Improving Deaf Children's Working Memory through Training

Terezinha Nunes, Rossana Barros*, Deborah Evans and Diana Burman

Department of Education, University of Oxford, Oxford, UK

Abstract: The aim of this study was to design and to assess the effectiveness of a working memory (WM) intervention for deaf children. A review of factors that explain deaf students' poor results in WM tasks was used to identify deaf participants' strengths and difficulties in WM tasks. This review formed the basis for the design of the WM training program assessed in the study.

Participants were 77 children in a comparison group and 73 in an intervention group, with the mean age of 8y5m at the start of the program. The participants' severity of hearing loss was at least moderate; approximately 68% of the children had one cochlear implant and the rest had hearing aids only. The design was quasi-experimental: teachers rather than children were assigned either to the comparison or the intervention group.

The children were pre- and post-tested in three WM tasks; the regression factor score was used as the measure of their WM. The intervention was implemented by the teachers and comprised two types of games: teacher led games, during which the teachers taught the children rehearsal strategies that combined linguistic and visual-spatial encoding, and web-based games, which the children played without a tutor and involved biased competition with the aim of developing attention control.

An analysis of covariance (controlling for pre-test WM scores, age, cognitive ability and pre- to post-test interval) showed that the intervention group differed significantly from the comparison group at post-test; Cohen's d effect size was 0.78. We conclude that it is possible to improve deaf children's performance in WM measures by training that targets their attention problems and teaches them rehearsal strategies.

Keywords: Working memory, deaf children, rehearsal training, attention control.

INTRODUCTION

"Working memory (WM) is a cognitive system that strongly relates to a person's ability to reason with novel information and direct attention to goal-relevant information" [1]. Baddeley and his colleagues [2, 3] proposed a model of WM that involves two storage components, the phonological loop (which stores auditory information) and the visuospatial sketchpad (which stores visual and kinesthetic information), an attention controller, termed the central executive (CE), and the episodic buffer, which allows for information from the phonological loop and the visuospatial sketchpad to be connected and for the chunking of information differently in WM, depending on how the information relates to long term memory (LTM). The episodic buffer is assumed to be accessible through conscious awareness [3] and thus its functioning is susceptible to the effect of intentional rehearsal.

In this paper, we describe an intervention program designed for improving deaf children's WM and report the outcomes of this program. This game-based intervention aims to use deaf people's better performance in visuospatial working memory tasks by helping them learn strategies for binding information from the visuospatial sketchpad with phonological information. It also aims to give deaf children practice in dual tasks in which there is competition between stimuli, providing them with more experience in tasks with which they have less experience than hearing children. In the next section of this paper, we briefly report the results of past research comparing hearing and deaf children's performance in WM tasks and explore possible explanations for deaf children's weaker performance in WM measures. Subsequently, an empirical study is described in which these explanations were considered in the design of a WM program to improve deaf children's performance. Finally, implications for further research and education are discussed.

DEAF CHILDREN'S PERFORMANCE IN WM TASKS

Research consistently shows that deaf children have lower scores in WM tasks than hearing children of the same chronological age [4]. Even after cochlear implantation, deaf children continue to score lower in WM measures than hearing children [5-10]. Deaf children's poor performance in WM measures is a cause for concern because the WM-CE component plays an important role in their learning. It is a predictor of their spoken language processing [6], reading achievement [8, 11] as well as reading comprehension [12], mathematical achievement [13] and geometry learning [14]. Thus it would be very important to attempt to improve deaf children's WM.

*Address correspondence to this author at the Department of Education, University of Oxford, 15 Norham Gardens, Oxford, OX2 6PY, UK; Tel: 01865 284893; Fax: 01865 274144; E-mail: rossana.barros@education.ox.ac.uk

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In order to help deaf children improve their performance in WM tasks, one should consider possible explanations for their lower scores. The comparisons between deaf and hearing participants are based on complex tasks which require the participant to manipulate the information encoded before producing a response, consistently with definitions of WM. These tasks have been extensively and are well validated in the UK as a predictor of children's educational performance [15-17]. As these measures are used in the empirical study reported here, they are described in some detail in the subsequent paragraphs.

In the remainder of this section, we consider three factors that might explain the poor performance of deaf children in WM measures and how deaf children might be helped to overcome their difficulties. These factors are their problems in the process of encoding information, their failure to use rehearsal strategies which build on their visuospatial strength, and their difficulties with attention orientation.

1. Deaf Children's Encoding of Information

The first possible explanation considered here relates to what resources deaf children use to encode information in WM-CE tasks. In particular, it is important to know how they perform when the information is presented orally or visually because the modality used might affect performance. WM-CE tasks developed for children typically involve stimuli which are presented orally and require the order of the stimuli to be preserved in the response for the children to succeed in the task. For example, the WM Test Battery for Children [17] contains three measures of the central executive component, Listening Recall, Backward Digit Recall, and Counting Recall.

The Listening Recall task, originally developed by Daneman and Carpenter [18], requires the child to listen to sentences, to indicate whether the sentence is true or false, and then to recall the last word in each sentence. The number of sentences increases during the task; the child's score, called span, is the maximum number of words recalled correctly in the order in which the sentences were presented. A second task, Backward Digit Recall, also used in the Wechsler Intelligence for Children [WISC; 19] and the British Ability Scale [BAS; 20], involves presenting the child with a sequence of digits orally; the child's task is to recall the digits in the reverse order of presentation. The length of the series of digits increases as the task progresses. The child's span is the longest sequence of digits that the child can reproduce in reverse order. Both tasks are presented orally and the child's answer is also expected to be given orally. As Marschark and his colleagues have shown [21, 22], speed of oral articulation is slower in deaf than hearing people, and consequently deaf people's use of the window of opportunity to input linguistic information into WM is not as efficient as hearing people's.

