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ORIGINAL CONTRIBUTION

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Does successful training of temporal processing of sound and phoneme stimuli improve reading and spelling?

Abstract *Objective* The aim of this study was to measure and train auditory temporal processing in children with dyslexia and to examine whether there was a transfer of improved auditory temporal processing to reading and spelling skills. *Methods* Computer-based procedures to measure and train temporal processing of sound and phoneme stimuli were developed. Test-scores for a normal control group consisting of 8-year-olds were established. Second graders with dyslexia were included in the training condition and divided into three groups: a control group, a group specifically trained in sound processing, and a third group specifically trained in phoneme processing. After an initial diagnostic procedure, both training groups received specific training every day for 4 weeks. All children, regardless of the group, received the same standard reading training programme designed for children with dyslexia at school. Outcome measures were assessed immediately after training as well as 6 and 12 months later. *Results* Tests for temporal processing of sound and phoneme stimuli proved to be highly reliable. Children with dyslexia ($N = 44$) showed impaired auditory processing of sound and phoneme stimuli compared to normal controls ($N = 51$). There was a specific significant improvement in sound, respectively phoneme, processing for the training groups immediately after the end of training. The improvement of phoneme processing remained stable after 6 months and as a trend after 12 months. After 6 and 12 months of training, children of all three groups improved significantly in reading no matter what group. In spelling, the sound training group had a slight advantage after 6 months, which was not stable after 12 months. *Conclusions* Auditory temporal processing could be trained effectively at the sound and phoneme levels. However, no significant stable transfer of these improved abilities on reading and spelling exceeding the effect of the school-based standard training was demonstrated.

Key words sound and phoneme training – reading – spelling – dyslexia – auditory temporal processing

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Introduction

The study presented refers to the work of Merzenich et al. [24] and Tallal et al. [36] who trained children with a developmental language disorder by phoneme and sound stimuli for 4 weeks through daily sessions of 20 min and later incorporated these elements to a commercially available training programme Fast ForWord (FFW) [31] for children impaired in language and/or reading development. They assumed that these children had problems mainly in processing rapid speech elements due to temporal auditory processing deficits. They supposed that this ability may be trained with a positive effect on language development, which was demonstrated in the above-cited 1996 studies in small samples of 7 and 22 children, respectively, with a gain of language development of 1½ years.

Since many children with dyslexia show a developmental language disorder as well and/or deficits in

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phonological processing, especially in rapid temporal discrimination tasks [22, 30], the conclusion has been made that such a training may not only improve the addressed basic deficits, but also reading and spelling skills [12, 28]. While these studies did not examine this hypothesis empirically, McAnnaly et al. [21] and Hayes et al. [14] could not show a transfer from improved auditory processing to reading or spelling.

According to the researchers who designed FFW, improvements in temporal processing are thought to make children more adept at learning and using spoken and written language [38]. There are two main concerns about this claim. Firstly, there are inconsistent results in exploratory studies with FFW [11]. They state that the question whether children will be in a better position to profit from regular classroom instruction in reading and writing after FFW training awaits further investigation. The reported effects of FFW are said to be inconsistent and might not be specific to FFW. Secondly, the FFW training programme contains not only training of temporal auditory processing, but also elements of training of phonological awareness, language comprehension, and grammatical structure and rules which may be responsible for possible training effects.

Many studies of recent years found deficits in phonological processing for children with reading and spelling disability [e. g. 9, 35, 40]. Phonological awareness in preschoolers has been shown to predict later reading and spelling ability [e. g. 3]; training of phonological awareness in kindergarten may even successfully prevent reading and spelling problems during elementary school [4, 20, 29]. There is an ongoing controversy in the scientific discussion, whether impaired phonological awareness is caused by impaired temporal auditory processing. While some studies provide evidence for the hypothesis [13, 25, 26, 34, 35], some recent studies doubt this causal linkage [4, 8, 15, 17, 27, 32].

Commercially distributed training programmes based on these assumptions are recommended by experts (e. g. Fast ForWord Language, Scientific Learning Corporation, Oakland, CA; Audiva GmbH, Kandern, Germany). While it has been shown that auditory processing can be trained successfully, evidence for a transfer of such a specific training to reading and spelling ability is still lacking.

The aim of the study presented here was to examine whether a successful training of auditory temporal processing of sounds and phonemes improves reading and spelling ability when combined with standard school-based training for children with dyslexia. A training similar to the procedures described by Merzenich et al. [24] was performed. It is supposed that improvements of temporal sound processing should facilitate various aspects of speech processing, such as phoneme perception, phoneme discrimination and phoneme sequencing, which finally might result in better reading and spelling. Better temporal processing of phonemes could even more directly influence language processing. Outcome in the trained modalities immediately after training and 6 and 12 months later, as well as a possible transfer to reading and spelling 6 and 12 months after training, was assessed and analysed.

