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Linköping University Post Print

N.B.: When citing this work, cite the original article.

Original Publication:

Cecilia Nakeva von Mentzer, Björn Lyxell, Birgitta Sahlén, Malin Wass, Magnus Lindgren, Marianne Ors, Petter Kallioinen and Inger Uhlén, Computer-assisted training of phoneme–grapheme correspondence for children who are deaf and hard of hearing: Effects on phonological processing skills, 2013, International Journal of Pediatric Otorhinolaryngology, (77), 12, 2049-2057.

<http://dx.doi.org/10.1016/j.ijporl.2013.10.007>

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Postprint available at: Linköping University Electronic Press

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-100465>

Computer-assisted training of phoneme-grapheme correspondence for children who are deaf and hard of hearing: Effects on phonological processing skills

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ABSTRACT

Objective: Examine deaf and hard of hearing (DHH) children's phonological processing skills in relation to a reference group of children with normal hearing (NH) at two baselines pre intervention. Study the effects of computer-assisted phoneme–grapheme correspondence training in the children. Specifically analyze possible effects on DHH children's phonological processing skills.

Methods: The study included 48 children who participated in a computer-assisted intervention study, which focuses on phoneme–grapheme correspondence. Children were 5, 6, and 7 years of age. There were 32 DHH children using cochlear implants (CI) or hearing aids (HA), or both in combination, and 16 children with NH. The study had a quasi-experimental design with three test occasions separated in time by four weeks; baseline 1 and 2 pre intervention, and 3, post intervention. Children performed tasks measuring lexical access, phonological processing, and letter knowledge. All children were asked to practice ten minutes per day at home supported by their parents.

Results: NH children outperformed DHH children on the majority of tasks. All children improved their accuracy in phoneme–grapheme correspondence and output phonology as a function of the computer-assisted intervention. For the whole group of children, and specifically for children with CI, a lower initial phonological composite score was associated with a larger phonological change between baseline 2 and post intervention. Finally, 18 DHH children, whereof 11 children with CI, showed specific intervention effects on their phonological processing skills, and strong effect sizes for their improved accuracy of phoneme–grapheme correspondence.

Conclusion: For some DHH children phonological processing skills are boosted relatively more by phoneme–grapheme correspondence training. This reflects the reciprocal relationship between phonological change and exposure to and manipulations of letters.

1. Introduction

Children who are deaf and hard of hearing (DHH) lag behind their hearing peers with respect to their phonological processing skills, PhPS, [1, 2]. DHH children's qualitatively different development of PhPS can be explained by various interacting factors, for example, age at diagnosis, age at implant, cause and degree of hearing impairment (HI), duration of unaided hearing, communication mode [3], and how well the technical aids provide temporal and spectral cues from the speech signal [4]. PhPS is closely related to the shaping of phonological representations, i.e., the mental representations of the speech signal encoded either by articulatory, acoustic or orthographic forms across speaking, listening and reading [5]. Recent findings indicate that DHH children with CI can develop relatively distinct phonological representations for familiar words [6]. This is probably not the case for unfamiliar words for which they show reduced sensitivity, thereby treating unknown words at a less refined grain-size [6-8]. PhPS and refined phonological representations play an essential part in a large number of cognitive processes, such as lexical access, reading, spelling, and learning new vocabulary [9-12]. PhPS are in turn closely connected to the phonological storage and rehearsal capacity in working memory, and to the semantic and phonological lexicon [7, 8, 13]. Since there is a considerable scientific support that DHH children have problems with PhPS, there is a point in addressing this in an intervention study. There are indeed studies that have examined how DHH children use PhPS in different tasks (e.g., reading [1, 14]. Additionally, there are studies that have examined alternative ways for DHH children to acquire different aspects of PhPS by the support of other modalities, e.g., speech-reading and articulatory feedback [15, 16]. Furthermore, the use of multimodality support to acquire grapheme-phoneme correspondence in DHH children with minimal speech perception has been examined [17]. There are, however, to our knowledge, no studies that have assessed this problem from a reversed perspective, i.e., to use phoneme-grapheme correspondence training to improve PhPS in DHH children.

In the present study, we use computer-assisted training of phoneme–grapheme correspondence to enhance PhPS in Swedish DHH children [18]. Enhanced associations between spoken and written language may possibly be accomplished in two directions. First, it may be achieved between the proposed different layers of phonological representations (lexical – as for example, familiar words, and sub-lexical – that is, phonemes, syllables, words or phrases [19]). Additionally, it may be accomplished between the speech-sounds and their written counterparts that have different transparency in different orthographies. The Swedish orthography is usually described as semi transparent with about 40–42 phonemes (P. Helgason, personal communication April 5, 2013) served by 29 letters and approximately 50 graphemes [20, 21]. Thus, transparent mapping between orthographic and phonological representations would favor the support of PhPS in Swedish DHH children [22].

There were several reasons behind the choice of a computer-assisted intervention program (Graphogame, [23]), delivered by means of the Internet. First, families were spread over a relatively large geographical area, which ruled out the possibility of a daily face-to-face practice with a speech and language pathologist. Second, Graphogame is an established intervention program [23] with documented positive outcome for children with specific reading difficulties [18, 23-27]. Third, the phonological deficit in children with dyslexia is recognized among the vast majority of researchers in the field. Thus, at a surface level the problem may be considered similar to DHH children's phonological processing deficit. [28]. Finally, the Swedish version of Graphogame delivers training for beginning readers. It emphasizes almost exclusively the transparent relationships between spoken and written language sometimes labeled phonemic orthography [20, 22]. This means that the opaque levels of the Swedish orthography are not exposed to the child at this stage (with the exception of three bi-graphs: “ng” [ŋ], “sj” [ʃ] and tj [tʃ], which are the earliest to be introduced for beginning readers in Swedish and therefore included in the Swedish version).

