Restorative Neurology and Neuroscience 25 (2007) 355–369
IOS Press

Computer-based multisensory learning in children with developmental dyslexia

Monika Kast[c,*], Martin Meyer[a,b], Christian Vögeli[c], Markus Gross[c] and Lutz Jäncke[a]
[a]*Departement of Neuropsychology, University of Zurich, Switzerland*
[b]*Institute of Neurordiology, University Hospital of Zurich, Switzerland*
[c]*Department of Computer Science, ETH Zurich, Switzerland*

Abstract. *Purpose:* Several attempts have been made to remediate developmental dyslexia using various training environments. Based on the well-known *retrieval structure model*, the memory strength of phonemes and graphemes should be strengthened by visual and auditory associations between graphemes and phonemes. Using specifically designed training software, we examined whether establishing a multitude of visuo-auditory associations might help to mitigate writing errors in children with developmental dyslexia.

Methods: Forty-three children with developmental dyslexia and 37 carefully matched normal reading children performed a computer-based writing training (15–20 minutes 4 days a week) for three months with the aim to recode a sequential textual input string into a multi-sensory representation comprising visual and auditory codes (including musical tones). The study included four matched groups: a group of children with developmental dyslexia ($n = 20$) and a control group ($n = 18$) practiced with the training software in the first period (3 months, 15–20 minutes 4 days a week), while a second group of children with developmental dyslexia ($n = 23$) (waiting group) and a second control group ($n = 19$) received no training during the first period. In the second period the children with developmental dyslexia and controls who did not receive training during the first period now took part in the training.

Results: Children with developmental dyslexia who did not perform computer-based training during the first period hardly improved their writing skills (post-pre improvement of 0–9%), the dyslexic children receiving training strongly improved their writing skills (post-pre improvement of 19–35%). The group who did the training during the second period also revealed improvement of writing skills (post-pre improvement of 27–35%). Interestingly, we noticed a strong transfer from trained to non-trained words in that the children who underwent the training were also better able to write words correctly that were not part of the training software. In addition, even non-impaired readers and writers (controls) benefited from this training.

Conclusion: Three-month of visual-auditory multimedia training strongly improved writing skills in children with developmental dyslexia and non-dyslexic children. Thus, according to the *retrieval structure* model, multi-sensory training using visual and auditory cues enhances writing performance in children with developmental dyslexia and non-dyslexic children.

Keywords: Developmental dyslexia, multisensory learning, computer- based training

1. Introduction

Developmental dyslexia[1] is a specific learning disability. Affected children and adults have inconsistent orthography speed and accuracy problems as well as difficulty in segmenting and manipulating phonemes in words. In addition to deficient writing and reading skills, poor speech production and poor spelling are other hallmarks of developmental dyslexia (Goswami,

---

*Corresponding author: Monika Kast, ETH Zürich, Computer Graphics Laboratory, Haldeneggsteig 4, 8092 Zürich, Switzerland. E-mail: monika.kast@inf.ethz.ch.

[1] Developmental dyslexia is characterized by low average reading and writing skills despite average IQ, good educational support and solid social background (World Health Organization, 1993). It is a widespread and probably the most common neurobehavioral disorder affecting children, with uncertain prevalence, ranging from 5% to 17.5% for English speaking countries (Shaywitz, 1998) and about 10% for Germany (Russeler, Gerth, & Munte, 2006).

2003). Dyslexic individuals demonstrate limitations in performance of phonics-based memory and show problems with rapid retrieval of phonological information from long-term memory (Elbro, Nielsen, & Petersen, 1994; Pennington, Van Orden, Smith, Green, & Haith, 1990; Mody, Studdert-Kennedy, & Brady, 1997; Wagner, Torgesen, & Rashotte, 1994). According to the double-deficit hypothesis the combination of deficts in both phonological processing and naming speed represents a further independent source of dysfunction in dyslexia (Vukovic & Siegel, 2006). In spite of decades of research in this area, the causes for reading and writing failures are still disputed. A neurological disorder with a genetic origin is currently thought to be the main current candidate for the origin of developmental dyslexia (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006; Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Demonet, Taylor, & Chaix, 2004; Schulte-Korne, Deimel, Bartling, & Remschmidt, 2004; Ziegler et al., 2005). Because dyslexic subjects show a wide variety of symptoms this disorder may well result from several distinguishable impairments. One of the core problems of developmental dyslexia is that of phonological processing (Ramus, 2003), which however falls far short of being able to explain the general auditory, visual, and motor impairments encountered by sufferers of developmental dyslexia. Other theories place particular emphasis on deficits in rapid auditory processing (Tallal, 1980); on deficits in visual processing (Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Hill & Raymond, 2002); on cerebellar dysfunction (Nicolson et al., 1999; Nicolson, Fawcett, & Dean, 2001) and/or suggest a magnocellular deficit (Stein, 2001; Skottun, 2000). In addition, attention deficits have been proposed as causing reading and spelling difficulties (Hari, Renvall, & Tanskanen, 2001; Hari, Valta, & Uutela, 1999). The divergence of symptoms has lead some authorities to argue that developmental dyslexia is a neurological disorder caused by a number of different factors (Russeler, Gerth, & Munte, 2006).

Several intervention programs for remediation of developmental dyslexia have been successfully evaluated in adults and children. Among them are procedures that (1) utilize low-level auditory perceptual learning (e.g., practicing to improve perception of tones, tone durations, auditory rhythms or gaps between successive acoustic stimuli) (Tallal, 2004; Robichon, Besson, & Habib, 2002; Santos, Joly-Pottuz, Moreno, Habib, & Besson, 2007; Besson, Schoen, Moreno, Santos, & Magne, in press; Gaab, Gabrieli, Deutsch, Tallal, & Temple, in press; Uther et al., 2006); (2) practice speech-like auditory stimuli (training of phoneme perception, improving phonological awareness) (O'Shaughnessy & Swanson, 2000; Hatcher et al., 2006); (3) practice specific manipulations of speech-like signals to support phoneme and speech perception (Tallal, 2004); (4) improve low-level and high-level visual functions (e.g., moving stimuli) (Bacon, Handley, & McDonald, 2007; Lorusso, Facoetti, Paganoni, Pezzani, & Molteni, 2006); or (5) combine training of auditory and visual functions at different levels of cognitive processing (Kujala et al., 2001). In addition to these remediation programs there are several training programs in use that combine training of reading and writing skills at different levels of complexity (Edwards, 2003; Vadasy, Jenkins, & Pool, 2000; Shaywitz et al. 2004).

A multi-modal training program developed by a Finnish group has recently been shown to induce strong reading improvements in dyslexic children and adults (Kujala et al., 2001). The basic principle of this program is that the participants learn to associate abstract audio-visual material. The training program is presented as a kind of computer game consisting of abstract, nonverbal tasks that require audio-visual matching. In this game, various sound patterns (3–15 sound elements varying in pitch, duration, and intensity) are simultaneously presented with horizontal sequences of rectangles. The display of the rectangles on the screen differs according to the presented sound pattern in terms of their vertical position, length, and thickness. The basic principle of this task is to learn associations between the visual and auditory stimuli. By learning to associate visual with auditory cues the trainee improves multi-modal coding of speech stimuli, thus improving reading and writing skills. Although the exact neurocognitive underpinnings of this training program are currently unknown, the training effect can be best explained by drawing on current theories of human associative memory (Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1992). In terms of this theoretical framework, the memory strength of a particular item (a letter or a phoneme) depends on the established retrieval structure, the sum strength of which depends on the individual strength of each of the three factors that affect retention: (1) the strength of each individual item (its sound, spelling, and its meaning), (2) the strength of associations between different items belonging together (e.g., associating sound with letters or sound with meanings), and (3) the strength of the associated