Methods

Participants

All children who participated in our study came from three primary schools from the Rhein-Neckar-county in southern Germany. These three schools were selected because they offered a special school training programme (training centres called "reading islands") for children with dyslexia. Three independent samples (A, B, C) of children, all between the end of first and the middle of second grade, were drawn. Only children with written consent from their parents were included.

Sample A was used to test the reliability of the sound and phoneme processing tasks. Two complete classes ($N = 37$) of children at the beginning of second grade of primary school were included. To be eligible for this sample, German had to be their first language.

Sample B consisted of a group of normal children ($N = 51$) who were used to determine the range of normal performance on the sound and phoneme processing tasks. Children (30 boys, 21 girls, mean age 8.0 years) without spelling problems from three classes, one from each school, at the beginning of the second grade of primary school were included. Eligibility criteria were: (i) first language German; (ii) IQ not below the normal range (IQ test-score ≥ 85); and (iii) normal spelling ability (test-score for spelling not more than 1 *SD* below mean). IQ and spelling tests were collected specifically for the study by group testing.

Sample C consisted of three groups of children with dyslexia ($N = 44$) who participated in one of three training programmes: (1) sound processing and reading training (10 boys, 5 girls, mean age 7.8 years); (2) phoneme processing and reading training (9 boys, 5 girls, mean age 8.0 years); or (3) reading training only (6 boys, 9 girls, mean age 8.3 years). All children took part in the school training programme for dyslexia. For a period of 10–12 weeks, they had 2 h every day of special intensive reading training in small groups. Eligibility criteria were: (i) first language German; (ii) normal IQ (IQ test-score > 85); (iii) reading and/or spelling problems (test-score for reading and/or spelling more than 1 *SD* below mean); (iv) IQ score more than 1 *SD* above reading or spelling score; and (v) no peripheral hearing problems. All children completed the pre- and post-training assessments and the follow-up evaluation 6 months after training. Due to financial and time limitations, only 27 children (9 from each group) completed the 12-month follow-up.

Design and instruments

In order to test the reliability of the sound and phoneme test, all children from sample A repeatedly accomplished sound (S) and phoneme (P) tests, with an interval of one week to measure retest-reliability. To control for sequence effects, one group received the test order SP-SP; the other group received the test order PS-PS.

The children of the control group from sample B completed a non-verbal IQ-test (CFT1: Culture Fair Test, Scale 1) (Cattell 1966, German version [41]), a spelling test (WRT1+) [5], as well as sound and phoneme processing tests. The spelling test WRT1+ is a text with blanks to fill in according to the teacher's dictation.

The children with dyslexia from sample C were divided into three subgroups: (i) group 1 (sound group) received an adaptive training of temporal processing of sounds (4 weeks) additionally to the intensive daily reading training for 3 months at school; (ii) group 2 (phoneme group) received an adaptive training of temporal processing of phonemes (4 weeks) in addition to the intensive daily reading training for 3 months at school; and (iii) group 3 (control group) received only an intensive daily reading training for 3 months at school.

The procedure allocating the children to the three different experimental training conditions was as follows. During one year (including three 10- to 12-week training periods), children with dyslexia from the three school training centres that fulfilled the selection criteria were included. Alternating for the three training periods, the children from one training centre served as the control group (group 3), while the children from the two other centres were allocated to the sound (group 1) or phoneme (group 2) training group using *block randomization* to achieve balance between groups in size and characteristics. Since reading and spelling were the most interesting outcome variables of our study, pairs of children with similar reading and spelling scores were assorted and, for each pair, a random procedure was used to determine which child was assigned to the sound and the phoneme training group.

Our prospective training study comprises a pre-test measure, a training period of 4 weeks, and three follow-up measures 0, 6 and 12 months after training. Children of group 1 (sound training) and group 2 (phoneme training) received their specific training for 4 weeks daily from Monday to Friday for 20 min integrated in the school training common for all three groups. Directly before the training (t_0), the mean interstimulus intervals (ISIs) of sound and phoneme processing tests [*A*daptive *T*est for *S*ound stimuli (*AT-S*) and *A*daptive *T*est for *P*honeme stimuli (*AT-P*), see description below] of all children were assessed, in addition to non-verbal intelligence (CFT1), reading (Salzburg Reading and Orthography Test, SLRT, [19], testing speed and correctness of reading aloud) and spelling (WRT1+, testing conventional spellings). Reading time was used for further analysis. Directly after the training (t_1), only AT-S and AT-P were measured. Six (t_2) and 12 (t_3) months later, all tests (without CFT1) were repeated (WRT2+, respectively WRT3+, according to grade [6, 7]) to assess variations over time and whether there is a transfer effect from sound and/or phoneme training on reading and spelling.