We constructed a global measure of PhPS, i.e., a phonological composite score that reflects various aspects of phonological representations [10]. The phonological composite score enabled us to measure and compare DHH and NH children's general PhPS skills with respect to their different auditory experience. First, we had participating children with CI who have experienced periods of deafness with varied consequences for language development [29]. Children with CI additionally develop spoken language with a less specified electrical signal (i.e., reduced spectral and temporal information) [4]. Second, we had children with HA who have had continuous acoustical stimulation but due to sensorineural hearing loss may lose important auditory information (which means, reduced information for high frequencies, as well as lost information of unstressed parts of the speech signal) [30]. Third, we had children with NH who develop spoken language with a fully specified auditory signal. Further, the phonological composite score had theoretical implications. In relation to the information-processing model of speech perception and production and lexical access [10], the phonological composite score can be viewed as tapping into different aspects of phonological representations. These are; conscious access and attention to phonological representations and their subunits, storage and active recycling of input and output of sub-lexical representations, as well as retrieval of lexical phonological representations.

The first purpose of the present study is to examine phonological processing skills, lexical access and letter knowledge, in children with CI, children with HA, and children with NH. The second purpose is to examine the effects of phoneme–grapheme correspondence training in all children. As the third purpose, we explicitly inspect specific effects on DHH children's phonological processing skills.

2. Material and methods

Two groups of children took part in this intervention study, one group of DHH children ($N = 32$; 20 girls, 12 boys) and an age-matched reference group of children with NH ($N = 16$; 5 girls, 11 boys). Medical case notes from the register of DHH children with CI, HA or a combination of both, who were five, six and seven years of age, were studied by audiologists and speech language pathologists (SLPs) in Stockholm, Uppsala and Lund, Sweden, in order to find children that fitted the inclusion criteria. The inclusion criteria for DHH were that they should have a mild, moderate to severe, or profound bilateral sensorineural HI and be full time users of CI and/or HA. No other disability that could affect their speech and language development should be present. They should speak Swedish at preschool or school, but could use another language at home. Ninety families had a DHH child who met the criteria for the study. They were invited to participate in the study. Approximately one third accepted the invitation and were given written and spoken information about the study.

Children with NH of the same age constituted the reference group. The inclusion criterion for the reference group was normal hearing as reported by their parents in a written consent form. They should speak Swedish in their educational setting and have no disability that could affect their speech and language development. Children with NH were recruited from preschools and schools in and outside the city of Stockholm. Written parental informed consent was obtained for all the participants. The study was approved by the Regional Committee for Medical Research Ethics in Stockholm, Sweden.

2.1 Participants

All participants were matched as for age and non-verbal intelligence [31].

Deaf and hard of hearing children. Seventeen of the children used CI (11 bilateral CIs), and 15 used bilateral HA. Nineteen of the children had a severe/profound hearing impairment (HI) with a Pure Tone Average (PTA) at 70 dB Hearing Level or more unaided. Eleven had a moderate HI and two had a mild HI (PTA 33). For the majority of children the cause of HI was hereditary or unknown.

Cytomegalovirus (CMV) (1 child) and toxicological exposure (1 child) were the causes of the known non-hereditary HI. The mean age at diagnosis was 1 year and 7 months, with a variation from 0 weeks to 5 years. Approximately half of the children were diagnosed before one year of age. Seven children were diagnosed with a progressive HI. One of these children was born deaf on one ear and developed a progressive HI on the other ear. The mean age of receiving HA was 2 years and 8 months ($N = 21$, bilateral HA and CI/HA) and the mean age of receiving CI ($N = 11$) was 1 year and 8 months. All children with CI were, as is routine in Sweden, fitted with bilateral conventional HAs after the diagnosis of HI. As for communication mode four of the children had another spoken language besides Swedish, two children used sign language at home as their main mode of communication and used spoken Swedish at school. Three children used sign to support their spoken language. One child had another language background and was exposed to the Swedish language at one year of age. Twenty-four children were mainstreamed and eight children attended special classes for children with HI. Approximately 75% of the DHH children had earlier experience from speech and language therapy, no child was receiving therapy during our study except for regular controls at the Audiological clinic.

Children with NH. In the reference group of children with NH there was one child who spoke another language besides Swedish.

2.2. Design and procedure

The main design was quasi-experimental with two assessments pre intervention (baseline 1; B1 and baseline 2; B2) and one assessment post intervention (PI). Baseline 2 served to control for maturation and test-retest effects. Tests were administered and monitored by a SLP. At B1 the children were given three testing options: at home, at school or at the clinic. B2 and PI were administered in a sound proof room at the Linguistic Department at Stockholm University, where the majority of the DHH children came with their parents for EEG-recordings. Six DHH children were administered at the Cognition, Communication and Language Lab at Lund University. Neurophysiological findings

constitute another part of the study [32]. B1 included eight tests. One pause was given after the child had completed four tests. The B1 test session lasted approximately 50 minutes. B2 and PI included 14 tests. Eight of these tests were the same as in B1. These eight tests are analyzed in the present study. Instructions were presented orally for the majority of children. When a child needed more detailed instructions, the parents were asked to give repeated instructions. A sign language interpreter was used in two cases for children with deaf parents. With the use of a sign interpreter the duration of the test session was slightly prolonged. The computerized tests used were selected from the Sound Information Processing System, i.e., SIPS [6]. All of the tests selected from SIPS were auditorily presented through two external loudspeakers (Logitech S-100). These were placed on each side of a portable laptop computer with 38 cm screen (1024x768 pixels). Before testing, the volume of presentation was adjusted to a comfortable level for each individual child. Additionally, the examiner asked the parent or the child whether the technical hearing device was working properly. To assure that the child could hear the speech stimuli, they were asked to repeat a short initial part of the Sentence Repetition Test from the SIPS [6]. The children's oral responses in the tests were recorded on the computer through the microphone of a Sennheiser headset, using Audacity recording software version 1.2.6. for later transcriptions and/or analysis.