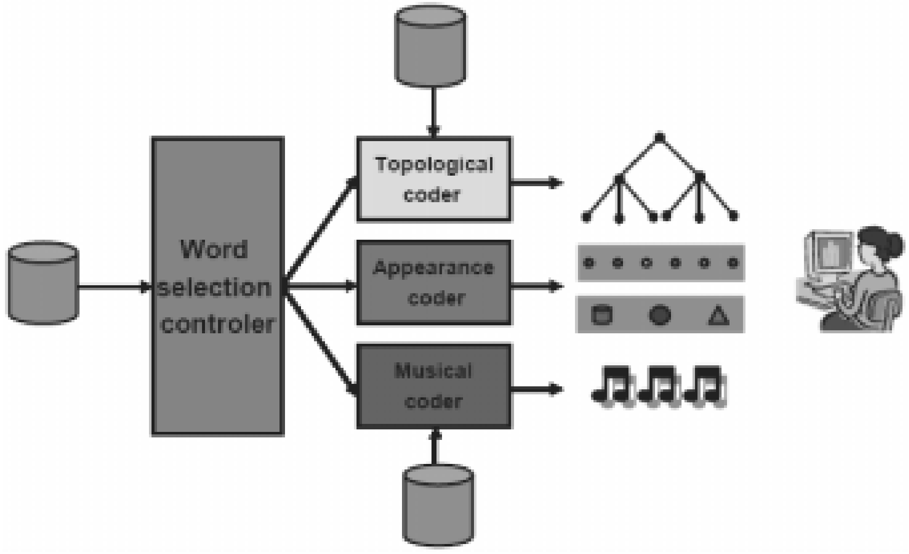

Fig. 1. Conceptual components of the method and framework.

context in which the information has been learned. In learning to read and write, the strength of the retrieval structure of a letter or phoneme is therefore determined by all three strength measures. From this follows that a good strategy for implementing optimal retrieval structures for letters or phonemes would be to increase the number of associations for letters and phonemes.

In this paper, we introduce a new training program (*Dybuster*) designed to establish cross-modal associations between different visual and auditory cues associated with the presentation of written words. It should be emphasized that the *Dybuster*-based training aims to improve the trainee's orthographical writing skills as tested before and after the training period. In contrast to the training program of Kujala et al. (2001), which is based on simple stimuli, our newly designed training program relies on meaningful visual and auditory stimuli. The basic idea behind this approach was to use a multitude of meaningful visual-auditory associations in order to build up the memory strength of graphemes and phonemes (see above for the theoretical background taken from the retrieval structure model). This idea currently receives substantial support from neuroscience research showing that multisensory (meaningful) experiences enhance perceptions and facilitate memory retrieval processes. Data of a recent neuroimaging study demonstrated that repeated visual stimuli could be discriminated according to whether they were initially encountered in a multisensory (auditory – visual) or unisensory (visual only) mode. The discrimination was evident both in terms of improved accuracy for images with multisensory associations and of differential hemodynamic responses within regions of the lateral-occipital complex, the anterior cingulate and frontal cortices (Murray, Foxe, & Wylie, 2005).

The objective of the present study was to evaluate the performance of a multi-medial learning-software called *Dybuster*. This new computer-based training program for the remediation of developmental dyslexia is based on information theory models from Computer Science. It utilizes Markovian language statistics derived from linguistic analysis of standard language corpora. *Dybuster* is based on the idea of recoding a sequential textual input string into a multimodal representation using a set of novel codes. These codes re-route textual information through multiple perceptual cues. There are topological, colour, shape, and auditory representations. The spatio-topological code is computed by recursive parsing trees of the string and decomposes it into words, syllables, and individual letters. The appearance code assigns appearance attributes (colours and shapes) to each symbol. An additional auditory code assigns Midi events (musical notes) to each symbol and thus generates a melody for each input string. Detailed information on the statistical algorithms and its implementation is available from a supplementary more technical publication (Gross & Vögeli, submitted).

Dybuster comprises three different games. The first is the *colour game* in which the users have to learn the association between a letter and a particular colour. Based on the information theory model of *Dybuster*, eight different colours are used. The mapping of letters to colours is the result of a multi-objective optimization, taking into account that, for example, letters, which dyslexics easily confuse, such as “t” and “d”, map to different colours. Other aspects considered include a uniform distribution of the colours over the alphabet, maximizing the information content of the letter to colour assignment measured as entropy. This approach of associating colours and letters is aimed to facilitate the elimination of mistakes.

In the second game, the *graph game*, the users have to segment graphically the word into syllables and letters. Developmental dyslexics have difficulty in segmenting and manipulating phonemes in words (Elbro, Nielsen, & Petersen, 1994; Mody, Studdert-Kennedy, & Brady, 1997). Reading acquisition in children requires the development of an appreciation for the segmental nature of speech, a skill known as **phonemic awareness**. Once the child realizes that spoken words are composed of smaller segments (the phonemes), he or she can learn to treat written words as multi-segment units and to grasp the correspondence between letters (or letter complexes) and phonemes (Fletcher et al., 1994; Stanovich & Siegel, 1994).

In the third game, the actual *learning game, Dybuster* presents all alternative representations of a word before the user enters the word itself with the keyboard: the graph appears on screen, and the colours and shapes (spheres for small letters, cylinders for capital letters, and pyramids for umlauts) are displayed for all letters. A voice dictates the word and the users hear a melody computed from the pertinent letters and the lengths of the syllables. The words are organized in modules, each module consisting of 100 words, and ordered according to their frequency and difficulty for dyslexics so that the users begin by learning the most frequent and easy words. For effective training, word selection adapts to the user's state and optimizes the learning process by estimating and minimizing error entropy.

This paper reports the first data from our training study. The study is based on a relatively large number of children with developmental dyslexia who underwent this audio-visual training procedure. We tested whether this training procedure resulted in an improvement of writing skills in dyslexic children compared with dyslexics who did not receive this training.

2. Methods

2.1. Subjects

Forty-three dyslexic children (15 females), aged 9–11 years (mean 10.3), and 37 controls (17 females), aged 9–11 years (mean 10.23), all native German speaking and with an IQ > 85 participated in the study (IQ dyslexics: 105; IQ controls: 113). Two children were excluded from the study because of poor performance in the classical writing tests and in the *Dybuster* writing test. Two additional children were excluded because they performed the writing test only once.

2.2. Test battery

At the beginning of the study, every child underwent a series of standard psychological tests. The battery included classical German writing (“Salzburger-Lese und Rechtschreibtest SLRT” (Landerl, H, & Moser, 1997), “Diagnostischer Rechtschreibtest für fünfte Klassen DRT5” (Grund, Haug, & Naumann, 1995)) and reading tests (“Zürcher Lesetest ZLT” (Linder, & Grissemann, 2000)) to quantify writing and reading errors, a standard German intelligence test (HAWIK III (Tewes, Rossmann, & U, 1999)) to exclude children with an IQ lower than 85, attention tests to exclude children suffering from attention-deficit-hyperactivity disorders (“ADHD/ODD-Elternfragebogen” (Steinhausen, 2002)), a categorization test to measure possible planning problems (MWCST (Cianchetti, Corona, Foscoliano, Contu, & Sannio-Fancello, 2007)), and a handedness performance test to measure hand performance skill (“Hand-Dominanz-Test” (Steingruber, 1971)). A summary of the main neuropsychological data separated for children with developmental dyslexia and controls is given in Table 1.

All children were recruited by local newspaper advertisements and with the cooperative support of the *Swiss Dyslexia Corporation*, and all were carefully examined using the above-mentioned neuropsychological test battery. Each child received the diagnosis of developmental dyslexia according to a discrepancy between his or her reading performance, as measured by the standardized German reading tests (see above), and to the child's general cognitive abilities, as measured by the standardized intelligence test. No further distinction was made between possible subgroups. All children had at least normal intelligence. Each child's performance in both reading tests was compared with that of the corresponding reference population of the SLRT and the ZLT. A performance below 2 SD (percentage rank $<3\%$) of that of the reference population in at least one of the two subtests was used as criterion of discrepancy. To serve as a control participant, a child had to perform within the norms of the reference population in both tasks (percentage rank $>17\%$; within one SD).