The analysis of the data from the training study was done using random-effects regression models with the statistics package Stata 8. Pairwise post hoc comparisons of the changes over time between the three groups were done with Wald tests and Sidak adjustment for multiple testing.

Methods of sound and phoneme test and training procedures

*A*daptive *T*est for *S*ound stimuli (AT-S)

The software (LTrain) of the test and training programmes generated at random four octave-per-second upward- or downward-gliding (U and D, respectively) frequency-modulated tonal pairs (U-U, U-D, D-U and D-D) as given by Merzenich et al. 1996. These sounds started at 1000 Hz, had a duration of 270 ms, and were separated by an interstimulus interval (ISI) of 500 ms (Fig. 1).

The child had to identify the type and order of the two stimuli. After three correct answers, the ISIs were reduced in non-linear steps (500, 400, 300, 250, 200, 170, 140, 110, 90, 70, 50, 40, 30, 25, 20, 15, 10, 7, 3, 0 ms). After one incorrect answer, the ISIs were raised respectively. A minimum of 60 and a maximum of 80 pairs of stimuli were given in total. Performance was defined by the mean of the ISIs over all trials. A minimum value of mean ISI (maximum performance) of 121 ms was reached in tests without mistakes in 60 trials; a maximum value of ISI (minimal performance) of 500 ms was reached, if no sequence of three correct answers was achieved over 80 trials.

Adaptive training of sound processing

Whereas the sound processing test was fixed at a stimulus duration of 270 ms, the stimulus duration in the training condition could vary stepwise in an adaptive way between 1000 and 80 ms (steps: 1000, 500, 380, 270, 160, 130, 100, 80 ms). In a pretest at the beginning of the training, the stimulus duration was adapted to the

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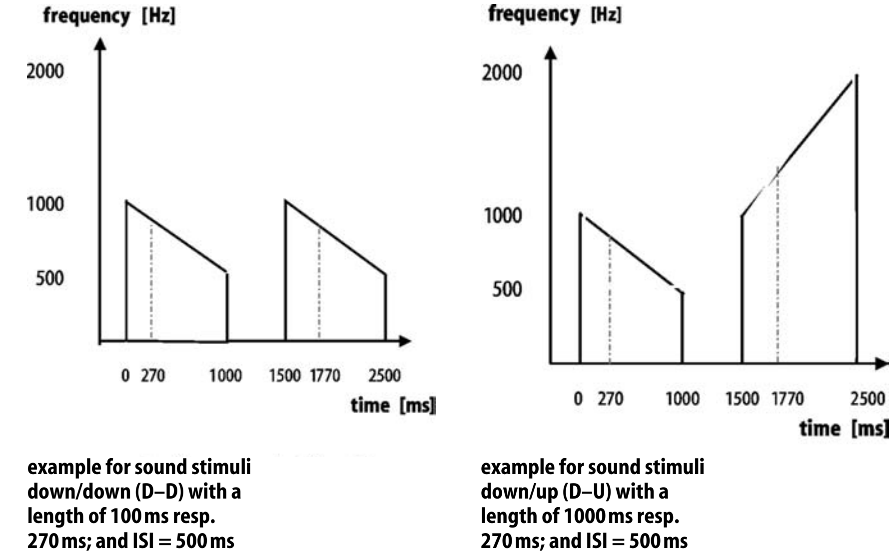
Fig. 1 Sound stimuli down – down and down – up with variations in sound duration and interstimulus interval (ISI) of 500 ms



child's ability. We started the training with the shortest stimulus duration (tonal pairs with ISI = 500 ms) at which the child was able to give six correct answers in sequence. The stimulus duration was reduced when an ISI of 0 ms was reached.

*A*daptive *T*est for *P*honeme stimuli (AT-P)

Using the software LTrain, random combinations of two consonant-vowel (CV) stimuli with contrasting consonants in rapid sequences were generated. Six different stimuli ("pa", "ba", "ta", "ga", "ka" und "da") were used allowing for 36 pairs. The children had to identify the two stimuli and their order. ISIs were adapted as given for the AT-S.

Adaptive training of phoneme processing

The phoneme training was made up of modified speech stimuli. The main variables were the duration of consonants (and reciprocally of the following vowels; the total CV duration was constant), the magnitude of a 0 to +20 dB amplification of the consonant elements vs. vowel intensity, and the ISIs between presented CV pairs. The same CV pairs as in the AT-P were used. Adaptations were as follows: duration of consonants started at 70 ms, amplification at +20 dB, and ISI at 500 ms. Adaptation of ISIs was from 500 ms to 0 ms using the same steps as in test condition, adaptation in consonant duration from 70 to 35 ms in seven steps and a final eighth step to the original natural length of the consonant. Adaptation in amplification was from +20 dB to 0 dB in seven steps.