2.3. Intervention program and setting

The computer-assisted intervention was accomplished by means of an originally Finnish-Swedish version of Graphogame [23, 24, 33, 34] translated into standard Swedish. The program focuses on the correspondence between phonemes and graphemes [35, 36]. It follows the bottom-up or phonics approach [37] by first introducing the spoken phonemes with their corresponding graphemes, then mono-syllabic words (CV, VC) and, finally, more complex words (CCV, VCV, VCC, CVCV). The program has been evaluated regarding its effectiveness for reading development and was found beneficial for children at risk for reading difficulties [25]. It enables individual intervention since it adapts itself to each child's level of performance. An algorithm in the program presents

approximately 20 % of the items from the pool of new connections, yet to be learned, in such a way that they benefit the player's learning optimally [23]. The training program demonstrates how to blend isolated sounds into syllables and words and, thus, offers basic exercises for spelling. Progression through the game is controlled so that around 80 % will be correct. The Swedish version includes 56 levels, categorized in three themes according to the phonological and orthographical complexity of the words. It starts with isolated capital letters and their corresponding sounds, then introduces the lower case letters, advances to one-syllable words with CV (consonant vowel) structure (theme 1), proceeds to VC, CVC, VCC and CVCC structures (theme 2), and finally delivers training for up to seven letter words (theme 3). The words at theme 3 contain initial consonant clusters as well as words with the first examples of larger grapho-phonemic units, namely the bi-graphs "ng" [ŋ], "sj" [ʃ] and tj [tʃ].

All participating children were asked to practice ten minutes per day for four weeks with the game. They were told to practice in a way that corresponded as closely as possible to their way of normally using a computer. If the DHH children listened through external loudspeakers or through a hearing loop in the normal case, they were instructed to continue to do so when they were practicing. In case the DHH child experienced difficulties to discriminate between voiceless plosives (i.e., p-t), the parents were advised to show the difference between the sounds by explicitly articulating i.e., showing their mouth movements to the child. The treatment integrity of the training program was accomplished by means of personal and written information, web, sms, e-mail correspondence and phone calls. In those cases where the families did not follow the training schedule, they were informed to compensate missing days by increasing the daily practice with additional training. Dates and time of day when training took place, total amount of training time (h: min), reached level in the game (max. 56), and percent tasks correct were registered automatically for each child.

2.4 Measures

The eight tests that were assessed at all points of time (B1, B2 and P1) are analyzed in the present study. Four tests were administered on a laptop computer and were parts of a test battery called the SIPS, i.e., the Sound Information Processing System [6]. These were the Nonword Repetition test, the Phonological Representation test, the Nonword Discrimination test and the Phoneme Identification test. Tests from the SIPS were presented in auditory-only mode with the same female speaker voice. Three tests were not computer-based; the Phoneme test/Naming test [38], letter knowledge of sounds and names [39], and letter naming [40]. Descriptions of each category of tests are given here. An extensive description of the tests and procedures from SIPS is given in Wass et al. [6].

2.4.1. Lexical access

Lexical access skills were assessed by the Naming/Phoneme test [38]. A picture with everyday objects was presented to the child. The child was asked to name orally the picture that the test leader pointed to. Children's performance was audio recorded. The score was the total number of named pictures. Semantic (e.g., “a car that drives people who are ill...-ambulance”) or phonological (e.g., “s...-star”) cues were given when the child was unable to name the picture. Independently named pictures were scored 1 p per item. Semantic and/or phonological cues gave 0,5 reduction in scores per item. Maximum score was 72.

2.4.2. Phonological Processing Skills

First the phonological composite score is described followed by each constituent measure.

A Phonological composite score was calculated by a unit weighted-procedure, i.e., each unit was calculated in percent accurate, and then summarized to a global score. Seven items from five tasks of phonological processing skills presented below constituted the phonological composite score. Items were; 1. Nonword repetition (percent nonwords correct; pnwc), 2.

Nonword repetition (percent consonants correct; pcc), 3. Phoneme test (percent words correct;

pwc) 4. Phoneme test (pcc), 5. Phonological Representations, 6. Nonword Discrimination, and 7. Phoneme Identification.

A phonological composite change-score was then created. The phonological composite change-score between the two time periods was calculated by subtracting the phonological composite score at B1 from the score at B2, followed by subtracting the score at B2 from the score at PI.

A Nonword repetition test was used to assess phonological working memory (SIPS; [6]). In this task, the children were asked to repeat individual 3-4 syllable nonwords. Children's performance was audio recorded and performance was scored in two different ways: percent nonwords (pnwc) and percent consonants (pcc) correctly reproduced.

The Naming/Phoneme test, described above was used to assess output phonology [38]. Children's performance was scored both binary (by calculating children's responses) as percent words correctly produced (pwc) and as pcc produced. Children's performance was audio recorded.