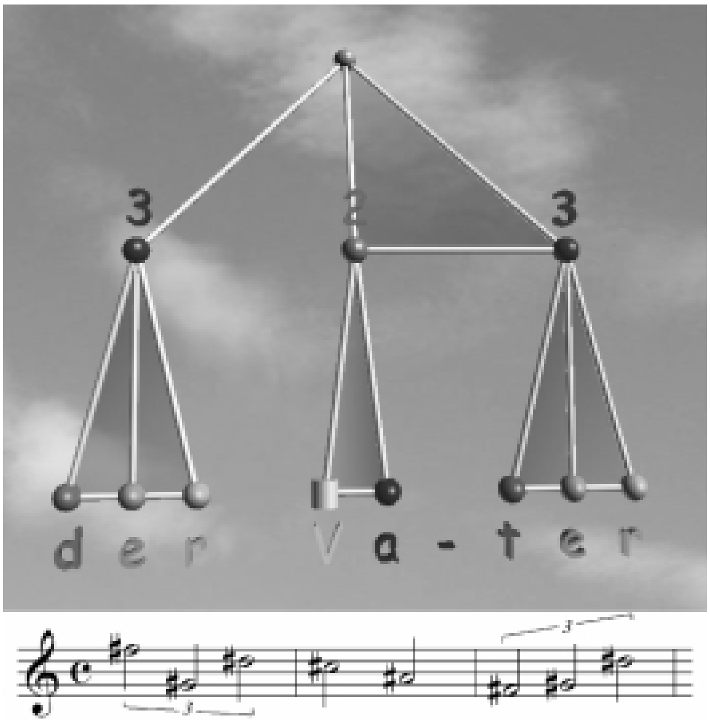

Fig. 2. Surface display of the learning game. Phonological information is represented by form of the graph, colour of the letters, and accompanying musical sequences.

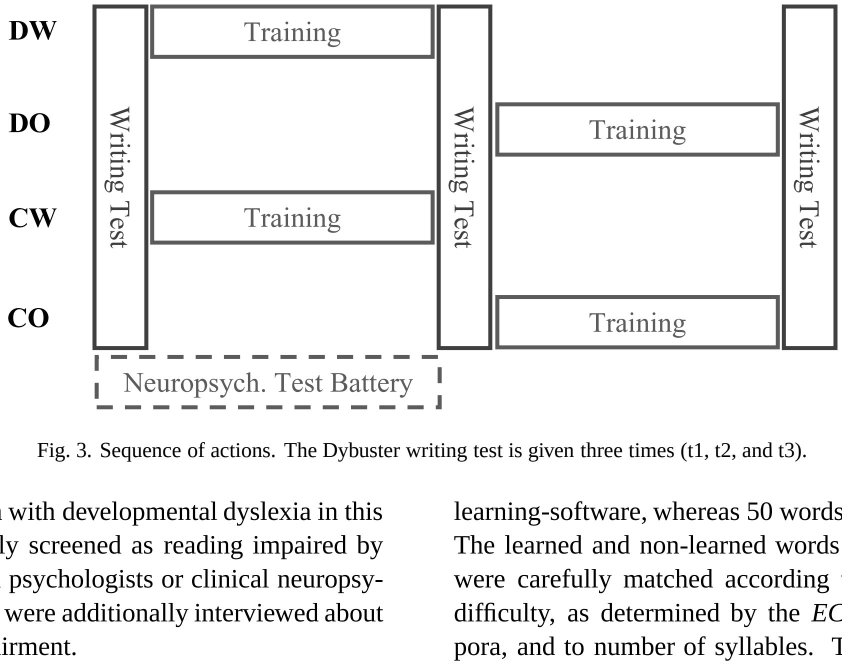

Fig. 3. Sequence of actions. The Dybuster writing test is given three times (t1, t2, and t3).

All of the children with developmental dyslexia in this study were initially screened as reading impaired by the school, school psychologists or clinical neuropsychologists, and all were additionally interviewed about their reading impairment.

Besides the above-mentioned tests, all children had to write a dictation containing 100 words before and after the training (*Dybuster* writing test). Fifty of the 100 words of the writing test were trained using the learning-software, whereas 50 words were not trained. The learned and non-learned words (set 1 and set 2) were carefully matched according to frequency and difficulty, as determined by the *ECI German 3* corpora, and to number of syllables. The writing errors were classified in O-, G-, and N-errors. O-errors were incorrectly written but phonologically correct words (e.g. Somer instead of Sommer, Kwalität instead of Qualität, Feler instead of Fehler). G-errors were considered mistakes in major and minor writing (e.g. non-capitalized nouns, capitalized adjectives). N-errors were regarded as mistakes originating from incorrect phoneme-grapheme correspondence (e.g. Grten instead of Garten, Bedeutun instead of Bedeutung; in English: grden instead of garden, meanin instead of meaning). Table 2 demonstrates the number of errors separated for each error type expressed as percentage values.

In terms of error rates, both word lists revealed strong between-test correlations ranging from $r = 0.7$ to $r = 0.9$, depending on the sample studied and the analyzed error types. These inter-test correlations were obtained from an additional sample ($n = 32$) of children, half of whom did not participate in this experiment. However, the between-test correlations were the same for the sample that participated in this experiment. The lower inter-test correlation was obtained for the dyslexic children, while the higher correlation was measured for normal non-dyslexic children. In addition, we estimated test reliability by calculating "consistency" using the Spearman-Brown formula ($R_{tt} = (2 * R_{12})/(1 + R_{12})$ (R_{tt}: consistency coefficient; R_{12}: Pearson correlation between halves of the "Dybuster writing test")). Because reliability depends heavily on test length (high reliability with long tests), the Spearman-Brown reliabilities had to be corrected for this effect. Thus, we calculated an estimate of reliability corrected for overall test length using the Spearman-Brown relation ($R'_{tt} = (n'/n * R_{tt})/(1 + (n'/n - 1) * R_{tt})$ ($R'_{tt} =$ corrected reliability, R_{tt}: original reliability, n: number of test stimuli, n': number of test stimuli for the longer test version). R_{tt}'s for the *Dybuster* writing test ranged between 0.90 and 0.97, depending on the error type and the sample studied (larger R_{tt}' for the non-dyslexic subjects). Please note that the R_{tt}' values represent the largest reliabilities possible for this test. The empirical reliabilities ranged between $r = 0.82$ and $r = 0.95$. The performances (in terms of error rates) in these dictation tests were used as dependent variables for this experiment. Thus, there were mean error rates for the learned and non-learned words and these were used to quantify the effect of the *Dybuster* training.

2.3. Procedure

The dyslexic and control subjects were randomly assigned to training or waiting groups. Two groups immediately began with *Dybuster* training (dyslexics with training: DW; controls with training: CW). The remaining two groups were assigned to waiting groups who performed the *Dybuster* training after a waiting period of 3 months (dyslexics and controls without training in the first period: DO and CO). The training groups practiced for three months, on average, four times a week for 15–20 minutes a day. After this training period, no further training was undertaken in the second period of the study. The children in the control group now began their training. But only five control children practiced with *Dybuster*, and just 9 children (CO) wrote the writing-test three times. All children used their home PCs for training. Psychologists and computer scientists involved in this project monitored the performance of the participants on a once-weekly basis. A schematic demonstration of the study design is presented with Fig. 3.