In all test and training conditions, stimuli were given by closed headphones. The tasks were explained to the child by the instructors who were present during all trials. Sufficient practice trials were given to ensure comprehension. The child gave verbal response and the instructor coded each answer into the computer program. Visual feedback was given after each correct answer. Tests and training were not presented in a game format. In training conditions, short video films were presented as reinforcements when a child achieved higher levels of performance. Each training session lasted about 20 min, irrespective of performance.

Data analyses

Sample characteristics and test-scores at different time points were described with means and standard deviation. Differences in the samples were tested with Pearson Chi-Square test for gender and analysis of variance for age, IQ, and baseline scores for reading, spelling and processing of sounds and phonemes. The effect of the treatment on reading, spelling, sound and phonemes processing were analysed using random effect regressions. For a detailed explanation of the advantages of random effect regressions over analysis of variance for repeated measurements, see Gibbons et al. [10]. Pairwise group comparisons were done with Wald tests and Sidak adjustment to compensate for multiple comparisons.

Results

Retest reliability

The retest reliability of the AT-S (sound processing) and the AT-P (phoneme processing) was assessed in two samples of 18 (A1) and 19 (A2) children, respectively. In both samples, the tests were given back-to-back and repeated after 1 week. In sample A1, the sequence was: AT-S/AT-P – 1 week interval – AT-S/AT-P, with reliability scores of $r_{tt} = 0.94$ for AT-S and $r_{tt} = 0.86$ for AT-P. In sample A2, the sequence was: AT-P/AT-S – 1 week interval – AT-P/AT-S, with reliability scores of $r_{tt} = 0.95$ for AT-P and $r_{tt} = 0.85$ for AT-S.

Comparison of children without and with dyslexia

Control children without dyslexia (sample B) and children with dyslexia (sample C) had very similar sex and age distributions [sample B: 59% boys, mean age 8.0 (SD = 0.4)/sample C: 57% boys, mean age 8.0 (SD = 0.6)]. Test-scores for IQ, spelling, temporal processing of sounds (AT-S) and phonemes (AT-P) are shown in Table 1.

The mean IQ was significantly higher for the children with dyslexia; therefore, group comparisons of spelling, sound and phoneme test-scores were controlled for IQ. As expected, the control group had normal spelling abilities with a mean score close to the norm population, whereas the mean spelling score of the dyslexic group was about 1.3 *SD* below the population norm. The children with dyslexia showed significantly lower abilities of sound and phoneme processing.

When compared with the control group, temporal processing was more impaired for phonemes (effect size = 1.7) than for sounds (effect size = 0.51) in the group of children with dyslexia. In the combined group of children without and with dyslexia ($N = 95$), the correlation between spelling ability and sound processing was $r = 0.28$ ($p < 0.05$), and between spelling ability and phoneme processing was $r = 0.50$ ($p < 0.05$).

Table 1 Test-scores for IQ, spelling, temporal processing of sounds (AT-S) and phonemes (AT-P) for children with and without dyslexia

	Control group n = 51 mean (sd)	Children with dyslexia n = 44 mean (sd)	Probability of Ho: difference = 0 prob
IQ	96.7 (10.2)	103.4 (11.4)	0.003[c]
spelling[a]	52.1 (7.3)	37.2 (6.3)	0.000[d]
mean ISI/AT-S[b]	320.5 (157.3)	400.5 (127.6)	0.01[d]
mean ISI/AT-P[b]	189.8 (106.4)	369.6 (119.1)	0.000[d]

[a] Scores (mean = 50 SD = 10 in norm population); [b] A minimum value of mean ISI (maximum performance) of 121 ms is possible in tests without mistakes, a maximum value of ISI (minimal performance) of 500 ms, if no sequence of three correct answers was achieved within 80 trials (see methods); [c] T-Test; [d] ANOVA controlling for IQ

Results from the training study

Training results

The levels reached at the end of the sound training varied widely (see Table 2). Most children started the training with sound durations longer than 270 ms (test condition) and reached a final level of 270 ms or even below. Only two children (T2 and T12) did not reach a stimulus duration of 270 ms at the end of training. In the phoneme training group, all but two children finished the programme successfully through all possible levels.

Comparison of the three training groups

Group characteristics and test-scores, including sex distribution, age, and data (mean and standard deviation) for IQ, spelling, reading, temporal processing of sounds (AT-S) and phonemes (AT-P) at different points of time are shown in Table 3.