The third task in the WM-CE Test Battery for Children, Counting Recall, originally developed by Case, Kurland, and Goldberg [23], uses visually presented stimuli: a series of dots on subsequent pages in a book is shown to the child. The child is asked to count the dots on each page and recall the number of dots. The number of pages presented increases as the task progresses. The child's span is the largest number of dot-counts correctly recalled and in the right sequence. When this task is presented to deaf children who sign, they can count and encode the information in sign, and one could think that this gives them the benefit of using a language that they process efficiently. However, sign span is lower than word span both for hearing people who sign and for deaf people educated bilingually [24-27]. Thus allowing deaf children to sign in the counting recall task does not set aside their disadvantage in encoding speed.

The use of language in the encoding of the stimuli may indeed be a significant source of difficulty for deaf people in WM tasks. The Corsi block test, in which the tester touches blocks arranged on a board in a particular order and the participants are asked to reproduce the order in which blocks were touched, is a visuospatial span task [17]. In this task, adult signers outperform hearing adults who do not sign and deaf children outperform hearing children who do not sign [25, 29, 30]. Thus one might argue that deaf children's disadvantage in WM-CE measures is an artifact of the measure: when they can use the visuospatial sketchpad, they perform better than hearing children even in tasks that require the sequential reproduction of information. However, it must be noted that the Corsi block test does not require manipulation of the information, and it is therefore not a measure of WM-CE, but a measure of the capacity of the visuospatial sketchpad.

The difference between tasks that require linguistic encoding and those in which the stimuli can be encoded spatially does not imply that the former are artificially hindering deaf children's performance in WM measures. The literature briefly reviewed earlier on in this paper leaves no room for doubting that deaf children and adults have lower WM-CE spans than their hearing counterparts. The question is whether they could be using their advantage in visuospatial span tasks to support their performance in WM-CE tasks, but have not learned to do so. Our hypothesis, tested in this intervention study, is that they can be taught to use their visuospatial skills to improve their performance in tasks that traditionally are only encoded linguistically. If deaf children learn to use their visuospatial strengths, they could attain better performance in tasks in which they typically score lower than hearing children.

2. The Use of Rehearsal Strategies

A second factor that might explain why deaf children show lower spans than hearing children in WM-CE tasks relates to the use of rehearsal strategies, which support the input of information into WM in adults with high spans [31]. Bebko and Metcalfe-Haggert [32] reviewed possible explanations for deaf students' lower WM spans and noted that deaf students show less evidence of using rehearsal, either in oral or signed form, than hearing students. MacSweeney, Campbell and Donlan [33] observed that visually based rehearsal strategies are effective for deaf adolescents, when these are used. This result suggests that visual rehearsal strategies may be difficult to acquire but can be effective, if implemented. Thus, a lack of tendency to rehearse, fluency problems in oral language and the late emergence of visual rehearsal strategies may affect deaf children's performance in WM-CE tasks.

There is evidence with hearing children and adults that training that seeks to engage the participants' intentional rehearsal during a task can lead to improvements in WM tasks. Positive results have been obtained in studies with hearing adults [31, 34] and young hearing children [35].

The implication of these findings for training that aims to improve deaf children's WM is that deaf children should benefit from training that leads them to rehearse. Furthermore, strategies that help them to bind verbal and visuospatial information during rehearsal should benefit from their better performance in visuospatial tasks, as documented in the Corsi block task [25, 29, 30].

3. Reduced Opportunities to Orient Attention

The third possible explanation for deaf people's weaker performance in WM tasks relates to processes involved in attention control. Performance on any task requires attention orientation because any task takes place in an environment where there are other objects and people [36]. Competition for attention interferes with performance; this is well documented in dual task performance, when someone has to attend to two messages at the same time [37]. Competition across modalities comprises a large part of hearing people's experience, who often must carry out a task while there is conversation in the room. Gregory [38] documented in her observations of deaf children and their parents the lack of experience with simultaneous visual and auditory information: parents of hearing children often count or label their actions as they carry them out (e.g. count steps as they climb stairs or plates as they lay the table) but parents of deaf children cannot do so. She argued [39] that this lack of simultaneous visual and auditory information interferes with deaf children's informal mathematics learning. Here it is suggested that it also results in deaf children having less experience with dual tasks in everyday life.

Attention orientation in dual tasks involves both implicit and conscious orientation to the task. Children who have poor WM may have attention problems at a basic level of task orientation [40]. Duncan [36] suggested that WM-CE is largely related to attention orientation, defined as a process that involves the selective description of information that is relevant to current thought or behavior. According to him, the brain establishes task relevance through a cumulative process; for example, in a test or experiment, the process starts with receipt of instructions and is further elaborated while a full task representation is constructed during the initial trials. This process, which can be documented in animals as well as humans, is not related to the use of rehearsal during the task, and thus is independent from the processes discussed in the preceding section. It involves the pre-activation of brain cells in response to the selection of attention targets.

Cowan, Morey, AuBuchon, Zwilling, and Gilchrist [41] have shown that children aged seven perform similarly to adults in such tasks, unless their working memory is overloaded. In their study, circles and triangles were presented as children, their spatial location was presented as their place in the classroom, and the recognition task was introduced as a judgment of whether the children belonged to the class or should be out of the door, thus making the task relevant to the children in a very ingenious way. By varying the number of objects in the tested shape (circle or triangle), they assessed the effect of overload on the participants' memory capacity, and by varying the proportion of the trials in which the shape was tested (a shape not tested in the recognition trials or tested only 20% of the time should be perceived as less relevant and receive less attention), they assessed attention control. Cowan *et al.* found that capacity increases with age as well as the ability to attend selectively to relevant stimuli when capacity is overloaded.