A Phonological representation task (SIPS; [6]) was employed to assess how children identified mispronunciations of real words. Thus, it taps into the child's phonological representations of words in long-term memory, working memory ability, and sensitivity to phonemic structure. First, the child was asked to name a picture. Then five different versions of the word were auditorily presented – one at a time. One version was correct and the others differed in one phoneme. The child was asked to decide whether the word was correct or not by responding “yes” or “no” after each stimulus. The score was the total number of correctly recognized items. 1 point was given for a correct identification of the right pronunciation, 0.25 p for versions that differed in one phoneme. Maximum score was 18.

A Nonword Discrimination task was used to assess discrimination of phonemes within nonwords (SIPS; [6]). In this test, the child was asked to decide whether two spoken nonwords were identical.

Responses were given by pressing a key on the computer. The nonwords were presented in 16 pairs and each target nonword was presented in two conditions, once paired with an identical nonword and once with a nonword differing by a single phoneme (e.g., patinadrup – patinadrup, patinadrup – patinavrup). The child had to make correct decisions in both conditions to receive a score. The maximum score was 8.

A Phoneme Identification task was used to assess the ability to identify a phoneme within a nonword (SIPS; [6]). A phoneme was presented to the child followed by a nonword. The task was to decide whether the phoneme was present or not in the nonword by pressing a key on the computer. The maximum score was 12.

2.4.3. Phoneme–grapheme correspondence

Two tasks were used to measure recognition of lower case letters from names or sounds [39]. In these tasks, letter sounds and letter names, the child was presented cards with four letters in a row. The child was instructed to point to one out of four letters as the test leader read the sound or the name of the letter aloud. The maximum score was 24.

The third task, letter naming, was used to measure naming of lower case letters [40]. The child was presented with a chart of letters in six rows. The task was to name each letter as the test leader pointed. The maximum score was 24. Children's performance was audio recorded.

2.5. Statistical analysis

All data are from baseline 1, baseline 2, and post intervention (B1, B2 and P1). An inter-rater reliability measurement was conducted for transcriptions of the Nonword repetition task at B1 (percent nonwords correct; pnwc, percent consonants correct; pcc) and the picture-naming task (percent words correct; pwc, and pcc). This was calculated with the Pearson correlation coefficient. Parametric tests were used to explore within- and between-group differences. Separate analyses for gender were carried out, but no gender differences were found. One-way ANOVA was conducted at

B1 and at B2 to reveal between-group differences. Between-subject factor at B1 and B2 was children's technical aid (3 groups; 1.CI, 2.HA and, 3.NH). Tukey's honestly significant test was used for multiple comparisons. The second between-subject factor was the time period for DHH children's phonological change (2 groups; 1.B1 to B2 ($N=14$), 2.B2 to PI ($N=18$), thus the group of DHH children ($N=32$) was divided according to the time period when their phonological composite score showed a positive change. A mixed design ANOVA was used to analyze within and between-subject effects related to time period B1 to B2, B2 to PI, and B1 to PI for the phonological composite score, i.e., to compare effects in participants' PhPS throughout the study, as well as between group effects (2 groups; 1.B1 to B2 ($N=14$), 2.B2 to PI ($N=18$)). Pearson's correlation was calculated to examine the effect of children's initial phonological composite score, on the phonological composite change-score between B1 and B2, as well as between B2 and PI. Pearson's correlation was calculated between DHH children's background variables and variables related to the intervention. A repeated measure ANOVA was used to analyze the constituent measures of the phonological composite scores in the two groups of DHH children separately (B1 to B2 vs. B2 to PI).

2.6. Inter-rater reliability

Inter-rater reliability was measured on 15 percent of the collected data for transcriptions of the Nonword Repetition task at B1 (percent nonwords correct, pnwc, percent consonants correct, pcc) and the picture-naming task (pwc and pcc). This was accomplished with Pearson's correlation coefficient between the first author and two SLPs. The inter-rater reliability between the SLPs was at least $r = .828$ ($p < .01$).

3. Results

Group comparisons for variables connected to the computer-assisted training are presented first. This is followed by group comparisons for lexical access, PhPS, and letter knowledge at B1 and at B2. Finally, post intervention results are displayed. These are presented in the following order: effects on the phonological composite score, the effect of the initial phonological composite score, individual DHH children's phonological changes, and effects on the phonological composite scores' constituent measures. Finally, effects on children's accuracy in phoneme-grapheme correspondence are presented.

3.1. Variables related to the computer-assisted training

The three groups of children (CI, HA, NH) were compared regarding variables connected to the computer-assisted training. These included time spent practicing (minutes, days and occasions), mean percent correct during practicing, and reached levels in the game. Additionally, background variables were compared for DHH children. These were: age at diagnosis and age when receiving HA and/or CI. The groups (CI, HA, NH) did not differ significantly on any aspect related to the computer-assisted training. For background variables, only age at diagnosis differed between children with CI and children with HA (CI=12 months vs. HA=27 months). Following this, correlations were calculated for all children between reached levels in the game, variables connected to the intervention program, and background variables for DHH children. Significant positive correlations were obtained only for age, $r = .51$, $p < .01$, that is, older children reached higher levels in the game. No other significant correlations were observed.