Firstly, group differences at t_0 (pre-treatment) were analysed. The three training groups showed no significant differences for sex distribution [$\chi^2(2, 41) = 2.64$, $p = 0.27$] and age [ANOVA $F(2, 41) = 2.85$, $p = 0.07$]. Since there were significant group differences for IQ [ANOVA $F(2, 41) = 4.09$, $p = 0.024$ and Kruskal-Wallis test $\chi^2(2, 41) = 6.63$, $p = 0.036$], all further analyses were performed controlling for IQ. At t_0, the groups showed no significant differences for spelling [ANCOVA group $F(2, 40) = 0.22$, $p = 0.92$], reading [ANCOVA group $F(2, 40) = 0.35$, $p = 0.71$], temporal processing of sounds [Robust regression $F(2, 40) = 0.46$, $p = 0.64$] or phonemes [ANCOVA group $F(2, 40) = 0.69$, $p = 0.51$].

Table 2 Individual training results for the children of the sound training group

Child	Sound duration at the start of training (ms)	Sound duration at the end of training (ms)	ISI at the end of training (ms)
S1	380	130	25
S2	1000	500	300
S3	1000	160	140
S4	270	80	110
S5	270	100	25
S6	1000	270	0
S7	500	80	50
S8	500	130	250
S9	380	100	25
S10	500	270	10
S11	500	270	0
S12	1000	380	25
S13	380	80	170
S14	380	80	30
S15	1000	270	140

Table 3 Group characteristics and test-scores at different points of time for the three training groups of children with dyslexia

		Standard training	Sound training	Phoneme training	Total
N[a]		15	15	14	44
Sex (boys/girls)		6/9	10/5	9/5	25/19
Age (years)	t_0	8.3±0.4	7.8±0.7	8.0±0.6	8.0 ±0.6
IQ	t_0	97.7±7.1	103.8±8.3	109.0±15.2	103.4±11.4
Spelling WRT (T-values)	t_0	37.2±9.3	36.5±4.0	38.0±4.2	37.2±6.3
	t_2	36.0±7.6	41.7±6.6	34.6±8.8	37.5±8.1
	t_3	38.3±3.3	40.2±7.2	34.2±10.3	37.6±7.6
Reading SLRT (T-values)	t_0	32.5±6.8	32.1±10.9	35.1±9.7	33.2±9.2
	t_2	37.3±8.4	41.1±8.9	39.6±8.0	39.3±8.4
	t_3	42.1±8.1	45.8±11.2	40.3±7.2	42.7±9.0
AT-S mean ISI (ms)	t_0	456±50	410±118	331±165	400±128
	t_1	418±109	203±125	298±139	306±151
	t_2	360±123	286±144	292±165	313±145
	t_3	394±96	235±134	223±135	284±142
AT-P mean ISI (ms)	t_0	383±124	341±122	385±114	369±119
	t_1	304±151	297±134	171±118	370±119
	t_2	292±142	228±137	172±99	232±135
	t_3	269±146	192±109	176±57	212±114

Note. Data are given as mean ± standard deviation; t_0 = pre-treatment; t_1 = post-treatment; t_2 = 6-month follow-up; t_3 = 12-month follow-up
[a] at t_3 sample size was n = 9 for each group due to termination of the study

Secondly, group differences for the variations of sound and phoneme test-scores across time were analysed (controlling for IQ) using random-effects regression models. In Figs. 2 and 3, the course of sound and phoneme test-scores for the three groups of children with dyslexia (control, sound, phoneme) at four points of time (t_0 = pre-training, t_1 = post-training, t_2 = 6-month follow-up, t_3 = 12-month follow-up) is graphically shown.

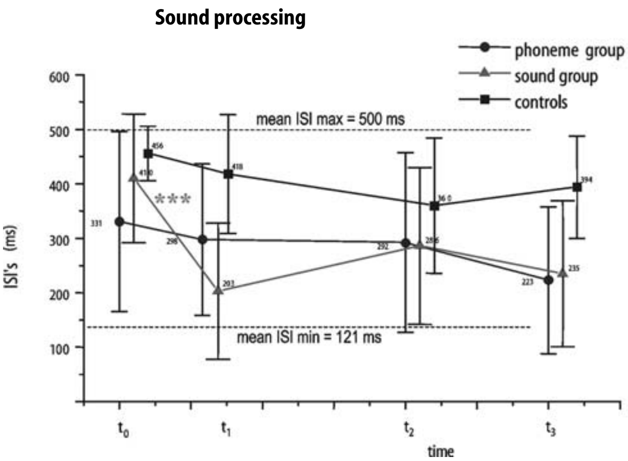


Fig. 2 Change of test-scores for sound processing (as given in Table 3) for three groups of children with dyslexia (group means by symbols and standard deviations by bars) with different training conditions (t_0 = pre-training, t_1 = post-training, t_2 = 6-months follow-up, t_3 = 12-month follow-up). Significant changes are marked by * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