Cowan *et al.*'s study [41] used a simple task, based on the recognition of shapes and their location in space, which contrasts with typical WM measures used in studies that relate WM to educational outcomes. In the tasks used in WM Test Battery for Children, all the tasks use recall rather than recognition. The children must be able to select the relevant information, which usually involves words (e.g. which digit was pronounced or what was the last word in a sentence) or quantity (e.g. how many dots were displayed) and attend to the order of stimuli (stimuli must be recalled in the order of appearance or reverse order). Other information must be disregarded: for example, the spatial arrangement of the dots on the page is considered irrelevant in the Counting Recall task and whether the sentence was true or false is irrelevant to performance in the Listening Recall task. If deaf children have less experience with dual task performance, their attention orientation may take longer to develop during the initial trials, with deleterious consequences for their performance because they will not attain the criterion in earlier spans (usually, four correct answers out of six trials) to proceed to the next span level.

If this is the case, one would expect deaf children to show weaker performance than hearing children even in measures of visual attention orientation, and there is in fact evidence to support this prediction. Mitchell and Quittner [42] studied deaf children's performance in a computerized visual attention task and compared their performance with hearing children's performance. They found that approximately 71% of the deaf children scored in the borderline/abnormal range in this task, in comparison to only 9% of the normal-hearing sample. Quittner, Leibach and Marciel [43] argued that deaf children's attention problems may stem from their very inability to orient to sound from an early age, and therefore their WM problems could result from difficulties in attention orientation. We suggest that their difficulty in attention orientation could result from initial problems in the development of the orientation reflex as well as from their less frequent exposure to dual tasks. Consequently, a program designed to promote deaf children's WM-CE performance should contain an element of attention orientation training in tasks in which there is competition for attention.

Orientation training can be promoted in biased competition tasks, in which the participant is instructed to report targets and ignore non-target stimuli. When people are asked to report letters in a visual field, their performance deteriorates as a result of competition if the number of letters increases. However, if people are asked to report white and ignore black letters, this biased competition produces improvement in performance when the number of letters is held constant, because some of the letters are no longer targets and can be ignored [36]. The implication of these findings may appear, at first sight, paradoxical: we conjecture that increasing task difficulty benefits performance, but this improvement would only take place in the long run. Children who have orientation difficulties should benefit from practice in tasks in which there is competition for attention, but the competition is biased. Because competition increases when the number of stimuli increases and when the similarity between targets and non-targets increases [36], a sensible training strategy is to increase the number of stimuli and the similarity of targets and non-targets throughout training. This scheme renders the task progressively more difficult while attention orientation is reinforced through practice in biased competition tasks.

Research with hearing children has shown that WM can be improved among typically developing children and children with attention disorders by repeated performance on WM tasks when the level of task difficulty is augmented by increasing the amount of information to be recalled [44-47]. This progressively more challenging program was shown to be effective, whereas a comparable amount of on-task training in non-challenging tasks was not effective. The successful training of WM in hearing children with attention problems indicates that a similar approach, involving training with progressively more difficult tasks, could be beneficial also for deaf children. In our program, we used dual tasks and increased the level of difficulty both by increasing the amount of information to be recalled and the similarity between the target and non-target stimuli.

In summary, there are three possible explanations for deaf children's poorer performance in WM tasks than hearing children's: the resources used in encoding information, the lack or inefficiency of rehearsal strategies, and reduced experience with dual tasks that entail attention orientation. Although we do not rule out other possible explanations, such as an inherently lower WM capacity, these alternative explanations are not relevant to the present study, which focuses on the documented difficulties that deaf children have with encoding and attention orientation.

With these possible explanations in mind, we designed a WM intervention program for deaf children that include the teaching of visual and verbal rehearsal strategies combined with practice in computer games, which aimed at developing orientation processes in biased competition tasks. The rehearsal practice games were played with the support of a teacher or teaching assistant and the computer games were played on the web without a tutor. We turn now to the description of the empirical study.

METHODS

Participants

Participants were 77 deaf children (44 boys) in a comparison group (80 were recruited but 3 did not complete the post-test) and 73 (42 boys) in an intervention group. They were recruited through their teachers, who volunteered to participate in response to an advert in a magazine for teachers of the deaf, which invited teachers to participate in research that aimed to investigate new approaches to promote deaf children's learning. In order to obtain a representative sample of deaf children in UK schools, all the pupils of the participating teachers who met the criterion of not having additional special educational needs were included in the study. The children's mean age at the start of the study was 8y5m (SD=1.5 years); the range was from 5 to 11 years. Children who had additional special educational needs apart from hearing loss were excluded from the study, but their teachers were allowed to use the intervention materials with them. Table **1** presents the severity of hearing loss by group.

In the comparison group, 26 children had one cochlear implant and 51 had hearing aids only; in the intervention group, 22 children had one cochlear implant and 51 had hearing aids only. All the children were in schools where both BSL and spoken English are used in interactions in and out of the classroom. The children's language ability was not assessed but they were asked in spoken English as well as BSL which language they preferred; 9 children had a preference for BSL and the rest for spoken English. All participants were tested in their preferred language by a researcher experienced in working with deaf children and proficient in BSL.

Design

This study uses a quasi-experimental design according to which teachers rather than children were assigned to the treatment groups. The model is an intention to treat model: all the children whose teachers volunteered and had parental permission were included in the study, irrespective of how much of the program they received.