3.2. Group comparisons of children with CI, HA, and NH at B1 and at B2

Table 1 displays means and standard deviations in lexical access, the phonological composite-score and its constituent measures, and letter knowledge in children with CI, HA and NH at the two baselines pre intervention to answer our first research question. Significant main effects of group

were obtained at B1 for all phonological processing tasks, except Phoneme Identification. These were: the Phonological composite score $F(2, 45) = 22.59, p < .001$, the Nonword Repetition test (pnwc) $F(2, 45) = 82.27, p < .001$, (pcc) $F(2, 45) = 33.78, p < .001$, the Phoneme test (pwc) $F(2, 45) = 3.63, p < .05$, (pcc) $F(2, 45) = 3.14, p = .05$, the Phonological Representation task $F(2, 45) = 6.26, p < .05$, and the Nonword Discrimination test, $F(2, 45) = 13.74, p < .01$. Post Hoc test Tukey revealed that children with NH outperformed the other two groups on the Phonological composite score, the Nonword repetition test, and the task of Phonological representations. For the Phoneme test (pwc and pcc) the significant difference was between children with NH and children with CI. For the Nonword Discrimination test children with CI had a significantly lower performance than the other two groups. No other significant differences were observed at B1. At B2 all significant group differences from B1 remained and one was added: the task for lexical access ($p = .06$ at B1, $p = .02$ at B2), $F(2, 45) = 4.11, p < .05$. Post Hoc test Tukey revealed that the significant difference was between children with NH and children with CI.

Table 1.

Test results in percent at the two baselines pre intervention on lexical access, the phonological composite score, the seven individual measures constituting the phonological composite score, and letter knowledge (percent mean $\pm$ SD, range) in three groups (CI (N=17), HA (N=15), NH (N=16)).

	BASELINE 1				BASELINE 2			
	Children with CI	Children with HA	Children with NH	p-value	Children with CI	Children with HA	Children with NH	p-value
Lexical access	90.4 $\pm$ 8.6 (69-100)	92.9 $\pm$ 4.1 (83-97)	96.0 $\pm$ 3.4 (88-99)	.06	93.0 $\pm$ 6.5 (79-100)	95.4 $\pm$ 3.6 (89-100)	97.5 $\pm$ 2.3 (90-100)	.02
Phonological composite score	56.8 $\pm$ 14.1 (30-76)	64.9 $\pm$ 9.1 (51-79)	82.2 $\pm$ 8.8 (63-93)	.00	59.0 $\pm$ 16.8 (27-78)	68.8 $\pm$ 10.5 (52-87)	85.1 $\pm$ 8.8 (66-96)	.01
Nonword repetition (pnwc)	2.0 $\pm$ 3.6 (0-13)	7.3 $\pm$ 7.7 (0-21)	43.4 $\pm$ 15.2 (4-58)	.00	6.1 $\pm$ 7.8 (0-25)	8.9 $\pm$ 12.3 (0-46)	52.6 $\pm$ 18.1 (12-80)	.00
Nonword repetition (pcc)	41.5 $\pm$ 17.1 (11-66)	55.3 $\pm$ 13.8 (23-75)	80.7 $\pm$ 9.3 (64-96)	.00	45.2 $\pm$ 19.5 (13-77)	58.9 $\pm$ 14.4 (38-83)	84.8 $\pm$ 8.5 (65-96)	.00
Phoneme-test (pwc)	71.0 $\pm$ 32.3 (8-100)	76.7 $\pm$ 26.3 (21-100)	94.0 $\pm$ 12.6 (50-100)	.03	70.0 $\pm$ 33.7 (3-100)	79.0 $\pm$ 24.9 (24-100)	94.0 $\pm$ 14.3 (43-100)	.03
Phoneme-test (pcc)	86.3 $\pm$ 17.2 (48-100)	90.0 $\pm$ 13.0 (57-100)	97.5 $\pm$ 5.7 (78-100)	.05	86.0 $\pm$ 18.0 (43-100)	91.4 $\pm$ 11.6 (63-100)	97.5 $\pm$ 6.0 (76-100)	.05
Phonological representation	88.0 $\pm$ 11.0 (65-99)	90.5 $\pm$ 10.3 (67-99)	98.4 $\pm$ 2.3 (93-100)	.00	88.7 $\pm$ 14.1 (57-100)	94.4 $\pm$ 7.5 (74-99)	99.7 $\pm$ 0.8 (97-100)	.01
Nonword Discrimination	51.5 $\pm$ 19.7 (25-75)	71.7 $\pm$ 21.9 (25-100)	88.3 $\pm$ 19.1 (38-100)	.00	56.7 $\pm$ 26.2 (13-88)	82.3 $\pm$ 14.1 (63-100)	89.1 $\pm$ 14.3 (50-100)	.00
Phoneme Identification	57.4 $\pm$ 19.8 (25-100)	63.3 $\pm$ 10.8 (42-83)	73.5 $\pm$ 24.7 (33-100)	.07	60.4 $\pm$ 26.3 (17-100)	65.0 $\pm$ 19.5 (42-100)	78.1 $\pm$ 23.1 (25-100)	.09
Letter knowledge - Names	87.1 $\pm$ 17.9 (46-100)	76.7 $\pm$ 26.5 (15-100)	92.8 $\pm$ 9.3 (77-100)	.07	89.6 $\pm$ 17.1 (46-100)	82.0 $\pm$ 23.6 (31-100)	95.0 $\pm$ 7.4 (77-100)	.11
Letter knowledge - Sounds	87.8 $\pm$ 16.3 (50-100)	75.1 $\pm$ 24.9 (35-100)	89.7 $\pm$ 15.1 (58-100)	.08	89.6 $\pm$ 14.6 (58-100)	77.1 $\pm$ 27.3 (23-100)	93.3 $\pm$ 12.8 (54-100)	.06
Letter knowledge - Naming	76.0 $\pm$ 26.1 (17-100)	57.7 $\pm$ 34.1 (4-100)	75.0 $\pm$ 28.2 (25-100)	.13	80.0 $\pm$ 23.3 (29-100)	60.1 $\pm$ 34.3 (8-100)	82.0 $\pm$ 19.0 (42-100)	.06

Note: CI = cochlear implant, HA = hearing aids, NH = normal hearing, pnwc = percent nonwords correct, pcc = percent consonants correct, pwc = percent words correct.