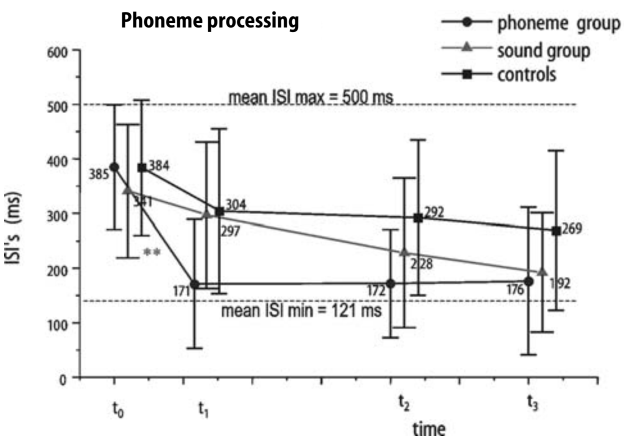


Fig. 3 Change of test-scores for phoneme processing (as given in Table 3) for three groups of children with dyslexia (group means by symbols and standard deviations by bars) with different training conditions (t_0 = pre-training, t_1 = post-training, t_2 = 6-month follow-up, t_3 = 12-month follow-up). Significant changes are marked by * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

To analyse the group differences of sound and phoneme processing across time, pairwise post hoc comparisons of the changes over time between the three groups were done with Wald tests and Sidak adjustment for multiple testing (for the total of nine resulting hypotheses for each dependent variable). The results including the probabilities and 95% confidence intervals of the observed group differences are shown in Table 4.

Overall, there were highly significant group differences in the course of test-scores for sound processing.

The difference between pre- and post-training test-scores of sound processing ability AT-S was significantly higher for children in the sound training group compared to the control group or phoneme training group, thus indicating a pronounced and specific training effect. However, this training effect was only temporary and no longer significant after 6 or 12 months.

There was a substantial training effect for phoneme training as well. The change of pre- and post-training test-scores of phoneme processing ability AT-P was significantly higher for children of the phoneme training group compared to the control group or sound training group. At 6- and 12-month follow-up, group differences were decreasing. The effect of phoneme training seemed to be stable for at least 6 months and as a trend for 12 months.

Thirdly, the variations of spelling and reading test-scores over time were analysed (controlling for IQ) using random-effects regression. Figs. 4 and 5 show the course of spelling and reading test-scores for the three groups of children with dyslexia (control, sound, phoneme) at three points of time (t_0 = pre-training, t_2 = 6-months follow-up, t_3 = 12-months follow-up).

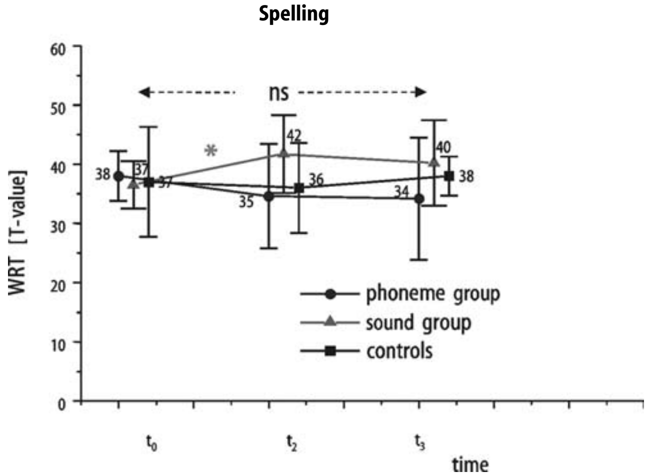


Fig. 4 Change of spelling values (as given in Table 3) for three groups of children with dyslexia (group means by symbols and standard deviations by bars) with different training conditions (t_0 = pre-training, t_2 = 6-month follow-up, t_3 = 12-month follow-up). Significant changes are marked by * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 4 Change in sound (AT-S) and phoneme (AT-P) processing comparing three groups of children with dyslexia[a] at different points of time[b]

Groups	chi2	df	p[c]	Group difference[d]	95% Confidence	Interval
AT-S (difference $t_0 - t_1$)						
C – S	16.36	1	0.0005	−169.0	−250.9	−87.1
C – P	0.01	1	1.0	4.6	−78.7	88.0
P – S	16.68	1	0.0004	−173.6	−257.0	−90.3
AT-S (difference $t_0 - t_2$)						
C – S	0.43	1	0.99	−27.4	−109.3	54.5
C – P	1.80	1	0.83	57.0	−26.4	140.3
P – S	3.94	1	0.35	−87.4	−167.7	−1.0
AT-S (difference $t_0 - t_3$)						
C – S	2.94	1	0.55	−85.5	−183.3	12.2
C – P	0.69	1	0.99	−41.5	−139.7	56.7
P – S	0.77	1	0.98	−44.0	−142.2	54.1
All group differences (sound)	27.41	6	0.0001			
AT-P (difference $t_0 - t_1$)						
C – S	0.68	1	0.99	35.3	−48.7	119.3
C – P	9.61	1	0.0173	−135.2	−220.7	−49.7
P – S	15.29	1	0.0008	170.6	85.1	256.0
AT-P (difference $t_0 - t_2$)						
C – S	0.25	1	0.99	−21.6	−105.6	62.4
C – P	7.90	1	0.0436	−122.6	−208.1	−37.1
P – S	5.36	1	0.17	101.0	15.5	186.5
AT-P (difference $t_0 - t_3$)						
C – S	0.16	1	1.0	−20.4	−120.5	79.7
C – P	5.44	1	0.16	−119.8	−220.4	−19.2
P – S	3.75	1	0.39	99.4	−1.2	200.0
All group differences (phoneme)	19.77	6	0.0030			