Recruitment took place over two years. Teachers recruited in the first project year were assigned to the comparison group, which was an active control group. These teachers participated in training to prepare them for delivering a program that aimed to improve their children's mathematical skills. The teachers delivered this program during this first project year and agreed to have their children pre- and post-tested on the measures required for this study as well as on mathematical attainment. The use of an active comparison group allows for controlling for the effects of having an additional, research related program in the classroom as well as for teachers' motivation to improve their children's academic performance. The mathematical skills program used also controlled for the children's practice with computer games, as the mathematical program included computer games

Table 1: Severity of Hearing Loss by Group

Severity of Hearing Loss	Group		Total
	Comparison	Intervention	
Moderate	12	10	22
Moderate/Severe	8	9	17
Severe	17	17	34
Severe/Profound	11	6	17
Profound	29	31	60
Total	77	73	150

related to mathematics. The games in the mathematical skills program and in the WM program were designed with the same game platform, which leads to similar routines during the game, although the content is different. Because it has been shown that WM and mathematical skills are related, even after controlling for the children's age and general cognitive skills [48], a program to develop mathematical skills which included computer games seemed a particularly well suited activity for the active control group.

Teachers recruited in the second year were assigned to the intervention group. They participated in a full-day of professional development before the start of the intervention and after their children had been pre-tested in the WM measures. The professional development program included a presentation by the researchers on WM concepts and measures, a description of the program by the researchers with some role play on how they could guide the children to rehearse during the teacher-led games, and the opportunity for the teachers to use the materials during the day. Teachers practiced how to guide rehearsal with each other in order to gain confidence in their role during the training.

All participating teachers were qualified teachers of the deaf and worked in special schools for the deaf or mainstream schools with a unit for the hearing impaired, or as peripatetic teachers.

Measures

Because WM is a concept, not directly observable, it is advisable to use more than one task in its measurement and draw on a model of measurement that attempts to separate the estimated parameters separately from measurement error [49]. Shipstead *et al.* [1] make the same recommendation with respect to the measurement of WM. In statistical terms, this means that it is advisable to use more than one task and combine the scores in the different tasks by using a factor score obtained in a principal component analysis. In this study, it was desirable to use measures in which deaf children tend to perform more poorly than hearing children of the same age i.e. recall tasks in which the information has to be manipulated and the order of presentation must be respected. Three measures of WM were used, two of which were from the WM Test Battery for Children, Counting Recall and Backward Digit Recall, described previously. The third task that assesses the central executive in the same battery, Listening Recall, was not included because variations in the children's preferred language modality, signed or oral, could have a considerable impact on this measure. For example, sometimes what is one word in BSL is more than one word in English and word order is not the same in English and BSL, so the last word in the sentence, which the children would be asked to recall, would not be the same across languages. Thus a third measure was developed for this project, Picture Recall. Because the Picture Recall Task was created for this project, its development and psychometric properties, analyzed in a previous study, are described in the subsequent paragraphs.

In the Picture Recall Task, the children are presented with two pictures on a computer screen. They are asked to name the pictures. After the pictures are named and before they disappear from the screen, a circle appears around one of them. The children are asked to recall the name of the object encircled. The same procedure is used for the next screen. For a span 2 trial, after two screens the children are asked to recall the name of the objects encircled in the order of appearance. This task requires children to process information about the pictures, as they need to name them, and recall the information in sequence, and thus is a measure of the central executive. In a pilot project, we assessed whether the children were able to name all the pictures to be used in the task and eliminated those pictures that the children found difficult to name, retaining only those which all the children were able to name in oral or signed language.

The number of screens with pairs of pictures increases during the task. Figure **1** presents a span 3 item. In order to meet the criterion for a span level, the child must pass 4 of the 6 trials within that span. The task is interrupted when the child does not meet this criterion for a span.

Before the use of Picture Recall in this study, the task was piloted with 233 deaf children (11 used primarily BSL and the remaining used primarily spoken English) in the age range 5 to 11 years, to scrutinize its psychometric properties. The children were all tested by experienced researchers who had met the required level of BSL for teaching deaf children in primary school. Instructions were given in the child's preferred language and the child was allowed to respond in English or BSL. On the same testing day, the other two WM measures used in this study, Counting Recall and Backward digit Recall, were given to all the children in order to provide information on the Picture Recall Task's validity.

Figure 1: An item from the Picture Recall Test illustrating an example for span 3.

A principal component analysis using the number of trials correct as the score for the children in each of the tasks was carried out in order to assess the relation between Picture Recall and the standardized measures, Counting Recall and Backward Digit Recall. If all three tasks measure the same thing, the scores should be significantly correlated and a single factor should be extracted, which should explain at least 50% of the variance.

The Picture Recall task's correlation with Counting Recall was .63 and with the Backward Digit Recall was .65; the correlation between the two standardized tasks was .70; all three correlations were significant at the .001 level. The principal component analysis produced a single factor, which explained 74.9% of the variance, strongly supporting the hypothesis that all three tasks measure the same construct. The factor loadings for the tasks in this factor were .85 for the Picture Recall Task, .88 for the Counting Recall Task and .87 for the Backward Digit Recall Task. Thus there is sufficient ground for the conclusion that all three tasks measure the children's WM-CE capacity. Therefore, in this study the measure of WM-CE will be based on the regression factor score plus 5, to eliminate negative scores and make the scores more easily interpretable.

At the time of pre-test, we also gave the children the sub-test Matrices of the British Ability Scale-II [BAS; 20], which is a non-verbal ability test. This test consists in presenting the children with matrices (2x2 or 3x3) which contain figures in all but one cell. The children are asked to analyze the matrix and identify, from six alternatives, which one best completes the matrix. Our aim with this assessment was to be able to control statistically for possible differences in cognitive abilities between the intervention and comparison groups, in view of the quasi-experimental nature of this design.

The Intervention

The intervention program comprised two types of activity, teacher-led games and web-based games. Both were delivered by means of computerized presentations. All the games were inspired by WM tasks described in the literature. There were three teacher-led games (the Colors Game, the Words Game and the Missing Digit Game) and three web-based games (the Animal Game, the Numbers Game and the Letters Game), described in the subsequent sections. In the sections that follow, the aims of the two sets of games are presented, followed by a description of each game.