3.3. Post intervention results

3.3.1. Phonological composite score

All children in the study displayed a significant improvement of the phonological composite score from B1 to PI $F(2, 90) = 36.5, p < .01, \eta_p^2 = .45$. The magnitude of improvement between B1 and B2 as well as between B2 and PI was equal. A significant effect of group was observed at the different points in time $F(2, 45) = 19.9, p < .01, \eta_p^2 = .47$. Post hoc test Tukey revealed that NH children performed at a significantly higher level than both of the other two groups at B2. The significant difference remained between NH and children with CI at PI.

3.3.2. Effect of children's initial level of the phonological composite score

Correlations were calculated in two steps: first, between the phonological composite change score from B2 to PI and the initial phonological composite score in all children. This was done to analyze whether the initial level of the phonological composite score had an effect on the change, independent of children's hearing status. The change-score at PI showed a significant negative correlation with the initial phonological composite score ($r = -.42, p < .01$). Thus, children with lower initial phonological composite scores showed a relatively larger change. Second, correlations were calculated between the changed phonological composite score from B1 to B2 and the initial phonological composite score in all children. The change-score at B2 showed a non-significant correlation with the initial phonological composite score. This two-step correlation-analysis was

repeated for the different groups; all DHH children ($N=32$), children with CI, and children with HA. The same significant correlation, where the change-score at PI showed a significant, negative correlation with the initial phonological composite score, was only obtained in children with CI ($r = -.63, p < .01$). Thus, for the whole group of children, and specifically for children with CI, a lower initial phonological composite score was associated with a larger phonological change-score after the computer-assisted intervention. For mean change-scores and standard deviation for all children; CI, HA, and the 18 DHH children (11 children with CI) who showed a positive change of their phonological composite score from B2 to PI, see Table 2.

3.3.3. Individual DHH children's progress

A visual inspection of each participants' phonological composite score at the different points in time (B1, B2, PI), revealed that 18 DHH children improved their phonological composite score to a varying extent from B2 to PI (eleven children with CI) $F(2, 34) = 31.5, p < .01, \eta_p^2 = .65$. The 14 remaining children improved to a varying extent from B1 to B2, $F(2, 18) = 21.9, p < .05, \eta_p^2 = .61$. For individual DHH children's progress, see figure 1. Following this, comparisons of variables connected to the computer-assisted training, variables related to DHH children's background and letter knowledge at B1 were computed, to see if there were differences between the groups. Only one variable differed, related to the children's background. The children with a positive change of the phonological composite score from B2 to PI, were significantly older when they received CI ($M = 30, SD = 18.0, t(13) = 2.48, p < .05$). Levene's test indicated unequal variances ($F = 4.61, p = .049$), so degrees of freedom were adjusted from 15 to 13. Following this, the children's mode of communication and level of hearing impairment were analyzed. This showed that four out of five children who used sign language to various extents, showed a positive change of the phonological composite score from B2 to PI. Additionally, 12 of the 18 DHH children (67%) with positive changes

from B2 to PI had a severe hearing impairment compared to 7 of the 14 children (50%) with positive changes from B1 to B2

Table 2.

The phonological composite score at B1 (percent mean $\pm$ SD, range), phonological change-scores in percent B1-B2, B2-PI, and B1-PI for all children ($N=48$), children with CI ($N=17$) and DHH children ($N=18$) with positive phonological change-scores B2-PI.

	Phon. composite B1	Phon. change B1-B2	Phon.change B2-PI	Phon.change B1-PI
All children	67.8 $\pm$ 15.3 (29.5-92.6)	2.85 $\pm$ 4.4 (- 7.6-15.4)	2.67 $\pm$ 4.3 (-5.4- 14.5)	5.5 $\pm$ 4.8 (-2.6- 15.7)
Children with CI	56.8 $\pm$ 14.1 (29.5-75.7)	2.18 $\pm$ 5.6 (- 7.6-15.4)	3.8 $\pm$ 4.8 (-5.4- 14.5)	6.0 $\pm$ 5.4 (-2.6- 15.7)
Children with HA	64.9 $\pm$ 9.1 (50.9- 79.0)	3.6 $\pm$ 3.2 (- 3.7-9.9)	3.0 $\pm$ 4.3 (-5.0- 7.7)	6.6 $\pm$ 4.5 (-1.9- 14.2)
Improved DHH children	57.4 $\pm$ 14.3 (29.5-75.7)	-0.04 $\pm$ 3.1 (- 7.6-4.4)	6.1 $\pm$ 3.3 (0.44- 14.5)	6.0 $\pm$ 4.6 (-2.6- 15.2)

Note: B1 = baseline 1, B2 = baseline 2, PI = post intervention, Phon. = phonological, CI = cochlear implant, HA = hearing aids, DHH = deaf and hard of hearing

Fig. 1. Individual DHH children's phonological composite change scores in percent B1 to B2 vs. B1 to PI.

Note: DHH=deaf and hard of hearing, B1 = baseline 1, B2 = baseline 2, PI = post intervention, CI = Cochlear implant, HA = Hearing aids * = children with improved scores B2 to PI.

3.3.4. *Changes of the constituent measures of the phonological composite score*

Group effects according to time period for children's positive change of the phonological composite score were then analyzed on all constituent measures separately; (2 groups: 1. positive change at B2 (14 children), and 2. positive change at PI (18 children). Binary scores were used for the Phonological Representation task, the Nonword Discrimination task and the Phoneme Identification task.

