training program had in addition gone through the extensive diagnosis procedure. We tested all children again five to ten days before the experiment. This was done in order to validate the previously given diagnosis. To this purpose we administered three pre-tests, Raven's Standard Progressive Matrices test in German (Heller et al 1998), and two subtests of the reading test Salzburger Lese- und Rechtschreibtest (SLRT—Landerl et al 1997), one of these for testing the ability to read frequently used words (FWR) and the other for testing non-word reading (NWR), both by means of reading times. In transparent languages like German, reading times discriminate better between groups than error rates (cf Landerl and Wimmer 2000; Landerl et al 1997).

Based on the Raven test, one candidate boy in the control group failed the criterion of normal intelligence ($IQ < 70$) and was therefore excluded from the study. All other children were at a normal intelligence level (see table 1).

The FWR and NWR scores of each child were compared to the reference population for a grade level. To enter the normal-reading group, a child had to perform within the norms of her or his reference population in both tasks (percentage rank > 16; within 1 SD of the population average); six normal readers failed this criterion for the non-word reading test and were, therefore, excluded from participation. To qualify as dyslexic, performance had to be below 2 SD (percentage rank < 3) of the population average in at least one of these tests. Eight children previously diagnosed as dyslexics were excluded from participation because they showed normal performance in both tasks (within 1 SD from the reference population mean).

3.1.2 *Stimuli.* For the primary task, tones were presented for 33 ms at either 900 Hz (high) or 300 Hz (low) through standard PC speakers. For the secondary task, the letters F, R, g, and their mirror images were visually presented in grey against a black background. Letters were composed of straight line segments drawn on an approximately 5 deg (horizontally) by 6.5 deg (vertically) grid displayed on a 14-inch standard PC monitor. Participants' heads were not fixated.

3.1.3 *Procedure.* Participants were seated comfortably at a 60 cm distance from the monitor in a sound-attenuated and darkened room. They were instructed to rest their hands on a panel 50 cm long, which contained four response keys, two on the left-hand side and two on the right-hand side. Each key was a 7.5 cm × 7.5 cm standard push-button, labelled with the words "high" and "low" on the left-hand side for the tone discrimination, and "normal" and "mirrored" on the right-hand side for the letter discrimination.

The experiment started with a training session for the auditory-discrimination task, consisting of 25 trials. Participants were instructed to respond as fast as possible whether a tone was high or low by pressing the corresponding key with their left hand. Subsequently they were trained for 30 trials on the letter task. In each trial a fixation cross appeared for 300 ms before the presentation of a letter in the centre of the screen. Participants were instructed to respond as fast as possible whether the letter was normal or mirrored by pressing the corresponding key with the right hand. The response alternatives of both tasks were counterbalanced.

Speed and accuracy feedbacks were given during both training sessions. After a correct trial, the response time in ms was briefly presented in green; after an incorrect response, the time was given in red. Feedback in the auditory task was given in the lower left corner of the screen; in the visual task in the lower right corner of the screen.

After training, the test session started with instruction specific to the dual-tasks setting. Participants were told to respond to the tone first and then to the letter. Although both tasks were important, focus should be on responding as fast as possible to the tone. At the beginning of a dual-task trial, a fixation cross was shown for 300 ms in the centre of the screen, followed by a tone. The visual stimulus was presented with either a short (50 ms) or long (400 ms) SOA to the tone. Visual stimuli were shown until the response occurred. As in the training session, after each trial a speed and accuracy feedback for both tasks was given in the lower corners of the screen. In addition to this, the following text appeared on the screen: "Please respond faster to the tone!" (in German), whenever the participant failed to respond to the tone within 1500 ms. Finally, if the average of the response times of the first 16 trials was above 1500 ms, the program was interrupted briefly and a full-screen text appeared (in German): "Please try to be a bit faster! Average response time to the tone: [eg 1692] ms". When, however, a response to a tone was given faster than 145 ms, the sentence: "Please do not guess the tone!" appeared (in German). The next trial started 2 s later.

A total of six blocks consisting of 24 trials each was presented, in which equal numbers of long and short SOA trials were randomly intermixed. All stimulus alternatives occurred with equal frequency. Halfway through and at the end of each block participants were offered an optional short break. After each block they received feedback on their within-block average response times and percentages correct on both tasks.