1. The Teacher-Led Games

In the teacher-led games, the teachers' role was to introduce rehearsal strategies to the children and then guide the children's rehearsal by rehearsing alongside them until the children started to rehearse spontaneously. In all the teacher-led games, during the practice trials the teacher demonstrated a rehearsal strategy and encouraged the child to use the strategy to support recall. The strategies were designed to promote the binding of visuospatial information with linguistic information and to eliminate common errors, such as the production of three instead of four items in the recall of trials of span 4, without the recognition that an item was missing. To exemplify the strategy: in the Colors Game, the children are asked to recall the colors that appear on a strip on the computer screen. For span 2, the children would be told to associate the first color with the thumb, the next color with the index and thus the child would know at the end how many items had to be recalled. The association between a finger and a color would also help the child use visual and kinesthetic cues in the recall process, if the binding process worked.

In all three games, the tasks were introduced with the support of a slide depicting a "teacher" dragon. The teacher dragon appeared in later slides before a sequence of trials asking the question, which was read by the teacher "What helps you remember?" The child was expected to say that rehearsal helps, but even if the child did not say this spontaneously, the next slide would make the point by presenting a "pupil" dragon that answered "Keep rehearsing". This maneuver was introduced because a previous intervention study [50] showed that children are more likely to use a meta-cognitive strategy if they instruct themselves to use it. It was noted that children often adopted the phrase "keep rehearsing" as an answer to the question posed by the teacher dragon. Each game is now described in turn.

The Colors Game

Before the game starts, the children are presented with a color strip and learn the positions of the colors on the strip, which are similar to a rainbow. When the game starts, the teacher dragon appears above the color strip and announces how many colors the child needs to remember; next, a blank strip appears and then the colors flash in sequence in their positions; when they disappear, the child is asked to name the colors in the reverse order of appearance (deaf children usually say or sign "swap" for reversing the order). The number of colors to be recalled increases over time. Visual rehearsal is encouraged by asking the child to point to the positions of the colors with a particular finger while naming or signing the color at the same time. At the end of the presentation, the child will know how many items are to be recalled because pointing and counting were executed together. The teacher engages in rehearsing with the child at the beginning of each game and leaves the child to rehearse alone once the child starts to rehearse spontaneously. Figure **2** illustrates a sequence of slides in this game, span 2. The correct answer would be red; blue (you have to reverse the order of appearance).

Although to a hearing person the idea of pointing and signing at the same time may seem to make the task very difficult for deaf children who sign, this is a natural gesture for children who use BSL, who count objects by pointing and signing at the same time with the same hand.

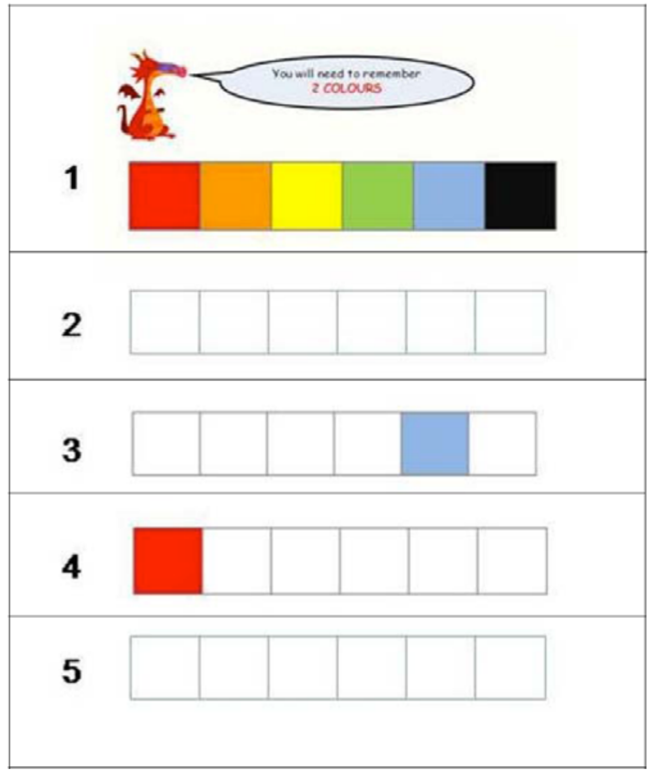

Figure 2: A sequence of the 5 slides that the children saw when presented with an item from span 2 in the Colors Game.

The Words Game

In this game, the teacher presents the children with a sentence in their language of instruction, oral or signed, and the children have to say whether the sentence is true or false of a picture on the screen; the children have to recall the last word in the sentence. The number of sentences increases over trials. Verbal or sign rehearsal of the last word is encouraged by the teacher, depending of the child's preferred language, and each word to be recalled is paired with a finger. The teacher engages in rehearsing with the child at the beginning of each game and allows the child to rehearse alone once the child starts to rehearse spontaneously. Figure **3** shows an example of the Words Game level 2, where the children need to recall two words; in this case, woman and cook. Note that for a training task it does not matter that children using oral or signed language will recall different words, as this is not an assessment of their WM.