2.4. Statistical analysis

The basic design is two-factorial with one grouping factor (4 levels: CO, CW, DO and DW) and one repeated measurements factor (3 levels for the three time points: t1, t2, and t3). Since the data did not entirely fulfil the prerequisites for conventional linear ANOVA analysis (normal distribution, homogeneity of variances, reasonable large number of subjects), distribution-free statistical models were applied (Krauth, 1988). The results of these analyses are not interpreted in terms of statistical significance, but interpreted using p-values as a measure of effect. The p-value is defined as the lowest significance level at which one would still have obtained a significant result for a given data set, a given significance test, and a given test problem. This has the advantage that other researchers can decide for themselves whether the results are significant at the significance level they find acceptable. Since we have to take into consideration the fact that p-values depend on sample size we also calculated effect sizes according to Cohen (1969). Here, the d-value was used, which is the difference between two means divided by the accompanying standard deviation. A $d > 0.5$ is considered as moderate, while a $d > 0.8$ is considered large (Cohen, 1969). All statistical analyses were performed using SPSS for MAC version 11.0. We will only comment on effects associated with a $p \leqslant 0.05$ or a $d > 0.5$ (moderate effect size). In order to handle the different conditions and the possible interactions between them, and to avoid an unnecessarily large number of statistical tests, we performed a series of statistical tests that were strongly guided by a priori hypotheses. (1) We first tested for between-group differences in terms of number of incorrectly written

Table 1
Summary of neuropsychological data. Age is given in years; IQ is given in Wechsler IQ scores; the values for the ZLR, SLRT and the DRT are presented as z-scores with negative scores indicating inferior performance compared to age-matched controls. The values for the Dybuster writing test are given as total number of errors made in the Dybuster writing test

	Dyslexics	Controls			Effect-d	p
	m	s.d.	m	s.d.		
age	10.3	0.9	10.2	1.0	0.1	n.s.
IQ	104.9	12.0	112.9	11.8	−0.67	0.002
VQ	108.4	12.3	115.5	12.9	−0.56	0.005
PQ	100.5	12.1	106.1	11.7	−0.47	0.016
ZLT (time) wordlist Z-Score	−4.1	4.7	−0.82	2.7	−0.89	0.000
ZLT (time) text Z-Score	−2.7	3.0	−0.9	2.3	−0.68	0.000
SLRT + DRT5	−1.3	0.7	−0.1	1	−2.7	0.000
Dybuster-writing test at T1	74.3	31.2	39.2	24.3	1.26	0.000

IQ = total IQ, VQ = verbal IQ, PQ = performance IQ, ZLT = Zürcher Lesetest; SLRT = Salzburger Lese- und Rechtschreibtest, DRT 5 = Deutscher Rechtschreibtest 5.

Table 2
Analysis of the error types: errors in percentage

Group	O-errors	G-errors	N-errors
Controls, Words to learn	59.1%	29.7%	11.2%
Controls, Words not to learn	64.2%	26.7%	9.1%
Developmental Dyslexics, Words to learn	64.2%	23.6%	12.2%
Developmental Dyslexics, Words not to learn	66.6%	22.5%	10.8%

words at t1 (baseline), using Kruskal-Wallis tests. In case of a p-value $\leqslant$0.05 for the Kruskal-Wallis analysis, subsequent *Dunn's Multiple Comparisons Test* were performed and corrected for multiple testing. (2) To answer our main question, we tested for significant t1–t2 and t1–t3 differences for each group separately, applying the Wilcoxon matched-pairs signed-rank test. (3) In order to examine group differences in practice effects we also compared t1–t2 and t1–t3 differences, where necessary using appropriate non-parametric tests (Kruskal-Wallis or Mann-Whitney U-test).

3. Results

3.1. *Number of incorrectly written words and writing errors at T1* (*baseline*)

Table 3 presents the mean number of incorrectly written words separately for each group. Table 4 represents the corresponding data for the number of errors. We have presented both Tables because each child can make more than one error within one word. However, a close look at both tables reveals that there is no basic difference. Subjecting the three measures of *incorrectly written words* (total number of words (*alll*), words learned during the *Dybuster* training (*learned*), words not learned during the *Dybuster* training (*not learned*)) obtained at the first time point (T1) to Kruskal-Wallis analysis revealed strong between groups differences (*total*: Chi^2 $= 29.7$, d.f. $= 3$, $p < 0.0001$; *learned*: Chi^2 $= 18.8$, d.f. $= 3$, $p = 0.0003$; *not learned*: Chi^2 $= 23.5$, d.f. $= 3$, $p < 0.0001$). Subsequently performed *Dunn's Multiple Comparisons Test* revealed significantly more incorrectly written words for the developmental dyslexics compared to the control subjects (all p values < 0.001). Similarly, subjecting the writing errors obtained at T1 to Kruskal-Wallis analysis also revealed strong between group differences (*total*: Chi^2 $= 27.7$, d.f. $= 3$, $p < 0.0001$; *learned*: Chi^2 $= 17.1$, d.f. $= 3$, $p < 0.001$; *not learned*: Chi^2 $= 23.2$, d.f. $= 3$, $p < 0.0001$). Subsequently performed *Dunn's Multiple Comparisons Test* revealed significantly more errors for the developmental dyslexics compared to the control subjects (all p values < 0.001). The only exception was that CO subjects made as many writing errors (and number of incorrectly written words) as the children with developmental dyslexia for words that were not learned in the *Dybuster* training. Closer inspection of the data revealed that two of the CO subjects made atypical many writing errors. Excluding them from the analysis revealed the same amount of writing errors of for the CW group. However, we kept these subjects in our analysis in order to adhere our conservative attitude to our study.

Table 3

Total number of incorrectly written words. Indicated are means (rounded) and standard deviations (in brackets) for the three time points (T1, T2, and T3) at which the Dybuster writing test was conducted. Means are given for all words (all), the words in the Dybuster training (learned), and the words not learned (not learned) in the Dybuster training. For the number of incorrectly written words at T1 the result of the Kruskal-Wallis test is presented as p-value (K-W result). d is Cohen's effect size measures representing the difference between two means (at T1 and T2, or T1 and T3) divided by the average standard deviation. The last two columns represent the percentage change from T1 to T2 and from T1 to T3. Positive d-values represent an improvement (less number of incorrectly written words at T2 or T3). Negative d-values represent a decline of writing performance (more incorrectly written words at T2 or T3)

	T1	T2 !	T3 !!	d T1–T2	d T1–T3	% T1–T2	% T1–T3
all							
CO	39	34	23	0.25	0.86*	12.8	41.0
	(20)	(20)	(17)				
CW	27	19	17	0.73*	0.91*	29.6	37.0
	(13)	(9)	(9)				
DO	57	53	40	0.24	1.03*	7.0	29.8
	(17)	(16)	(16)				
DW	59	45	45	0.76*	0.74*	23.7	23.7
	(19)	(18)	(19)				
K-W result	$P < 0.001$						
learned							
CO	13	16	10	−0.29	0.33	−23.1	23.1
	(9)	(12)	(9)				
CW	13	8	8	1.00*	1.11*	38.5	38.5
	(6)	(4)	(3)				
DO	23	23	16	0.00	0.78*	0.0	30.4
	(9)	(9)	(9)				
DW	21	15	16	0.80*	0.67*	28.6	23.8
	(8)	(7)	(7)				
K-W result	$P < 0.001$						
not-learned							
CO	35	17	14	1.06*	1.17*	51.4	60.0
	(22)	(12)	(14)				
CW	14	10	9	0.57*	0.71*	28.6	35.7
	(8)	(6)	(6)				
DO	33	30	24	0.24	0.75*	9.1	27.3
	(13)	(12)	(11)				
DW	37	30	29	0.48*	0.55*	18.9	21.6
	(15)	(14)	(14)				
K-W result	$P < 0.001$						

! The groups CO and DO did not receive *Dybuster* training from T1 to T2.
!! The groups CW and DW did not receive *Dybuster* training from T2 to T3*
Significant difference between two time point with a p at least <0.01.