3.2 *Results*

RTs of the first and second task were positively correlated, $r = 0.419$, $p < 0.01$, and so were error rates ($r = 0.594$, $p < 0.01$). In neither of the tasks, however, was there a correlation between RT and error rates ($r = 0.200$, ns, and $r = -0.119$, ns, respectively, for the first and the second task). This suggests that there was no speed–accuracy trade-off, neither within, nor between, tasks. We therefore report ANOVA results only for the RTs.

3.2.1 *Task 1 (auditory classification).* A total of 6912 responses were registered. Responses with RTs under 145 ms and over individual 5 SD in one or both of the tasks were excluded as outliers (1.7% for task 1; 3.9% for task 2). For RT analyses, data were used only when responses to both tasks were correct. The overall mean RT was 1186 ms (SD = 697 ms), the mean error rate was 16.8%. No speed–accuracy trade-off was evident:

individual RTs and error rates were not correlated ($p > 0.1$). An ANOVA on RTs was run. Here and later, the Greenhouse – Geisser correction was used to evaluate the level of significance; whereas F-values remained unchanged.

An ANOVA of RTs with factor group (dyslexia versus control) as between-subjects factor, and SOA (long versus short) and mirror (straight versus mirrored of the second, visual, pattern) as within-subjects factors revealed a main effect of group ($F_{1,46} = 10.80$, $p < 0.01$), with 1402 ms (SD = 825 ms) for dyslexics and 1055 ms (SD = 567 ms) for normal readers. An interaction between SOA and group was found ($F_{1,46} = 5.78$, $p < 0.05$). This interaction was due to a smaller SOA effect in normal readers (SOA = 50 ms: 1062 ms; SOA = 400 ms: 1048 ms) as compared to dyslexics (SOA = 50 ms: 1369 ms; SOA = 400 ms: 1434 ms); the latter slightly failed the 5% level of significance (see figure 2a). This means that the significance of the effect must have emerged from opposing trends between normal readers and dyslexics. No other main effects or interactions approached significance.

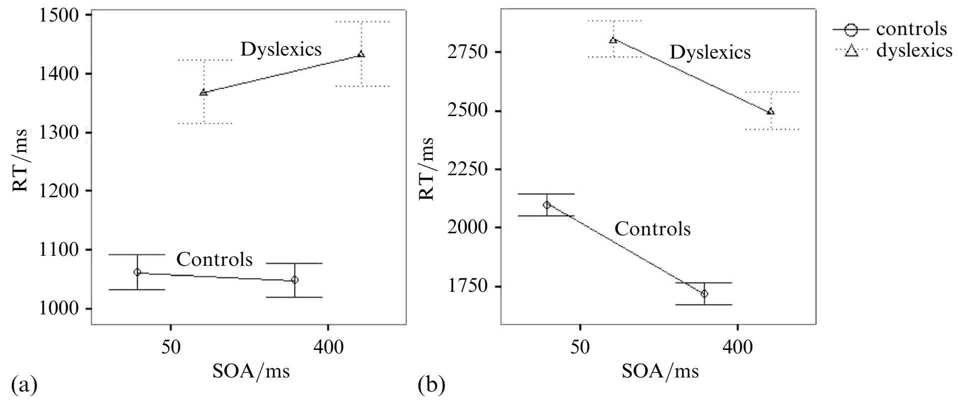

Figure 2. Effect of SOA on reaction times in experiment 1: (a) task 1 (auditory task) and (b) task 2 (letter task) in normal readers and dyslexics. The lines between the data points of single subjects were added for illustration.

3.2.2 *Task 2 (visual classification).* Outlier criterion was the same as for task 1. The overall mean RT of correct responses was 2187 ms (SD = 1090 ms), the mean error rate was 15.9%; no speed – accuracy trade-off was evident for task 2: individual RTs and error rates were not correlated ($p > 0.1$). An ANOVA on RT with factors group and SOA and mirror revealed a main effect of group (dyslexics: RT = 2651 ms, SD = 1199 ms; normal readers: RT = 1905 ms, SD = 909 ms; $F_{1,46} = 20.14$, $p < 0.01$) and a main effect of SOA (short SOA: RT = 2363 ms, SD = 1067 ms; long SOA: RT = 2016 ms, SD = 1084 ms, $F_{1,46} = 112.70$, $p < 0.01$). No mirror main effect ($F < 1$), nor interactions between SOA, mirror, or group were found. Figure 2b displays the SOA effect for controls (SOA = 50 ms: 2097 ms; SOA = 400 ms: 1719 ms; SOA effect: 378 ms) and dyslexics (SOA = 50 ms: 2808 ms; SOA = 400 ms: 2501 ms; SOA effect: 307 ms). Note that these SOA effects do not differ significantly between the groups, even though the difference in their numerical values appears to be high (71 ms).