The Missing Digits Game

On each slide, the children see a digit string and name the digits orally or in sign. At random places in the sequence of slides, a slide appears in which the digits are missing and are replaced by a dash; the last digit(s) is(are) replaced by a question mark to indicate

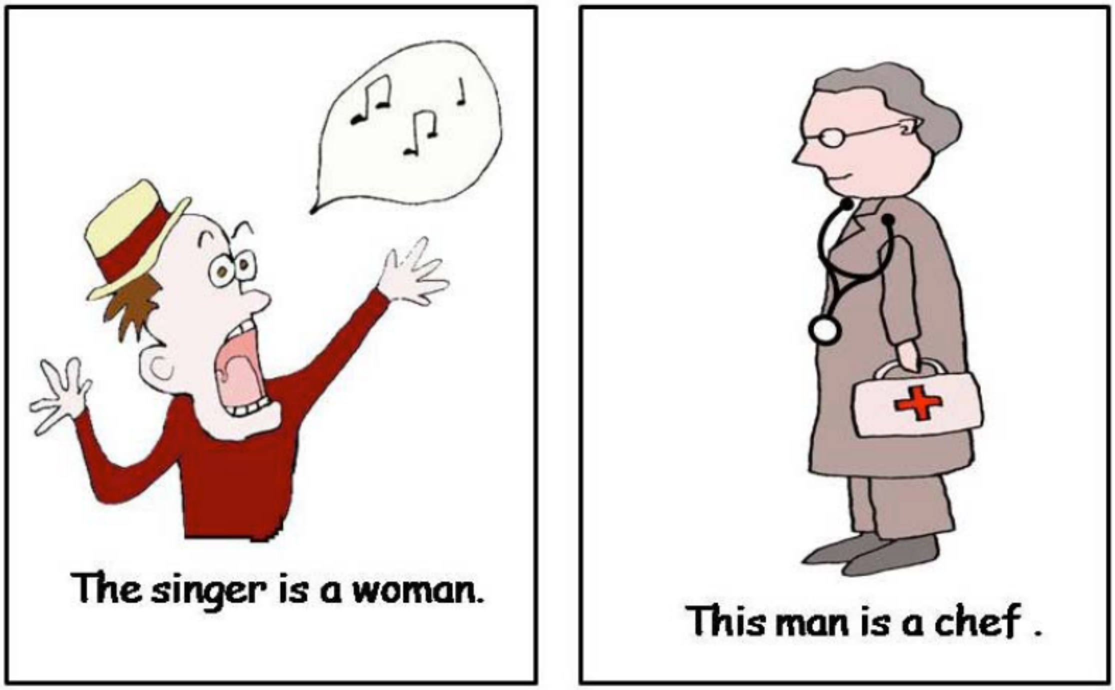

Figure 3: Each picture appears by itself in sequence and the sentence is said or signed to the child. The child must answer true or false before the next slide appears. (Note that chef/cook is a common word among deaf people as there are quite a few deaf chefs/cooks in the UK).

how many digits that the child needs to recall. The subsequent slide shows the string of digits again with the question mark indicating which digit(s) must be recalled. Figure **4** shows an example of the Missing Digits Game, level 1. The number of digits to be recalled increases over time. Rehearsal in oral or signed language is encouraged; as in the other games, the teacher initially rehearses with the children, but later leaves the child to rehearse alone, once the child has started to do so spontaneously. For level 2, the children would need to recall the last two digits, for level 3 the last three digits and so forth.

For all the games, the teachers move the children to the next level of difficulty in the game when the children meet the criterion of 4 trials correct out of 9. In each teacher-led session, the children are expected to play the same game a few times, attaining a new level of performance in comparison to the previous teaching session, but the teacher can move them on to a different game if the children become discouraged by their own lack of success. The children should play at least two different teacher-led games in each session. There are alternative games of the same type for children to play when they need to repeat a level more than once. All games have been designed to support practice up to span 7, which is typical of adult performance.

2. The Web-Based Games

There are three games to be played on the web. The children access the games in this link: http://www.education.ox.ac.uk/ndcs/memory_corner.php. The games were designed to involve minimal amounts of written information because many deaf children have difficulty with literacy. As the children played a game, their score was automatically kept: if they met the criterion of success (100% correct), they were rewarded by being directed to a bonus-games corner, where they had a choice of three computer games that are popular with children and not related to WM. After three minutes in the bonus-games corner, they were redirected to the WM games. The children were told that getting to the bonus games showed that they had played the memory games really well. When they did not meet the criterion, they were automatically directed to another game of the same type and at the same span level.

Teachers were asked to help the children start the session in order to make sure that the children started the games at a level immediately above what they had completed in the previous session. When the children played each of the web games for the first time, teachers were asked to help the children learn how the game worked. Children who have lots of experience with computers have no difficulty in figuring out how the

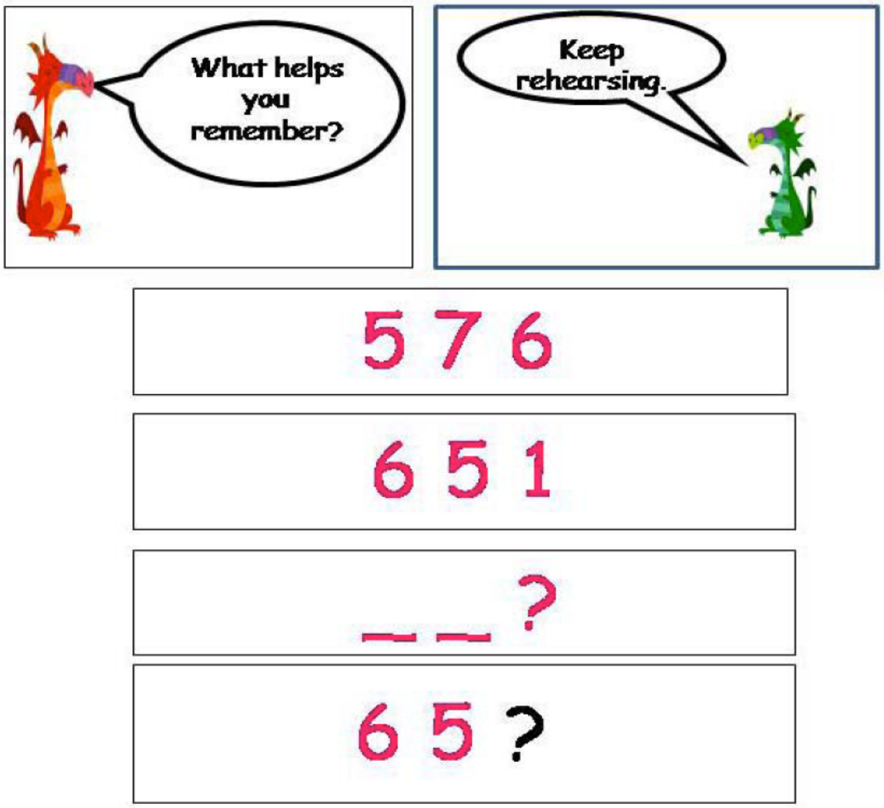

Figure 4: A sequence of slides from the Missing Digits Game, which also illustrates the prompting of the children to say that what helps them remember is to keep rehearsing.

games work but others who have less experience need guidance. Each of the games is now describe in turn.