Note. Overall variation between persons in random-effects GLS regression (ISI sound sigma_e = 81.4/ISI phoneme sigma_e = 81.8)
[a] (control group = C, sound training = S, phoneme training = P); [b] (t_0 = pre-treatment, t_1 = post-treatment, t_2 = 6-month follow-up, t_3 = 12-month follow-up); [c] Sidak adjusted p-values; [d] Mean ISI (ms)

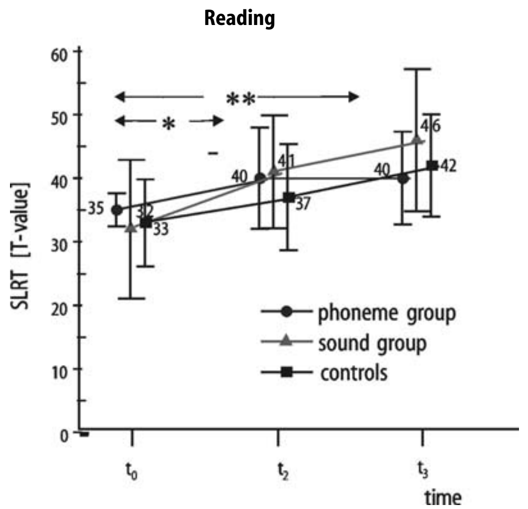


Fig. 5 Change of reading values (as given in Table 3) for three groups of children with dyslexia (group means by symbols and standard deviations by bars) with different training conditions (t_0 = pre-training, t_2 = 6-month follow-up, t_3 = 12-month follow-up). Significant changes are marked by * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

To analyse the group differences of spelling and reading over time, pairwise post hoc comparisons of the changes over time between the three groups were done with Wald tests and Sidak adjustment for multiple testing (for the total of six resulting hypotheses for each dependent variable). The results including the probabilities and 95 % confidence intervals of the observed group differences are shown in Table 5.

For spelling at 6-month follow-up, significant group differences for the changes of test-scores ($WRTt_2 - WRTt_0$) were found with a superior development for the sound training group. At 12-month follow-up, the differences between the three groups comparing the changes of their spelling scores ($WRTt_3 - WRTt_0$) were no longer statistically significant.

For reading ability, no significant group differences of variations of test-scores over time could be observed; therefore, no relevant effects of sound or phoneme training on the development of reading ability were found. Independent from our specific auditory training, all groups showed significant improvements of reading ability over time, probably due to the school training programme [$SLTt_3 - SLTt_0 = 9.0 \pm 1.56$; $z = 5.8$; $p = 0.000$; 95 % confidence interval (5.9–12.1)].

Discussion

A reliable measurement of the ability of temporal processing of sound (AT-S) and phoneme (AT-P) stimuli as defined in this study was possible. Even if there is a lot of literature about measuring perception of rapid sequences in children with dyslexia, this is by no means to be taken for granted as has been shown recently [16]. Children with dyslexia showed significantly reduced scores in phoneme and sound processing tasks compared to children without dyslexia; the group difference was more pronounced for phoneme processing.

As expected due to the literature [23], basic auditory

Table 5 Change in spelling and reading (WRT and SLT/T-scores) comparing three groups of children with dyslexia[a] at different points of time[b]

Groups	χ^2	df	p^{c*}	Group difference[d]	95 % Confidence	Interval
Spelling (difference $t_0 - t_2$)						
C – S	5.08	1	0.14	6.3	0.8	11.8
C – P	0.61	1	0.97	−2.2	−7.8	3.4
P – S	8.96	1	0.0165	8.6	3.0	14.2
Spelling (difference $t_0 - t_3$)						
C – S	1.00	1	0.90	3.4	−3.2	9.9
C – P	1.57	1	0.76	−4.2	−10.8	2.4
P – S	5.05	1	0.14	7.6	1.0	14.2
All group differences (spelling)	11.24	4	0.0240			
Reading (difference $t_0 - t_2$)						
C – S	1.89	1	0.67	4.3	−1.8	10.5
C – P	0.01	1	1.0	−0.2	−6.5	6.1
P – S	2.03	1	0.63	4.6	−1.7	10.8
Reading (difference $t_0 - t_3$)						
C – S	1.43	1	0.79	4.5	−2.9	12.0
C – P	0.58	1	0.97	−2.9	−10.4	4.6
P – S	3.81	1	0.27	7.4	−0.1	14.9
All group differences (reading)	4.86	4	0.30			