3.3 *Discussion*

The auditory-classification task (task 1 of the present dual-task paradigm) showed an effect of SOA. This indicates resource sharing between the performance of the first and second tasks (Jolicoeur 1999). Of specific interest is the effect depicted in figure 2a, where opposite trends were found in the RT between dyslexics and normal-reading children as a function of SOA. Paradoxically, dyslexics tended to take longer in the first task for longer SOAs. This result can be taken as an indication that dyslexics have difficulties in decision-making already in the first task. For instance, dyslexics were found to have difficulties in discrimination of tones that differ in frequency (Lachmann et al 2005). These difficulties may be enhanced by interference from second-task stimulus presentation, interrupting a late stage of processing in the first task.

In the visual-classification task (task 2 of the present dual-task paradigm), dyslexics were slower overall, as compared to normal readers. In addition, neither normal readers nor dyslexics showed any effects of mirror reversal. Both of these results contrast with those of Corballis et al (1985b), who obtained effects of mirror reversal, but no differences between normal-reading and dyslexic children. The contrasting results could be explained by differences between the tasks. In the study of Corballis et al, items were identified through naming without, however, having to distinguish between normal versus mirrored items. In the present experiment, the distinction between mirror images was the classification criterion. This difference is crucial: the naming task could be performed through symmetry generalisation, ie by creating representations of items in which transformed images are treated as equivalent. Longer response times for reversed items may then be a consequence of mapping these, more unfamiliar, items onto their representation. Failure to obtain group differences in the naming task may be the result of the symmetry strategy. FCD suggests that dyslexics, in contrast with normal readers, habitually fail to suppress symmetry generalisation for letters. They may use this failure to their advantage in the naming task (Lachmann and van Leeuwen 2007a), and thereby compensate for their deficit. That such a strategy is possible is, in particular, the result of excluding items such as 'b', 'p', 'q', and 'd', for which symmetry generalisation could lead to naming confusion.

This explanation would lead us to predict a group effect for Corballis et al (1985a), where the letters 'b' versus 'd' were to be named as fast as possible. However, the group difference of 76 ms (dyslexics were slower) in their study failed to reach significance. The absence of a group effect in Corballis et al (1985a) may be due to the small group size (nine subjects per group).

In our task 2 we found no interaction between group and SOA, and no triple interaction of group, SOA, and mirror. Such effects would have occurred if processes that differentiate controls and dyslexics on this task had been pre-bottleneck effects. We might therefore conclude that the group difference must be a late effect. However, the results are somewhat inconclusive, given the high numerical value of the difference in SOA effect between the two groups.

No mental rotation was needed to solve task 2 in experiment 1. In experiment 2 we apply the dual-task paradigm to compare dyslexics and normal readers in a mental-rotation task. For both groups mental-rotation rate and its location with respect to the bottleneck should be the same.

4 Experiment 2

Experiment 2 adopts a version of Cooper and Shepard (1973) in a dual-task setting, thus replicating Ruthruff et al (1995, experiment 1), for controls versus dyslexics. We expected higher overall RTs for dyslexics as compared to controls, but equal mental-rotation rate for both groups. We further expected mental-rotation effects to be late, post-bottleneck effects. Finally, we expected the difference between controls and dyslexics to be additive with SOA.

4.1 *Method*

4.1.1 *Participants.* The participants were the same children as in experiment 1.

4.1.2 *Stimuli.* Stimuli were the same as in experiment 1. The only difference was that the letters F, R, g, and their mirror images were visually presented at several different angular orientations—0°, 90°, and 180° clockwise from the normal upright.

4.1.3 *Procedure.* Experiment 2 took place directly after experiment 1. The procedure was almost the same as in experiment 1. Participants started with a 5-trial training session of the auditory-discrimination task and then were trained for 30 trials on the letter-discrimination task with rotated letters. Afterwards a total of two blocks of 72 trials each were run, in which equal numbers of long SOA and short SOA trials and the three different angular rotations of the letters were randomly intermixed.

4.2 *Results*

RTs in the first and second task were positively correlated ($r = 0.724$, $p < 0.01$), but error rates were not ($r = 0.244$, ns). RTs and error rates were positively correlated ($r = 0.472$, $p < 0.01$) for the first task, but not for the second task ($r = 0.112$, ns). Hence, no evidence for speed–accuracy trade-off was found, and results are reported for RT only.