3.2. *T1–T2 differences*

The T1–T2 differences reflect the writing performance difference (either as number of incorrectly written words or as number of writing errors) between T1 (baseline) and T2. These differences are represented as effect size measures (d). As one can see from Tables 3 and 4 as well as from Figs 4 and 5 the effect sizes for the T1–T2 differences for those receiving *Dybuster* training (CW and DW) are mostly large ($d > 0.5$ to $d > 1$). To demonstrate a training effect due to *Dybuster* training, the T1-T2 difference should be larger for the children with developmental dyslexia and controls receiving training (DW and CW) compared with the subjects who did not receive any training and waited for the next *Dybuster* training session (waiting groups DO and CO). Before conducting this statistical test, we first tested for significant T1–T2 differences. The statistical evaluation (using Wilcoxon matched pairs signed rank test) of these differences revealed highly significant decreases of incorrectly written words and writing errors for all groups (**number of incorrectly written words**$=$ *total*: DW: $p < 0.0001$; CW: $p < 0.001$; *learned*: DW: $p < 0.0001$; CW: $p < 0.001$; *not-learned*: DW:

Table 4

Total number of errors (O, G and N errors). Indicated are means (rounded) and standard deviations (in brackets) for the three time points (T1, T2 and T3) at which the *Dybuster* writing test was conducted. Means are given for all words (*all*), the words in the *Dybuster* training (*learned*), and the words not learned (*not learned*) in the *Dybuster* training. For the number of incorrectly written words at T1 the result of the Kruskal-Wallis test is presented as p-value (K-W result). d is Cohen's effect size measures representing the difference between the means divided by the average standard deviation. The last two columns represent the percentage change from T1 to T2 and from T1 to T3. Positive d-values represent an improvement (less number of errors at T2 or T3). Negative d-values represent a decline of writing performance (more errors at T2 or T3)

	T1	T2 !	T3 !!	d T1–T2	d T1–T3	% T1–T2	% T1–T3
all							
CO	48	41	25	0.25	0.94*	14.6	47.9
	(29)	(27)	(20)				
CW	30	20	19	0.77*	0.83*	33.3	36.7
	(15)	(11)	(11)				
DO	69	66	48	0.12	0.83*	4.3	30.4
	(25)	(25)	(21)				
DW	77	57	58	0.59*	0.54*	26.0	24.7
	(36)	(32)	(32)				
K-W result	$P < 0.001$						
learned							
CO	17	20	12	−0.19	0.45	−17.6	29.4
	(12)	(19)	(10)				
CW	14	9	9	0.83*	0.83*	35.7	35.7
	(7)	(5)	(5)				
DO	29	28	19	0.08	0.83*	3.4	34.5
	(13)	(13)	(11)				
DW	28	20	21	0.64*	0.54*	28.6	25.0
	(14)	(11)	(12)				
K-W result	$P < 0.001$						
not-learned							
CO	43	21	17	0.94*	1.08*	51.2	60.5
	(31)	(16)	(17)				
CW	16	11	10	0.59*	0.71*	31.3	37.5
	(10)	(7)	(7)				
DO	40	38	30	0.12	0.65	5.0	25.0
	(17)	(17)	(14)				
DW	50	38	37	0.46*	0.51*	24.0	26.0
	(27)	(25)	(24)				
K-W result	$P < 0.001$						

! The groups CO and DO did not receive *Dybuster* training from T1 to T2.
!! The groups CW and DW did not receive *Dybuster* training from T2 to T3
*significant difference between two time point with a p at least <0.01.

$p = 0.0006$; CW: $p = 0.0004$; **number of writing errors** $=$ *total*: DW: $p < 0.0001$; CW: $p < 0.001$; *learned*: DW: $p < 0.0001$; CW: $p < 0.001$; *not-learned*: DW: $p > 0.0001$; CW: $p = 0.0003$). There were also some decreases for the controls and the developmental dyslexics receiving no training, however to a lesser degree (**number of incorrectly written words** $=$ *total*: DO: $p = 0.02$; CO: $p = 0.01$; *learned*: DO: $p = 0.02$; CO: $p = 0.01$; *non-learned*: DO: $p = 0.02$; CO: $p = 0.01$; **number of writing errors**: *total*: DO: $p = 0.2$ n.s.; CO: $p = 0.009$; *learned*: DO: $p < 0.0001$; CO: $p = 0.14$, n.s.; *non-learned*: DO: $p = 0.28$; CO: $p = 0.07$, n.s.). Importantly, the T1–T2 differences were strongest for the children with developmental dyslexia receiving training from T1 to T2 compared with those who did not receive training (DW vs. DO, all p-values $p < 0.001$; Mann-Whitney U-test). The DW group also revealed stronger improvements than the control subjects who did not receive *Dybuster* training (DW vs. CO: p value <0.001; Mann-Whitney U-test).

One can see from Tables 3 and 4 children with developmental dyslexia are still outperformed by the controls even after training (more writing errors at T2 for

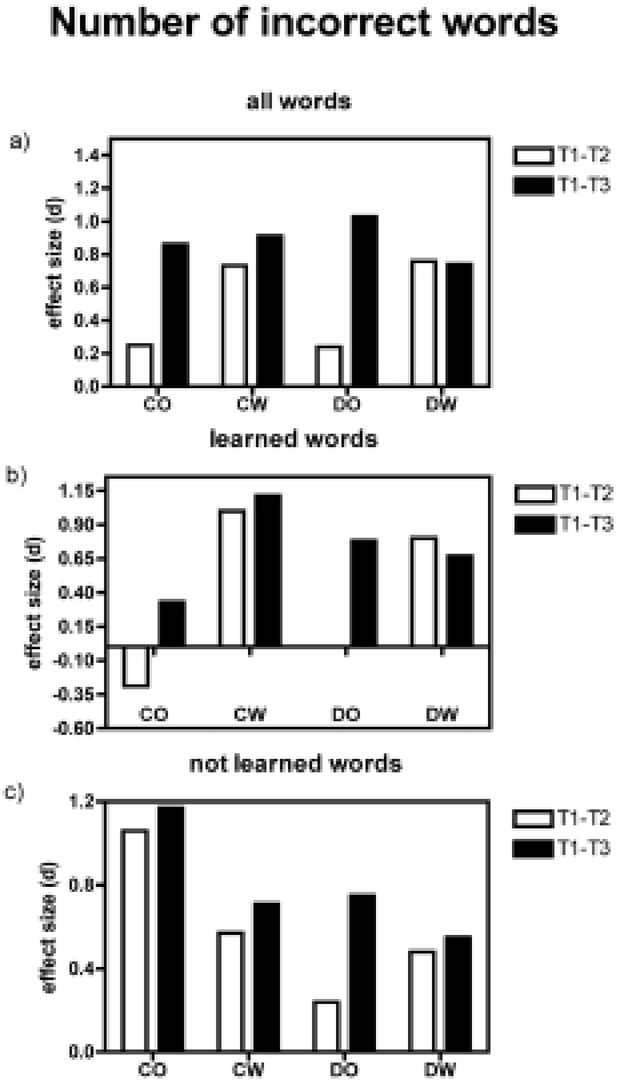

Fig. 4. Effect sizes for the t1–t2 and t1–t3 differences (as d-values) obtained for the *incorrectly written* words in the *Dybuster* writing test. An effect size > 5 indicates a moderate and a $d > 0.8$ a large improvement. Improvement is defined as reduced number of incorrectly written words and is indicated by a positive d.

DW vs. CW; all p values <0.0001).