A mixed design Anova revealed that two measures showed a significant effect from B1 to PI but not from B1 to B2, nor from B2 to PI. These were the Phonological representation task $F(2, 60) = 8.46, p < .01, \eta_p^2 = .22$, and the Phoneme Identification task $F(2, 60) = 3.78, p < .05, \eta_p^2 = .12$. Of these two measures the Phonological Representation task showed a significant effect of group (1.B1 to B2 $N=14$, 2.B2 to PI $N=18$) $F(1, 30) = 4.96, p < .05, \eta_p^2 = .14$, and a significant interaction effect between test occasion and group $F(2, 60) = 5.25, p < .01, \eta_p^2 = .15$. The group effect was only observed at B2, where the 18 children with improved scores from B2 to PI had a significantly lower score (15.5 p. vs. 17.6 p.). Two measures showed a significant improvement from B2 to PI but not from B1 to B2. These were the Naming/Phoneme test, pwc $F(2, 60) = 3.86, p < .05, \eta_p^2 = .11$, and pcc $F(2, 60) = 6.16, p < .01, \eta_p^2 = .17$. No group or interaction effects were observed. The two measures from the Nonword repetition task showed a significant improvement from B1 to B2 as well as from B2 to PI, pwc $F(2, 60) = 7.87, p < .01, \eta_p^2 = .21$, and pcc $F(2, 60) = 17.70, p < .001, \eta_p^2 = .37$. Finally, the Nonword Discrimination task showed a significant improvement from B1 to B2 and from B1 to PI, but not from B2 to PI $F(2, 60) = 7.03, p < .05, \eta_p^2 = .32$. Group effects were observed in the Nonword discrimination task $F(1, 30) = 13.91, p < .01, \eta_p^2 = .14$, where

the 18 children with effects from B2 to PI showed lower scores (5.44 p. vs. 6.44 p.) at B1. To summarize, positive changes were seen in six out of seven measures at PI for all DHH children. Improvement was either observed *only* from B1 to PI (the tasks of Phonological representation and Phoneme Identification) or *both* between B1 and B2, and between B2 and PI.

For the 18 DHH children with a positive change from B2 to PI, three constituent measures were significantly improved from B2 to PI. These were the Phonological representation task $F(2, 34) = 8.08, p < .01, \eta_p^2 = .32$, the Phoneme Identification task $F(2, 34) = 3.61, p < .05, \eta_p^2 = .17$, and the Nonword Repetition task (pcc) $F(2, 34) = 12.85, p < .01, \eta_p^2 = .43$.

3.3.5. Phoneme–grapheme correspondence

Main effects were seen from B2 to PI for one of the letter knowledge tasks; letter sounds $F(2, 67) = 19.4, p < .01, \eta_p^2 = .30$ in all children (CI, HA, NH). There was no significant difference between the groups. Scores for letter sounds are displayed in figure 2.

Main effects from B1 to B2, and from B2 to PI were observed on letter names $F(2, 90) = 20.3, p < .01, \eta_p^2 = .32$. There was no significant difference between the groups.

Main effects were seen on letter naming $F(2, 90) = 30.5, p < .01, \eta_p^2 = .40$. There was a significant difference at B2 as well as at PI, indicating a constant improvement through the study. There was no significant difference between the groups. It should be noted that children with HA showed an overall lower performance level than the other two groups on letter knowledge at all points in time.

After this a repeated measures ANOVA was conducted on a letter knowledge composite score in the 14 DHH children with a positive change of the phonological composite score from B1 to B2, and the 18 DHH children with a positive change from B2 to PI, respectively. Analysis showed that for the 14 children there was a significant effect from B1 to P1 as well as from B2 to PI $F(2, 14.72) = 9.29, p <$

.01, $\eta_p^2 = .42$ (moderate to strong effect). The same was shown for the 18 children $F(2, 34) = 21.40$, $p < .01$, $\eta_p^2 = .56$ (strong effect).

Fig. 2. Results on letter knowledge for sounds at B1,B2 and PI in three groups of children:

CI, HA, and NH.

Note: CI = cochlear implant, HA = hearing aids, NH = normal hearing.

4. Discussion

This study explored phonological processing skills, lexical access and letter knowledge in 48 children (32 DHH and 16 NH) who took part in an internet-based computer-assisted study that focused on phoneme–grapheme correspondence training [23]. The first purpose was to examine phonological processing skills, lexical access and letter knowledge at two baselines pre intervention in the different groups of children. Results showed that children with NH outperformed DHH children in the majority of tests. This was expected and corroborates the results of similar studies using the same test-paradigm [6]. In tasks assessing expressive phonology, children with HA and children with NH

performed at comparable levels. Thus, as previous studies have shown, output phonology for real words is relatively often within normal range for children with HA [30, 41]. Additionally, for letter knowledge no significant difference was found between the groups, although visual inspection revealed that children with HA showed an overall lower performance. Differences between the groups for all measures remained stable at both baselines pre intervention except for the task of lexical access, which was added at B2. Here, children with CI performed at a significantly lower level than both of the other groups. Thus, although the task of lexical access was relatively easy, as was indicated by scores close to the ceiling, it still differentiated children with CI as having relatively weaker naming skills [3].