4.2.1 *Task 1 (auditory classification).* A total of 6912 responses were registered. The outlier criterion was the same as in experiment 1 (1.8%). For RT analyses only correct responses were used. The overall mean RT was 1124 ms (SD = 671 ms), the mean error rate was 13.2%; no speed–accuracy trade-off was evident: individual RTs and error rates were positively correlated ($p < 0.01$). An ANOVA on RTs with factors group (dyslexia versus control) as between-subjects factor, and with SOA (long versus short), angle of rotation, and mirror as within-subjects factors revealed a main effect of group ($F_{1,46} = 12.03$, $p < 0.01$), with 1339 ms (SD = 803 ms) for dyslexics and 987 ms (SD = 527 ms) for normal readers, as well as an effect of task 2 angle of rotation ($F_{2,90} = 3.99$, $p < 0.05$), with 1129 ms (SD = 676 ms) for 0°, 1139 ms (SD = 692 ms) for 90°, and 1103 ms (SD = 643 ms) for 180°. A posteriori pairwise comparisons revealed significant differences only between 90° and 180° ($F_{1,47} = 4.87$, $p < 0.05$). No other effects reached significance. Figure 3a illustrates the SOA effect for controls (SOA = 50 ms: 996 ms; SOA = 400 ms: 978 ms) and dyslexics (SOA = 50 ms: 1325 ms; SOA = 400 ms: 1351 ms). Note that there are no SOA effects on the first task, either for dyslexics or for normal readers.

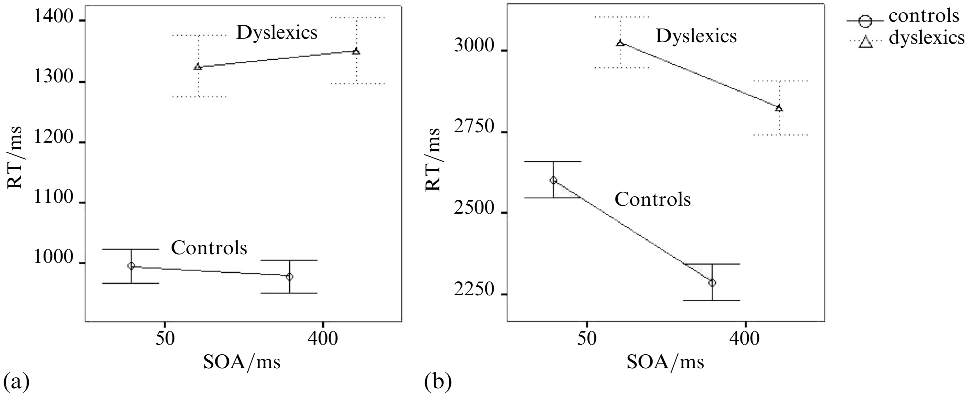

Figure 3. Effect of SOA on reaction times in experiment 2: (a) task 1 (auditory task) and (b) task 2 (letter task) in normal readers and dyslexics. The lines between the data points of single subjects were added for illustration.

4.2.2 *Task 2 (visual classification).* Outlier criterion was the same as for task 1 (1.8%). For RT analyses only correct responses were used. The overall mean RT was 2628 ms (SD = 1173 ms), the mean error rate was 17.9%; no speed–accuracy trade-off was evident for task 2: individual RTs and error rates were not correlated ($p > 0.1$). An ANOVA on RT was run with the factors: group (dyslexics versus controls) as between-subjects factor and with angle of rotation, mirror, and SOA (long versus short) as within-subjects factors. For RT, a main effect of group ($F_{1,46} = 7.22$, $p < 0.01$) was found with 2920 ms for dyslexics and 2440 ms for normal readers. There was a main effect of angle of rotation ($F_{2,92} = 59.21$, $p < 0.01$), with 2348 ms for 0° rotation, 2611 ms for 90° rotation, and 2954 ms for 180° rotation, all differing from each other with $p < 0.01$. Furthermore we obtained effects of mirror ($F_{1,46} = 5.64$, $p < 0.05$ straight: 2549 ms, mirror: 2706 ms, and SOA ($F_{1,46} = 29.79$, $p < 0.01$, with 2500 ms for SOA = 400 ms and 2765 ms for SOA = 50 ms). Group and SOA interacted ($F_{1,46} = 5.68$, $p < 0.05$—see figure 3b): the SOA effect was found to be larger in normal-reading children (SOA = 50 ms: 2602 ms; SOA = 400 ms: 2286 ms; SOA effect = 316 ms) as compared to dyslexics (SOA = 50 ms: 3026 ms; SOA = 400 ms: 2823 ms; SOA effect = 203 ms). No interaction was found between group, SOA, and rotation (see figure 4).