3.3. T1–T3 differences

The T1–T3 differences reflect the difference between the number of incorrectly written words and writing errors obtained at T1 (baseline) and T3. These differences are also represented as effect size measures (d) (Tables 3 and 4 as well as Figures 4 and 5). As shown in Figs 4 and 5, the effect sizes for the T1-T3 differences are mostly large ($d > 0.5$ – $d > 1.0$). The T1–T3 differences reflect the differences between the number of incorrectly written words (and writing errors) between T1 (baseline) and T3. The T1–T3 differences are significant for the developmental dyslexics (all p-values <0.001). Thus, the DO subjects benefited from the *Dybuster* training and revealed stronger writing improvements than during the T1-T2 period. A similar specific improvement was found for the controls, however only for the all words and for the learned words (all p values at least <0.01). For the not-learned words there was no difference depending on the extraordinary

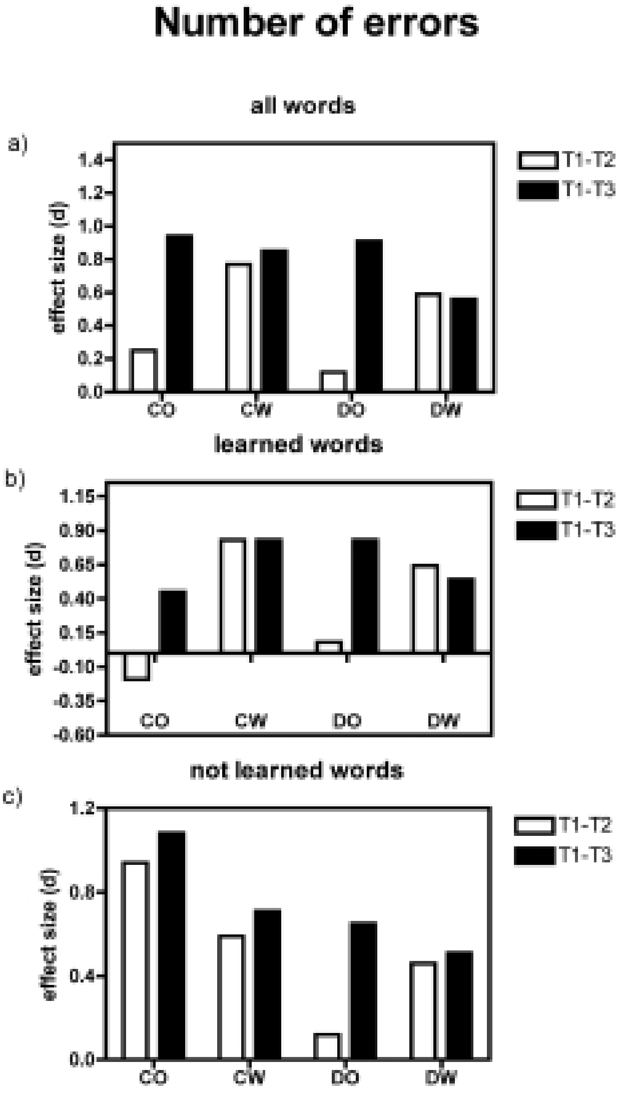

Fig. 5. Effect sizes for the t1–t2 and t1–t3 differences (as d-values) obtained for the *number of errors* in the *Dybuster* writing test. An effect size >5 indicates a moderate and a $d > 0.8$ a large improvement. Improvement is defined as reduced number in writing errors and is indicated by a positive d.

larger number of incorrectly written words (and writing errors) at T1. As mentioned above these extraordinary large numbers of incorrectly written words are due to two subjects. Eliminating those two subjects changed the figures substantially and revealed that the T1–T3 difference is larger than the T1–T2 difference in the CO subjects ($p < 0.01$).

While all subjects (even the control subjects) improved their writing skills from T1 to T3 (all p values <0.01), the developmental dyslexics who underwent *Dybuster* training during the T1–T2 period (DW) stabilized their performance and slightly improved their writing skills from T2 to T3, although they did not receive any further formal *Dybuster* training (difference between T1–T2 and T1–T3 difference not significant; $p = 0.8$).

As one can see in Tables 4 and 5, the children with developmental dyslexia are still outperformed by the controls even after training (more incorrectly written words at T2 for DW (mean ± S.D.: 45 ± 18) vs. CW (19 ± 9); all p values <0.0001). The same is true for the children with developmental dyslexia receiving

Dybuster training during the T2 to T3 time period (more incorrectly written words at T3 for DO (mean ± S.D.: 40 ± 16) vs. CO (23 ± 17); all p values <0.0001).

3.4. *Percent measures*

Impressive changes were revealed by calculating the writing improvements as percentage changes (T1–T2 difference and T1–T3 difference related to T1). Children with developmental dyslexia (DO) without training reduced their writing errors from T1 to T2 testing by about 4–7%. Thus, these children would appear to derive little benefit from regular schooling if they do not receive intensive additional support. The children with developmental dyslexia receiving *Dybuster* training reduced their writing errors by about 19–29% (depending on the writing performance measure used). Comparing the developmental dyslexics and control subjects with training reveals that both groups benefited to the same extent from the learning-software.

The results for the T1–T3 difference demonstrate that the groups with training in the second period of the study benefited from the learning software even more (descriptively) than the first training groups. Developmental dyslexics with training in the second period reduced the errors by about 25–35% (depending on the writing performance measure used). The findings also demonstrate that suspended dyslexics, that is, those who underwent the first period of training, were unable to improve their writing skills any further by simply attending school and other therapies. The suspended controls did further improve their writing skills but showed less improvement than with training. These results indicate that average writers benefit much more from regular schooling compared with dyslexics, and show that dyslexics can improve their writing skills when they undergo *Dybuster*-training.

3.5. *Transfer from learned to non-learned words*

The data further demonstrate that the children were able to improve their writing skills for the learned as well as for the non-learned words. The learned and non-learned words in *Dybuster* were carefully selected on the basis of equivalent frequency, difficulty and number of syllables. This is an important finding which indicates that both children with and without developmental dyslexia succeeded in the transfer of writing rules and linguistic knowledge in all textual strings. The data reveal a high error correlation ($r = 0.9$) between learned and non-learned words, this indicating similar difficulty in the two groups.

4. Discussion

The present experiment clearly demonstrates that this training has a beneficial effect on writing skills in developmental dyslexic and non-dyslexic children. The obvious enhancement in writing skills was achieved with a multi-medial approach designed especially to increase cross-modal associations between various visual and auditory cues. This training-related effect is also evident for words that were not trained but similar in terms of difficulty, number of syllables and occurrence in the German language corpus, thus clearly indicating processes of learning transfer from writing learned to non-learned words. It is important to note that dyslexic children derived very little benefit from regular schooling. What these children do need is an intense re-mediation to ameliorate their writing skills. The developmental dyslexics did benefit from the *Dybuster* training (19% to 35% improvement depending on the writing performance measure used) but were still outperformed by the non-dyslexics. Given that some degree of writing impairment is still present, it may be advantageous to expand or combine the training with other approaches. But there is, nevertheless, a remarkable reduction of writing errors in developmental dyslexics following *Dybuster* training, a reduction that also extends to non-learned words, thus indicating that some kind of transfer from learned to non-learned words had taken place.

The precise impact on the underlying neurological and psychological mechanism is still not fully understood. Various factors (and the interaction between different factors) may have caused the training effects: (1) The intense multisensory (visual and auditory) stimulation provided by the learning software might enhance the processing of graphemes and/or phonemes, in which case the perception of graphemes would be enhanced by our training procedure. (2) The intense three-month training period might have strengthened the memory trace and lead to a more efficient activation of the underlying associative network. If this were the operative mechanism, the *retrieval structure of graphemes* and/or *phonemes* would have been changed due to the explicit coupling of colours, symbols, and musical notes. (3) The direct feedback and presentation of the correctly written word might support learning and thus strengthen the memory trace of words, graphemes, and phonemes. (4) The motivation and ambition of the children to work with computer-based training is also a further possible contributory factor: the participating children demonstrated great pleasure working with the *Dybuster* program and understood the training more as a game than as a conventional writing training. (5) And finally, the support and interest of adults (parents, therapists, psychologists and computer scientists) might have motivated the children to work with *Dybuster*.