Note. Overall variation between persons in random-effects GLS regression (T-score spelling WRT sigma_e = 5.4/T-score reading SLT sigma_e = 6.1)
[a] (control group = C, sound training = S, phoneme training = P); [b] (t_0 = pre-treatment, t_1 = post-treatment, t_2 = 6-month follow-up, t_3 = 12-month follow-up); [c] Sidak adjusted p-values; [d] Mean T-value differences

processing and specific phonological skills may be improved markedly by specific, intensive and continuous training. Our results showed specific significant training effects for both sound and phoneme processing immediately after the training phase. The effect of training weakened over 12 months of time due to an age-related improvement for both not specifically trained groups over time, but remained still significant for the phoneme training at follow-up after 6 months and as a trend even after 12 months.

McAnally et al. [21], however, did not find any systematic improvement in identifying correct consonant-vowel-consonant stimuli after their training. Possibly the difference in results was due to sample selection. Some studies report about several subgroups to distinguish the temporal processing abilities of children with dyslexia [1, 15, 27]. Other studies report training effects comparable to ours [12, 14, 24, 28]. In our study, children with dyslexia and control children differed highly in the trained modalities before the start of training, which might be a factor different to the above-mentioned study [21].

Hautus et al. [13] find that early temporal resolution deficits in their subjects with reading impairment may significantly ameliorate over time without any specific intervention. This might explain our findings of non-specific gain of temporal processing over 12 months at follow-up. Without further empirical data concerning transfer of trained auditory temporal processing to reading or spelling for example, Habib et al. [12] argue that their "studies provide further justification for a rational, indication-based temporo-phonological treatment of dyslexia".

In our study, there were no significant differences in the development of reading ability between the training groups. Reading ability improved for our whole sample starting from a value clearly below average (t_0: T = 33.2) to a value in the lower average range (t_2: T = 39.3; t_3: T = 42.7). This effect was probably due to the intensive standard school-based reading training common for all pupils. Due to the original aims of our study, there was no control group for this question.

Spelling ability, 12 months after training, did not improve in our sample and remained clearly below average (t_0: T = 37.2; t_3: T = 37.6). As the emphasis of the training at school was on reading and not on spelling, this conclusion may be well understood.

Considering the size of our sample and the initial differences of AT-S and AT-P values in our three groups, an interpretation of the small, but significant, improvement of spelling for the sound training group 6 months after training (but not after 12 months) should be given cautiously. The sound group in our study showed a transitional improvement of sound processing and spelling ability. As the improvement of sound processing was not stable over time in our study, one might ask whether an ongoing or repeated sound processing training might lead to a persistent advantage in spelling ability.

Possible specific effects of our training may be levelled off because not all children of our sample showed marked deficits in the trained modalities. A replication of the study with a sample of children showing more severe auditory processing deficits will give a more reliable answer as to whether such a training may be useful at all, and will be closer to the question if an effective specific training for a specific subtype of dyslexia is possible.

Hayes et al. [14] report positive training effects on auditory temporal processing in children with "learning problems", while they did not find improvement of reading and spelling. Temple et al. [37] suggest that a partial remediation of language-processing deficits, including phonological processing, results in improved reading in children with dyslexia and ameliorates disrupted function in brain regions associated with phonological processing, producing additional compensatory activation in other brain regions. However, in this study – as in a similar study [2] – not only auditory temporal processing was trained, but also other language skills. FastForWord comprises other language training aspects too, which has been shown in the study of Temple et al. [37] to improve reading. The other studies mentioned above did not examine empirically whether improved auditory temporal processing really leads to improved reading and spelling.

In conclusion, our results confirm the findings that temporal processing of sounds and phonemes may be markedly improved by specific training. However, the proposed strong transfer effects to reading and spelling could not be shown in our study. We were interested in an effect in addition to standard school-based reading training. This training comprises elements of phonological awareness as well as phoneme discrimination. Therefore, we believe that there is no rationale to promote isolated highly specific training methods for all children with dyslexia in general. However, there is sufficient evidence to highly recommend training of phonological awareness in kindergarten or elementary school combined with specific training of reading and spelling. Due to the limited sample size and the main effect of standard school-based reading training, we could not prove that there is no effect of our specific sound and phoneme training at all. The 95 % confidence intervals given in Tables 4 and 5 show that small, but considerable, training effects might be overlooked by our study. There is, therefore, still a challenge for further research.

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