A triple interaction of SOA, rotation, and mirror reached significance ($F_{2,290} = 4.55$, $p < 0.05$). This effect could be understood as somewhat faster than expected RTs for the mirrored item in the 90° rotation position with short SOA. This effect did not interact with group. No other effects approached significance.

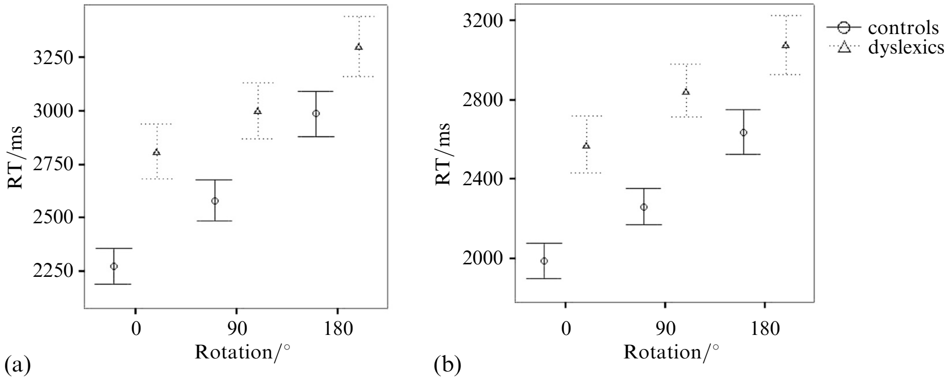

Figure 4. Effect of mental rotation on reaction times in experiment 2: task 2 for (a) SOA = 50 ms and (b) SOA = 400 ms condition in dyslexics and controls.

4.3 *Discussion*

On the first task, as in experiment 1, evidence for resource sharing was found: angle of rotation of the second task affects RT of the first task. In addition, a group difference was found, suggesting that dyslexics have difficulties in decision-making initially in the first task. In contrast with experiment 1, increasing the SOA did not lead to increased response times in the first task. The absence of SOA effects indicates that greater priority than in experiment 1 was given to the tone task.

On the second task, there was a main effect of angle of rotation, which did not interact with SOA. The additivity of mental rotation effects and SOA effects replicates the result of Ruthruff et al (1995), which confirms that mental rotation is a late, controlled effect and extends this finding for children. This result is the same for both normal readers and dyslexics, indicating that there are no differences in the rate of mental rotation between the groups. This is in accordance with our earlier finding of equal mental-rotation rates for controls and dyslexics (Rusiak et al 2007) but contrasts with the findings of Rüsseler and colleagues (2005). These findings correspond to results (experiment 2: mental-rotation task) in Corballis et al (1985a), in which participants had to name the letters ‘b’ and ‘d’ presented at varying angular orientations. The authors found a mental-rotation effect and no difference in mental-rotation rate between the groups.

Dyslexics were found to be 480 ms slower overall than normal readers. In the study of Corballis et al (1985a) dyslexics showed a general delay of 171 ms as compared to controls. The latter difference failed to reach significance, even though the relative difference between the groups is 13.5%, which is quite close to the 19.7% found in the current study. Note, however, that the group size in Corballis et al is rather small (nine subjects per group) and that the task as well as the procedure are different (eg naming task, voice key, only two letters which enables a visual strategy, mirror images have an alternative meaning, error trials were presented again).

The effect of SOA on task 2 differs between normal-reading and dyslexic children. Even though this difference failed to reach significance in task 2 of experiment 1, the numerical values of the effects are in the same direction. The interaction observed between group and SOA is sub-additive with decreasing SOA. This result is opposed to our first hypothesis; according to PRP logic, we should conclude that the group difference occurs early in processing, ie prior to the bottleneck.

Note, however, that according to our second, alternative hypothesis, dyslexics may already have difficulties in the first task. This means that they benefit less from increased SOAs. In accordance with this hypothesis, dyslexics take 1339 ms to complete the first task, as opposed to 987 ms for normal readers, a difference of 353 ms.

If the difference in SOA effects were due to early processes, we would expect a negative correlation between the RTs of the first and second task. This is the case, because if the decision process in the first task takes longer, more of the second-task group difference could be buried into it. On the other hand, if the second, alternative, explanation holds true, we should expect a positive correlation between RT in the first and second task, as decision processes are involved in both tasks. The positive correlation observed between the first and second task is in accordance with our second hypothesis.