The performance of the DHH children was characterized by a high degree of individual variation. This was particularly obvious in the Nonword repetition task used to assess phonological working memory, and specifically for output phonology in children with CI. This finding supports earlier studies regarding the heterogeneity in this population and confirms the importance of not relying solely on mean scores when interpreting the data [1, 42]. The Nonword repetition task involves both perception and production. According to the information-processing model of lexical access [10, 43], it is at the level of sub-lexical phonological processing the different constituting parts of a perceived word (known or unfamiliar) start to activate the associations built up around the word. These activated associations are all aiming at integrating sound, articulatory features and meaning [5]. Specific problems with nonword repetition were observed in all children with CI. This indicates that the sub-lexical phonological representations are more vulnerable in this group of children than in NH children; both due to a less specified speech signal [4] and to a less developed phonological and semantic lexicon [3] [9]. Thus, the present outcome among DHH children supports the results of studies within psycholinguistics and dyslexia [43, 44]. That is, the different steps in how words are perceived, retrieved and produced are closely intertwined.

The second purpose was to examine the effects of phoneme–grapheme correspondence training in the children. All children spent an equal amount of time practicing, and differences between the groups could thus not be related to differences in time or days spent practicing. Overall, the intervention showed most positive effects on phoneme–grapheme correspondence with moderate to strong effect-sizes [24], and relatively sparse effect on expressive phonology for all children. Since the computer-assisted intervention program focuses on phonemic differentiation and does not include speech production, this result is expected. Law’s review on efficacy of treatment for children with speech or language delay [45] showed that perceptual training is often not sufficient to accomplish changes in expressive phonology. As for phonological processing skills, the correlation analysis between children’s phonological composite score and the phonological change-score (at B2 or PI) suggests that children with weak initial skills benefited relatively more. This was evident when we included all children in the analysis as well as when the children with CI were analyzed separately. For children with HA this developmental pattern was not evident. Children with HA also improved their phonological composite score, but it was not related to an initially weaker level.

The visual inspection of the data revealed that 18 DHH, thereof 11 children with CI, showed specific benefit of the intervention, i.e., significant improvement of the phonological composite score from B2 to PI. These 18 children differed from the remaining children in three ways. First, they were older when they received their CI. Second, the majority of DHH children who used sign as their communication mode at home, as well as to support their spoken language ability in general, was in this group. Third, the majority of these children had a severe HI (with CI or HA). This could indicate that computer-assisted training of phoneme–grapheme correspondence may be one alternative way to enhance PhPS in DHH children, who do not develop these skills as an effect of oral communicative interaction with their environment [2].

Finally, we analyzed the constituent parts of the phonological composite score. The analysis showed that for all DHH children six out of seven measures had improved at PI. The improvement was either observed from B1 to PI or *both* between B1 and B2, as well as between B2 and PI. For the tasks of Phonological representation and Phoneme Identification the effect was only evident from B1 to PI. The strongest effect sizes were observed in the Nonword repetition task, evident at B2 as well as at PI. Despite the fact that we are not able to specifically identify the cause of this improvement (maturation, test-retest, or intervention effects), this must be interpreted as a positive outcome for the DHH children in our study. Several studies show strong associations between phonological working memory and the ease with which children learn new words, as well as another spoken language [13, 46]. Phonological working memory is also involved when a child needs to pick up important cues when engaging with peers, as well as when they later in their educational setting, learn to spell and decode unfamiliar words [47]. When we compared the effect sizes of improved letter knowledge-scores between the DHH children with an improved phonological composite score during different time periods (B1 to B2 vs. B2 to PI), relatively stronger effect sizes were observed in the latter group, i.e., after four weeks of intervention. This might mirror that for some DHH children PhPS are boosted relatively more by phoneme-grapheme correspondence training, i.e., it reflects the reciprocal relationship between growth in PhPS and exposure to and manipulations of letters [34]. Hulme, Bowyer-Crane, Carroll, Duff, and Snowling (2012) showed that the combination of improved letter knowledge and PhPS had positive consequences on word decoding in children with poor verbal abilities [48]. In the present study this may be reflected by significant gains in PhPS in 18 children. For the remaining children with improved letter knowledge and output phonology we might very well find progress in PhPS in the long run. This will be explored in an ongoing follow-up study. In previous studies within the Graphogame framework [34, 48] letter knowledge was found to be a significant predictor of gains in reading acquisition. Thus, we also expect that improved accuracy in

phoneme–grapheme correspondence will presumably have positive effects on the participating DHH children’s reading ability, and as a consequence also on their general language development.

5. Conclusions

All participating children improved their accuracy in phoneme–grapheme correspondence and output phonology between B2 and PI, i.e., after four weeks of computer-assisted intervention. The effect sizes for improved phoneme–grapheme correspondence were moderate to strong for DHH children. For the whole group of children, and specifically for children with CI, a lower initial phonological composite score was associated with a relatively larger change-score between B2 and PI. Finally, 18 children, whereof 11 children with CI, showed specific intervention effects on their phonological processing skills, and strong effect sizes for their improved accuracy of phoneme–grapheme correspondence. It is, nevertheless, important to take into account the large individual variations in DHH children’s phonological processing skills when interpreting the intervention effects on a group level.

Acknowledgements

This research was funded by The Swedish Research Council for Working Life and Social Sciences (Forskningsrådet för Arbetsliv och Socialvetenskap), and the Linneaus Center HEAD at Linköping University, and Cognition, Communication and Learning (CCL) at Lund University. We acknowledge all the children and parents participating in the study and their teachers. We thank Jonas Lindsjö, Lena Asker-Árnason, Lund University, Elisabet Engström, Karolinska University Hospital, and Anna Ericson, Stockholm University, for their assistance in the data-collection. We also thank Ulla-Britt Persson, Linköping University, for her assistance in proofreading.

Conflict of interest statement

No conflict of interest is declared, including financial, personal or other relationships with other

people or organizations for any of the authors in this study. All authors have approved the final article.

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