The Animals Game

This is a biased competition task in which the target animals are randomly mixed with "Gremlins" (robot-like figures). The Gremlins become more similar to the target animals as the game proceeds; at first, they differ from the targets in size and color and later they are similar in size and color to the target animals.

In a series of screen presentations, the number of which depends on the span that the child is practicing, the animals and Gremlins appear. The child's task is to count the animals, enter their number into the computer, then count the next set of animals, enter the new number in the computer (and so on, depending of the span trial). When the target animals for the trial have been counted, the child is asked to recall the number of animals. There are two levels of difficulty for each span: in the first, recall is in the same order of appearance and in the second recall is in the reverse order. The number of screens with target animals increases over trials. Figure **5** illustrates span 2 in this game, in which the children must recall how many ducks and how many monkeys. This game gives the children the opportunity to use the rehearsal technique of binding visuospatial information with linguistic information and also opportunity to practice attention orientation.

The Numbers Game

This game gives the children the opportunity to practice visuospatial rehearsal, learned in the teacher-led games. The children learn the position of the 9 digits on a 3x3 matrix. During the game, digits appear sequentially in their place in the matrix on the screen and disappear; the children type each digit as they appear. At the end of the sequence, a blank matrix appears indicating that it is time for recall: the children have to type the digits in the reverse order of appearance. The number of digits to be recalled increases over time, increasing the level of difficulty. Figure **6** shows the initial blank matrix, a sequence of two digits, and the blank matrix as the cue to recall. The correct answer is 8 3 (the digits are to be named in the reverse order).

The Letters Game

This game gives the children another opportunity to practice visuospatial rehearsal strategies. The procedure is similar to the previous game but the

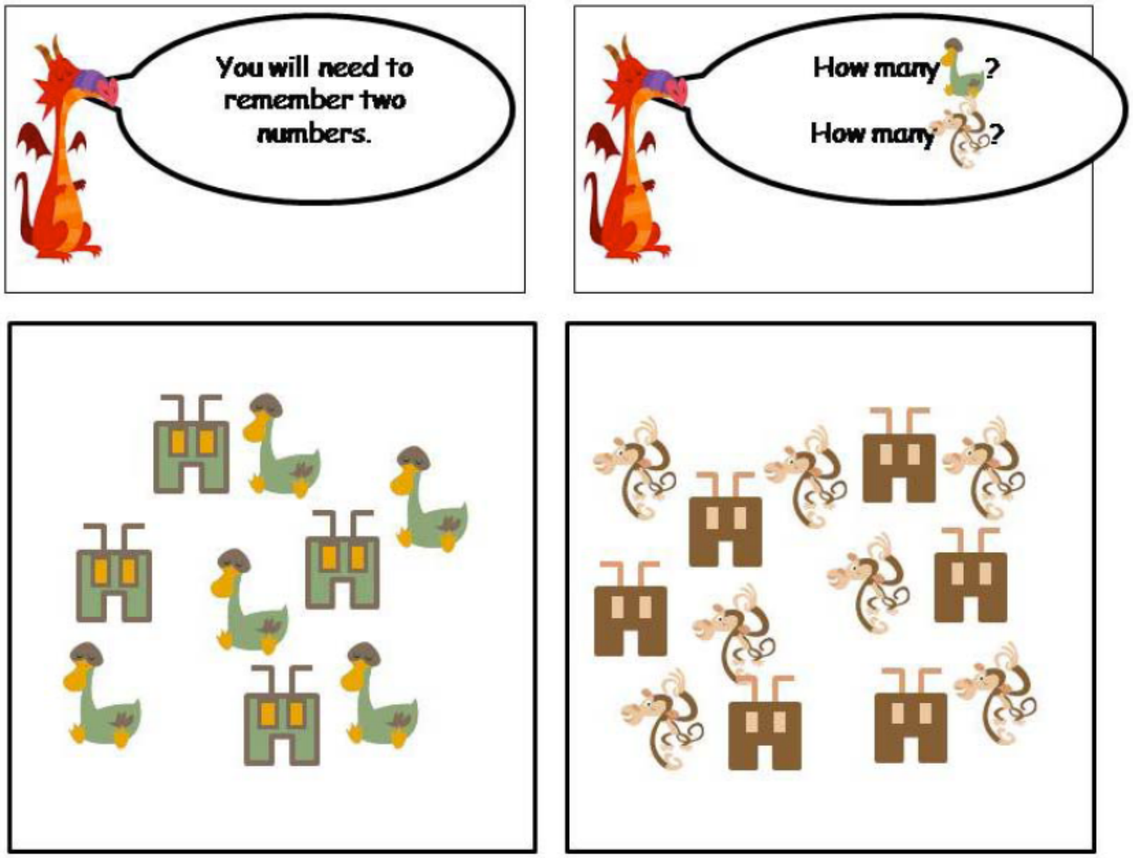

Figure 5: A sequence of four screens (the two on top appear first, followed by the two in the bottom) illustrating a late trial in the animals game, span 2.

letters A to I are used instead of digits. It is more difficult because the sequence of digits is usually better known by the children than the sequence of letters. Children need practice with the teachers to learn the placement of the letters before they can play this game successfully. The recall is in reverse order of appearance. As in the other games, the level of difficulty is increased by having the child recall a larger number of letters.