Our results indicate that mental-rotation effects, as well as the difference between normal readers and dyslexics, are both manifested in late, controlled effects, according to the PRP approach. This allows us to test and compare between the cerebellar-deficit hypothesis and our FCD hypothesis. According to the first, both effects should be super-additive, according to the second they should be additive. The additive character found in the present study constitutes a case for the FCD explanation of dyslexia.

5 Summary and conclusions

Normal-reading and dyslexic children performed visual classification (experiment 1) and mental-rotation tasks (experiment 2), both preceded by auditory discrimination in a dual-task setting. SOA between the first and second task was systematically varied. In experiment 1 we found that differences between the normal-reading and dyslexic groups were additive with respect to SOA. Following PRP logic, we concluded, in accordance with the functional coordination deficit approach to dyslexia (Lachmann 2002) that for these kinds of tasks the group differences originate in a late stage of processing.

In experiment 2 we found a main effect of mental rotation, which was additive with SOA. This additivity replicates Ruthruff et al (1995). According to these results, mental rotation of letters is a late, controlled process. Mental-rotation rates were equal for normal-reading and dyslexic children. Rusiak et al (2007) obtained similar results in a single-task paradigm. This, in combination with the previous observation that for both groups the effects were additive with respect to SOA, indicates that both groups of children perform this task equally well. This result opposes the prediction of the cerebellar-deficit hypothesis (Nicolson and Fawcett 1994) and is in accordance with the notion of a FCD in developmental dyslexia. This, however, does not exclude that the cerebellum has a role in automatisation of specific components of the reading process, in particular symmetry-generalisation suppression.

As in Rusiak et al (2007), an overall difference in response times was found between normal-reading children and dyslexics. Rusiak et al proposed that this effect is located in central rather than in encoding or motor processing components. The present results endorse this interpretation, even though the group effects were not additive with respect to SOA. Dyslexics are slower than normal readers also on the first task, and therefore benefit less from the long-SOA condition. This, in combination with the positive correlation between the RTs of the first and second task, informs us that the difference between dyslexics and normal readers in the second task manifests itself at the level of central, controlled, resource intensive processing. Dyslexics have greater difficulty in ultimately deciding whether the outcome of their mental rotation is a normal or mirrored letter.

Acknowledgments. Many thanks are due to Steffen Hübner (Leipzig) for technical support, Claudia Steinbrink (Kaiserslautern), Catherine Black (Oxford), and Monique R Rowles (Brisbane) for their helpful comments, and to the children, their teachers, and parents (3rd, 49th, and 85th Grundschule, Leipzig) for their cooperation. Many thanks are also due to two anonymous reviewers for their very helpful comments and suggestions to an earlier draft of this paper.

References

American Psychiatric Association, 1994 *Diagnostic and Statistical Manual on Mental Disorders* 4th edition (DSM+V) (Washington, DC: American Psychiatric Press)

Badian N A, 2005 "Does a visual-orthographic deficit contribute to reading disability?" *Annals of Dyslexia* **55** 28 – 52

Becker C, Elliott M, Lachmann T, 2005 "Evidence for impaired visuo-perceptual organization in developmental dyslexia and its relation to temporal processes" *Cognitive Neuropsychology* **21** 273 – 278

Brady S A, Shankweiler D P, 1991 *Phonological Processes in Literacy: A Tribute to Isabelle Y. Liberman* (Hillsdale, NJ: Lawrence Erlbaum Associates)

Breuer H, Weuffen M, 1995 *Lernschwierigkeiten am Schulanfang: Lautsprachliche Lernvoraussetzungen und Schulerfolg* [Learning difficulties at the beginning of schooling] (Weinheim, Switzerland: Belz)

Calhoun V D, Adali T, McGinty V B, Pekar J J, Watson T D, Pearlson G D, 2001 "fMRI activation in a visual-perception task: Network of areas detected using the general linear model and independent components analysis" *NeuroImage* **14** 1080 – 1088

Cooper L A, Shepard R N, 1973 "Chronometric studies of the rotation of mental images", in *Visual Information Processing* Ed. W G Chase (New York: Academic Press) pp 75 – 176

Corballis M C, Beale I L, 1970 "Bilateral symmetry and behavior" *Psychological Review* **77** 451 – 464

Corballis M C, Beale I L, 1993 "Orton revisited: Dyslexia, laterality, and left – right confusion", in *Visual Processes in Reading and Reading Disabilities* Eds D Willows, R S Kruk, E Corcos (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 57 – 73