Taken together, a multitude of factors might have contributed to the training effect. Which of the above-mentioned factors or combination of factors are indeed responsible for the results of our study has to be shown in additional future experiments. There are also a number of unanswered questions, which should be investigated in further studies. Specifically, it should be examined whether the training also influences other language skills such as reading, reading comprehension, phonological awareness and rapid automatized naming. Furthermore, research in developmental dyslexia has revealed a deficit in verbal-memory functions (Jeffries & Everatt, 2004; Russeler, Johannes, Kowalczuk, Wieringa, & Munte, 2003; Russeler, Johannes, & Munte, 2003; Schulte-Korne, Deimel, Bartling, & Remschmidt, 2004). Because we assume that the *Dybuster* training strengthens the memory trace for phonemes and graphemes, working memory for visual and auditory verbal information might also be enhanced. It would also be helpful to examine whether the Dybuster training exerts influence on other memory functions such as phonological short-term memory, working memory, and long-term representations of graphemes or phonemes. One should also discuss the difference in general IQ of children with developmental dyslexia (IQ = 104.9) and children who served as controls (112.9). Even though one would have wished to perform the study with groups that match in general IQ we do not think that this difference has any serious implications for the study. It is rather interesting to note the large improvements in writing skills of children with developmental dyslexia albeit they had a lower general IQ.

A further open question is whether our remediation program induces cortical functional plasticity. Only few studies have investigated the changed neural activation patterns due to developmental dyslexia remediation. Two of the few published studies have employed a widely used dyslexia re-mediation program (Fast ForWord-Language®) in children with developmental dyslexia (Temple et al., 2003; Temple et al., 2001). Before training, the children with developmental dyslexia exhibited an absence of left temporo-parietal activation and a displacement of the left prefrontal activation exhibited by typical reading children performing a phonological task. After training, the dyslexic children's oral language and reading performance had significantly improved. In addition, the children with developmental dyslexia showed increased activations in the left temporo-parietal and left prefrontal regions during phonological task performance after training. Thus, the pattern of brain activation in dyslexic children bears greater similarity to normal-reading children after re-mediation. A similar finding was reported of increased activation in left hemisphere posterior language regions and left inferior frontal gyrus in children with developmental dyslexia following a phonologically-based remediation, using an auditory-visual cross-modal phonological task (Shaywitz et al., 2004). A very recent paper examined the neural correlates of rapid auditory processing in dyslexic and non-dyslexic children, using fMRI. The children listened to nonlinguistic acoustic stimuli, with either rapid or slow transitions, designed to mimic the spectro-temporal structure of consonant-vowel-consonant speech syllables (Gaab, Gabrieli, Deutsch, Tallal, & Temple, in press). While normal-reading children showed activation for rapid compared with slow transitions in left prefrontal cortex, children with developmental dyslexia did not show any differential response in these regions to rapid versus slow transitions. After eight weeks of re-mediation focusing primarily on rapid auditory processing, the children with developmental dyslexia showed significant improvements in language and reading skills, and exhibited activation for rapid relative to slow transitions in left prefrontal cortex. Taken together, these studies demonstrate that appropriate developmental dyslexia remediation is also accompanied by changed activation patterns in a left-sided language-related network.

5. Conclusion

We explored whether a newly designed software program (*Dybuster*) for remediation of developmental dyslexia has a beneficial effect on writing errors in dyslexic and non-dyslexic children. *Dybuster* is designed to strengthen multimodal associations between visual and auditory cues in the context of a game-like training. The children with developmental dyslexia and controls substantially improved their writing by practicing 15–30 minutes a day for about 3 months. This improvement was even evident for non-learned words that they did not practice in the *Dybuster* training, thus revealing the involvement of learning transfer mechanisms.

Acknowledgement

We thank the Swiss Dyslexia Association for helping to recruit the dyslexic children; all children and parents for participating in the user study; Basil Weber and Ghislain Fourny for their support in programming the *Dybuster* prototype; and Doo-Young Kwon for designing its interface. We would also like to express our gratitude to the "Schweizerischer National Fonds" (Swiss National Foundation) that sponsored the work of LJ and MM (SNF grant 46234101 and SNF grant 3200B0-105877).

References

Bacon, A. M., Handley, S. J., & McDonald, E. L. (2007). Reasoning and dyslexia: a spatial strategy may impede reasoning with visually rich information. *Br J Psychol*, *98*(Pt 1), 79-92.

Besson, M., Schön, D., Moreno, S., Santos, A., & Magne, C. (in press). Influence of musical expertise and musical training on pitch processing in music and language. *Restorative Neurology and Neuroscience*.

Cianchetti, C., Corona, S., Foscoliano, M., Contu, D., & Sannio-Fancello, G. (2007). Modified Wisconsin Card Sorting Test (MCST, MWCST): Normative Data in Children 4-13 Years Old, According to Classical and New Types of Scoring. *Clin Neuropsychol*, *21*(3), 456-478.

Cohen, J. (1969). *Statistical Power Analysis for the Behavioral Sciences*. New York: Academic Press.

Demonet, J. F., Taylor, M. J., & Chaix, Y. (2004). Developmental dyslexia. *Lancet*, *363*(9419), 1451-1460.

Edwards, L. (2003). Writing instruction in kindergarten: examining an emerging area of research for children with writing and reading difficulties. *J Learn Disabil*, *36*(2), 136-148; discussion 149-150.

Elbro, C., Nielsen, I., & Petersen, D. K. (1994). Dyslexia in adults: Evidence for deficits in non-word reading and in the phonological representations of lexical item. *Annals of Dyslexia*, *44*, 205-226.

Fletcher, J. M., Shaywitz, S. E., Shankweiler, D. P., Katz, L, Liberman, I. Y., Stuebing, K. K., et al. (1994). Cognitive Profiles of Reading Disability: Comparisons of Discrepancy and Low Achievement Definitions. *Journal of Educational Psychology*, *86*, 6-23.

Gaab, N., Gabrieli, J. D. E., Deutsch, G. K., Tallal, P., & Temple, E. (in press). Neural correlates of rapid auditory processing are disrupted in children with developmental dyslexia and ameliorated with training: an fMRI study. *Restorative Neurology and Neuroscience*.

Galaburda, A. M., LoTurco, J., Ramus, F., Fitch, R. H., & Rosen, G. D. (2006). From genes to behavior in developmental dyslexia. *Nat Neurosci*, *9*(10), 1213-1217.

Galaburda, A. M., Sherman, G. F., Rosen, G. D., Aboitiz, F., & Geschwind, N. (1985). Developmental dyslexia: four consecutive patients with cortical anomalies. *Ann Neurol*, *18*(2), 222-233.

Gillund, G. & Shiffrin, R. M. (1984). A retrieval model for both recognition and recall. *Psychol Rev*, *91*(1), 1-67.

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends Cogn Sci*, *7*(12), 534-540.

Gross, M. & Vögeli, C. (submitted). The Display of Words Using Visual and Auditory Recoding, IEEE Transactions on Visualization and Computer Graphics.

Grund, M., Haug, G., & Naumann, C. L. (1995). Diagnostischer Rechtschreibtest 5. Klasse. Weinheim: Beltz-Verlag.

Hari, R., Renvall, H., & Tanskanen, T. (2001). Left minineglect in dyslexic adults. *Brain*, *124*(Pt 7), 1373-1380.

Hari, R., Valta, M., & Uutela, K. (1999). Prolonged attentional dwell time in dyslexic adults. *Neurosci Lett*, *271*(3), 202-204.