Corballis M C, Macadie L, Beale I L, 1985a "Mental rotation and visual laterality in normal and reading-disabled children" *Cortex* **21** 225 – 236

Corballis M C, Macadie L, Crotty A, Beale I L, 1985b "The naming of disoriented letters by normal and reading-disabled children" *Journal of Child Psychology and Psychiatry and Allied Disciplines* **26** 929 – 938

Fawcett A J, Nicolson R I, 2001 "Dyslexia: the role of the cerebellum", in *Dyslexia: Theory and Good Practice* Ed. A J Fawcett (London: Whurr) pp 89 – 105

Frith U, 2001 "What framework should we use for understanding developmental disorders" *Developmental Neuropsychology* **20** 555 – 563

Garner W R, Clement D E, 1963 "Goodness of pattern and pattern uncertainty" *Journal of Verbal Learning and Verbal Behavior* **2** 446 – 452

Heil M, Wahl K, Herbst M, 1999 "Mental rotation, memory scanning, and the central bottleneck" *Psychological Research* **62** 48 – 61

Heller K A, Krantzmeier H, Lengfelder A, 1998 *Matrizen-Test-Manual.* Band 1. *Ein Handbuch mit deutschen Normen zu den Standard Progressive Matrices von J. C. Raven* (Göttingen: Hogrefe)

Jansen-Osmann P, Heil M, 2007 "Developmental aspects of parietal hemispheric asymmetry during mental rotation" *NeuroReport* **18** 175 – 178

Jaskowski P, Rusiak P, 2005 "Posterior parietal cortex and developmental dyslexia" *Acta Neurobiologiae Experimentalis* **65** 79 – 94

Jolicoeur P, 1999 "Dual-task interference and visual encoding" *Journal of Experimental Psychology: Human Perception and Performance* **25** 596 – 616

Jordan K, Heinze H-J, Lutz K, Kanowski M, Jäncke L, 2001 "Cortical activations during the mental rotation of different visual objects" *NeuroImage* **13** 143 – 152

Lachmann T, 2002 "Reading disability as a deficit in functional coordination and information integration", in *Basic Functions of Language, Reading, and Reading Disability* Neuropsychology and Cognition series, Eds E Witruk, A D Friederici, T Lachmann (Boston, MA: Kluwer/Springer) pp 165 – 198

Lachmann T, Berti S, Kujala T, Schröger E, 2005 "Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes" *International Journal of Psychophysiology* **56** 105 – 120

Lachmann T, Leeuwen C van, 2005 "Individual pattern representations are context-independent, but their collective representation is context-dependent" *Quarterly Journal of Experimental Psychology: Human Experimental Psychology* **58** 1265 – 1294

Lachmann T, Leeuwen C van, 2007a "Paradoxical enhancement of letter recognition in developmental dyslexia" *Developmental Neuropsychology* **31** 61 – 77

Lachmann T, Leeuwen C van, 2007b "Goodness takes effort: perceptual organization in dual-task settings" *Psychological Research* **71** 152 – 169

Landerl K, Wimmer H, 2000 "Deficits in phoneme segmentation are not the core problem of dyslexia: Evidence from German and English children" *Applied Psycholinguistics* **21** 243 – 262

Landerl K, Wimmer H, Moser E, 1997 *Salzburger Lese- und Rechtschreibtest: Verfahren zur Differentialdiagnose von Störungen des Lesens und Schreibens für die 1. bis 4. Schulstufe* (Bern: Hans Huber)

Lovegrove W, Bowling A C, Badcock D, Blackwood M, 1980 "Specific reading disability: differences in contrast sensitivity as a function of spatial frequency" *Science* **210** 439 – 440

Marsolek C J, Burgund E D, 2008 "Dissociable neural subsystems underlie visual working memory for abstract categories and specific exemplars" *Cognitive, Affective, and Behavioral Neuroscience* **8** 17 – 24

Miles E, 1995 "Can there be a single definition of dyslexia?" *Dyslexia* **1** 37 – 45

Navon D, Miller J, 2002 "Queuing or sharing? A critical evaluation of the single-bottleneck notion" *Cognitive Psychology* **44** 193 – 251

Nicolson R I, Fawcett A J, 1994 "Comparison of deficits in cognitive and motor skills among children with dyslexia" *Annals of Dyslexia* **44** 147 – 164

Orton S T, 1928 "Specific reading disability—strephosymbolia" *Journal of the American Medical Association* **90** 1095 – 1099

Pashler H, 1984 "Processing stages in overlapping tasks: Evidence for a central bottleneck" *Journal of Experimental Psychology: Human Perception and Performance* **10** 358 – 377

Pashler H, 1989 "Dissociations and dependencies between speed and accuracy: Evidence for a two component theory of divided attention in simple tasks" *Cognitive Psychology* **21** 469 – 514

Pashler H, 1994 "Dual-task interference in simple tasks: Data and theory" *Psychological Bulletin* **116** 220 – 244

Pashler H, Johnston J, 1989 "Chronometric evidence for central postponement in temporally overlapping tasks" *Quarterly Journal of Experimental Psychology A* **41** 19 – 45

Rack J P, Olson R K, 1993 "Phonological deficits, IQ, and individual differences in reading disability: Genetic and environmental influences" *Developmental Review* **13** 269 – 278

Rentschler I, Jüttner M, 2007 "Mirror-image relations in category learning" *Visual Cognition* **15** 211 – 237

Rusiak P, Lachmann T, Jaskowski P, Leeuwen C van, 2007 "Mental rotation of letters and shapes in developmental dyslexia" *Perception* **36** 617 – 631

Rüsseler J, Scholz J, Jordan K, Quaiser-Pohl C, 2005 "Mental rotation of letters, pictures, and three-dimensional objects in German dyslexic children" *Journal of Child Neuropsychology* **11** 497 – 512

Ruthruff E, Miller J O, Lachmann T, 1995 "Does mental rotation require central mechanisms?" *Journal of Experimental Psychology: Human Perception and Performance* **21** 552 – 570

Schubert T, 1999 "Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks" *Journal of Experimental Psychology: Human Perception and Performance* **25** 408 – 425

Schulte-Körne G, 2001 "Annotation: Genetics of reading and spelling disorder" *Journal of Child Psychology and Psychiatry* **42** 985 – 997

Schwarz W, Ischebeck A, 2001 "On the interpretation of RT vs. SOA functions: Application to dual task and precue-utilization paradigms" *Journal of Mathematical Psychology* **45** 452 – 479

Shaywitz S E, Shaywitz B A, Fletcher J M, Escobar M D, 1990 "Prevalence of reading disability in boys and girls" *Journal of the American Medical Association* **264** 998 – 1002

Shepard R N, Metzler J, 1971 "Mental rotation of three-dimensional objects" *Science* **171** 701 – 703

Skottun B C, 2001 "On the use of metacontrast to assess magnocellular function in dyslexic readers" *Perception & Psychophysics* **63** 1271 – 1274

Slaghuis W L, Ryan J F, 1999 "Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in development dyslexia" *Vision Research* **39** 651 – 668

Snowling M, 2001 "From language to reading and dyslexia" *Dyslexia* **7** 37 – 42

Stanley G, Hall A, 2005 "Short-term visual information processing in dyslexics" *Child Development* **44** 841 – 844

Stein J, 2001 "The magnocellular theory of developmental dyslexia" *Dyslexia* **7** 12 – 36

Stein J, Talcott J, Witton C, 2001 "The sensorimotor basis of developmental dyslexia", in *Dyslexia: Theory and Good Practice* Ed. A J Fawcett (London: Whurr) pp 65 – 88

Steinbrink C, Klatte M, 2008 "Phonological working memory in German children with poor reading and spelling abilities" *Dyslexia* **14** 217 – 290

Telford C W, 1931 "The refractory phase of voluntary and associative responses" *Journal of Experimental Psychology* **14** 1 – 36

Tombu M, Jolicoeur P, 2002 "All-or-none bottleneck versus capacity sharing accounts for the psychological refractory period phenomenon" *Psychological Research* **66** 274 – 286

Van Selst M, Jolicoeur P, 1994 "Can mental rotation occur before the dual-task bottleneck?" *Journal of Experimental Psychology: Human Perception and Performance* **20** 905 – 921

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

Weigt R, 1980 *Zur Auswahl von Schülern für LRS-Klassen* [Berlin (GDR): Verlag Volk und Wissen]

Welford A T, 1952 "The 'psychological refractory period' and the timing of high-speed performance—a review and a theory" *British Journal of Psychology* **43** 2 – 19

Willows D M, Terepocki M, 1993 "The relation of reversal errors to reading disabilities", in *Visual Processes in Reading and Reading Disabilities* Eds D Willows, R S Kruk, E Corcos (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 31 – 56

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 38 2009

www.perceptionweb.com