Hatcher, P. J., Hulme, C., Miles, J. N., Carroll, J. M., Hatcher, J., Gibbs, S., et al. (2006). Efficacy of small group reading intervention for beginning readers with reading-delay: a randomised controlled trial. *J Child Psychol Psychiatry*, *47*(8), 820-827.

Hill, G. T. & Raymond, J. E. (2002). Deficits of motion transparency perception in adult developmental dyslexics with normal unidirectional motion sensitivity. *Vision Res*, *42*(9), 1195-1203.

Jeffries, S. & Everatt, J. (2004). Working memory: its role in dyslexia and other specific learning difficulties. *Dyslexia*, *10*(3), 196-214.

Krauth, J. (1988). *Distribution-free statistics. An application-oriented approach*. New York, Oxford: Elsevier.

Kujala, T., Karma, K., Ceponiene, R., Belitz, S., Turkkila, P., Tervaniemi, M., et al. (2001). Plastic neural changes and reading improvement caused by audiovisual training in reading-impaired children. *Proc Natl Acad Sci USA*, *98*(18), 10509-10514.

Landerl, K., H, W., & Moser, E. (1997). *Der Salzburger Lese- und Rechtschreibtest* (*SLRT*). Bern: Verlag Hans Huber.

Linder, M. & Grissemann, H. (2000). *Zürcher Lesetest*. Bern-Göttingen: Hogrefe-Verlag.

Livingstone, M. S., Rosen, G. D., Drislane, F. W., & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proc Natl Acad Sci USA*, *88*(18), 7943-7947.

Lorusso, M. L., Facoetti, A., Paganoni, P., Pezzani, M., & Molteni, M. (2006). Effects of visual hemisphere-specific stimulation versus reading-focused training in dyslexic children. *Neuropsychol Rehabil*, *16*(2), 194-212.

Lovegrove, W. J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability: differences in contrast sensitivity as a function of spatial frequency. *Science*, *210*(4468), 439-440.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: auditory processing or phonological coding? *J Exp Child Psychol*, *64*(2), 199-231.

Murray, M. M., Foxe, J. J., & Wylie, G. R. (2005). The brain uses single-trial multisensory memories to discriminate without awareness. *Neuroimage*, *27*(2), 473-478.

Nicolson, R. I., Fawcett, A. J., Berry, E. L., Jenkins, I. H., Dean, P., & Brooks, D. J. (1999). Association of abnormal cerebellar activation with motor learning difficulties in dyslexic adults. *Lancet*, *353*(9165), 1662-1667.

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: the cerebellar deficit hypothesis. *Trends Neurosci*, *24*(9), 508-511.

O'Shaughnessy, T. E. & Swanson, H. L. (2000). A comparison of two reading interventions for children with reading disabilities. *J Learn Disabil*, *33*(3), 257-277.

Pennington, B. F., Van Orden, G. C., Smith, S. D., Green, P. A., & Haith, M. M. (1990). Phonological processing skills and deficits in adult dyslexics. *Child Dev*, *61*(6), 1753-1778.

Raaijmakers, J. G. & Shiffrin, R. M. (1992). Models for recall and recognition. *Annu Rev Psychol*, *43*, 205-234.

Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensorimotor dysfunction? *Curr Opin Neurobiol*, *13*(2), 212-218.

Robichon, F., Besson, M., & Habib, M. (2002). An electrophysiological study of dyslexic and control adults in a sentence reading task. *Biol Psychol*, *59*(1), 29-53.

Russeler, J., Gerth, I., & Munte, T. F. (2006). Implicit learning is intact in adult developmental dyslexic readers: evidence from the serial reaction time task and artificial grammar learning. *J Clin Exp Neuropsychol*, *28*(5), 808-827.

Russeler, J., Johannes, S., Kowalczuk, J., Wieringa, B. M., & Munte, T. F. (2003). Developmental dyslexics show altered allocation of attention in visual classification tasks. *Acta Neurol Scand*, *107*(1), 22-30.

Russeler, J., Johannes, S., & Munte, T. F. (2003). Recognition memory for unfamiliar faces does not differ for adult normal and dyslexic readers: an event-related brain potential study. *Clin Neurophysiol*, *114*(7), 1285-1291.

Santos, A., Joly-Pottuz, B., Moreno, S., Habib, M., & Besson, M. (2007). Behavioural and event-related potentials evidence for pitch discrimination deficits in dyslexic children: improvement after intensive phonic intervention. *Neuropsychologia*, *45*(5), 1080-1090.

Schulte-Korne, G., Deimel, W., Bartling, J., & Remschmidt, H. (2004). Neurophysiological correlates of word recognition in dyslexia. *J Neural Transm*, *111*(7), 971-984.

Shaywitz, B. A., Shaywitz, S. E., Blachman, B. A., Pugh, K. R., Fulbright, R. K., Skudlarski, P., et al. (2004). Development of left occipitotemporal systems for skilled reading in children after a phonologically- based intervention. *Biol Psychiatry*, *55*(9), 926-933.

Shaywitz, S. E. (1998). Dyslexia. *N Engl J Med*, *338*(5), 307-312.

Skottun, B. C. (2000). The magnocellular deficit theory of dyslexia: the evidence from contrast sensitivity. *Vision Res*, *40*(1), 111-127.

Stanovich, K. E. & Siegel, L. J. (1994). Phonotypic Performance Profile of Children With Reading Disabilities: A Regression-Based Test of the Phonological-Core Variable-Difference Model. *Journal of Educational Psychology*, *86*, 24-53.

Stein, J. (2001). The Magnocellular Theory of Developmental Dyslexia. *Dyslexia*, *7*, 12-36.

Steingruber, H. J. (1971). [Measuring of laterality]. *Z Exp Angew Psychol*, *18*(2), 337-357.

Steinhausen, H. C. (2002). Psychische Störungen bei Kindern und Jugendlichen Lehrbuch der Kinder- und Jugendpsychiatrie (5. Aufl.). München, Jena: Verlag Urban & Fischer.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain Lang*, *9*(2), 182-198.

Tallal, P. (2004). Improving language and literacy is a matter of time. *Nat Rev Neurosci*, *5*(9), 721-728.

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., et al. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. *Proc Natl Acad Sci USA*, *100*(5), 2860-2865.

Temple, E., Poldrack, R. A., Salidis, J., Deutsch, G. K., Tallal, P., Merzenich, M. M., et al. (2001). Disrupted neural responses to phonological and orthographic processing in dyslexic children: an fMRI study. *Neuroreport*, *12*(2), 299-307.

Tewes, U., Rossmann, P., & U, S. (1999). *Hamburg-Wechsler-Intelligenztest für Kinder* (3. Auflage). Bern: Verlag Hans Huber.

Uther, M., Kujala, A., Huotilainen, M., Shtyrov, Y., & Naatanen, R. (2006). Training in Morse code enhances involuntary attentional switching to acoustic frequency: Evidence from ERPs. *Brain Res*, *1073-1074*, 417-424.

Vadasy, P. F., Jenkins, J. R., & Pool, K. (2000). Effects of tutoring in phonological and early reading skills on students at risk for reading disabilities. *J Learn Disabil*, *33*(6), 579-590.

Vukovic, R. K. & Siegel, R. S. (2006). The Double-Deficit Hypothesis: a comprehensive analysis of the evidence. *J Learn Disabil*, *39*(1), 579-590.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related. Phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology*, *30*, 73–87.

Organization, W. H. (1993). *ICD-10. The international classification of diseases, Vol. 10: Classification of mental and behavioural disorders.* Geneva: World Health Organization.

Ziegler, A., Konig, I. R., Deimel, W., Plume, E., Nothen, M. M., Propping, P., et al. (2005). Developmental dyslexia–recurrence risk estimates from a german bi-center study using the single proband sib pair design. *Hum Hered*, *59*(3), 136-143.