RESULTS

Preliminary analyses were first carried out to investigate possible differences between the intervention and the comparison group. The first two analyses investigated whether there was an association between severity of hearing loss and group or an association between the use of a cochlear implant and group. The severity of hearing loss by group is reported in Table **1** and the amplification used by the children is reported in the description of participants immediately after Table **1**. The Contingency Coefficient was used for both analyses and showed that there was not a significant association between these demographic factors and group.

Further preliminary analyses investigated whether there was a significant difference between the groups with respect to the number of children who preferred BSL to spoken English, the children's age, their performance in the pre-test both in the BAS and WM-CE measure, and the interval between pre- and post-test. Although we attempted to carry out the pre- and post-tests with as similar intervals as possible for the comparison and intervention children, dates have to be agreed with schools and it is not always possible to schedule testing for the target dates. As indicated in Table **2**, the pre- to post-test interval for the intervention group was four and a half months and for the comparison group was almost seven months. Table **2** presents the results of these preliminary analyses.

Inspection of Table **2** shows that the groups were comparable with respect to the number of children who preferred BSL to spoken English. They differed significantly in terms of the interval between the pre- and the post-test, in favor of the comparison group who had a longer interval between the tests, but the intervention group was older, had higher BAS raw scores in the Matrices sub-test and also higher WM scores at pre-test. These results suggest that four

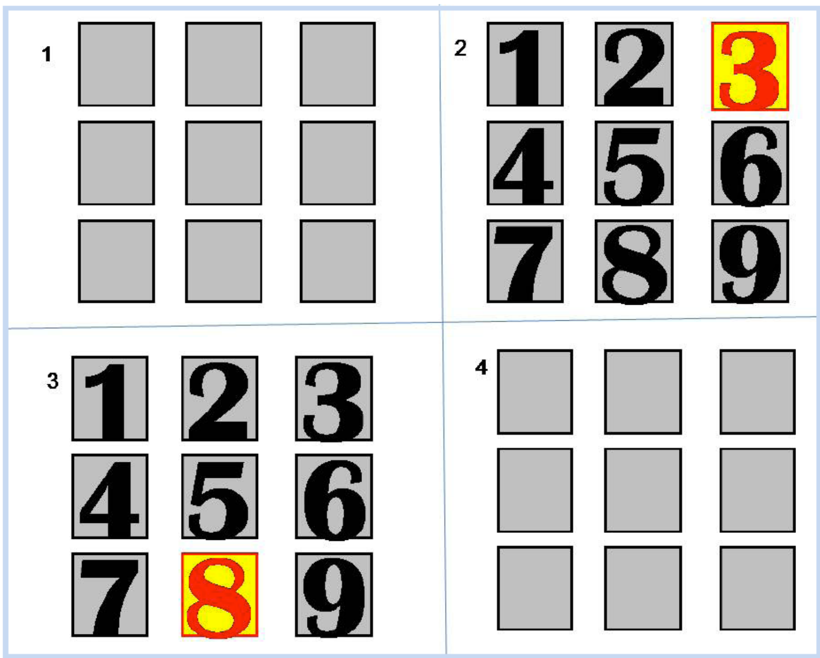

Figure 6: A series of screens that appear in the web-based Numbers Game.

Table 2: Number of Children who Preferred BSL and Means (SD in Brackets) for Age in Months, BAS Matrices Raw Score, Pre-Test WM Factor Score (Plus 5), and Pre-to-Post-Test Interval by Group

Measure	Intervention Group (N=73)	Comparison Group (N=77)	Significance of the Difference
Number of children who preferred BSL	3	6	Contingency Coefficient n.s.
Age in months	107.63 (19.85)	95.31 (14.65)	t=3.28; df=148; p<.01
BAS Matrices Raw Score	11.22 (5.95)	8.47 (4.26)	t=3.27; df=148; p<.01
Pre-test WM-CE factor score	5.43 (0.83)	4.83 (0.97)	t=5.13; df=148; p<.001
Pre-to-post-test interval in months	4.5 (0.44)	6.9 (0.68)	t= 26.80; df=148; p<.001

variables must be entered as controls in the analysis of covariance (ANCOVA), which will be used to compare the groups at post-test.

The adjusted scores at post-test (controlling for the pre- to post-test interval, as well as the children's age at post-test, and their pre-test BAS and WM scores) were 4.62 for the comparison group and 5.40 for the intervention group. Although this numerical difference of 0.78 might seem small, Cohen's d effect size is equal to 0.78 SD (note that in the factor score the standard deviation is equal to 1), which is considered a large effect size. The results of the ANCOVA showed that the covariates age at post-test, interval between pre- and post-test and BAS scores were not significant whereas the pre-test scores produced a significant result: F=113.42; p<.001. The difference between the groups at post-test was significant: F=7.37; p=.007, which indicates a significant effect of the intervention on the children's WM score.

A more conservative analysis of covariance was also carried out, in which the children's age, non-verbal ability and pre-test WM factor score were controlled but the interval between the pre- and post-test (which favored the comparison group) was not controlled; the dependent variable was the post-test WM factor score. The adjusted mean score (controlling for age, non-verbal ability and pre-test score) for the children in the comparison group in the post-test was 4.87 and the mean for the intervention group was 5.14. Thus, the intervention group had an advantage of 0.27 points in comparison to the baseline group. This difference between the groups was again significant (p<.001). Cohen's d effect size was 0.27. This confirms the effectiveness of the intervention.

CONCLUSIONS AND DISCUSSION

The aim of this study was to develop and assess a WM intervention that considered deaf children's strengths and difficulties in WM task performance. The results of the ANCOVA allow us to conclude that the intervention was effective in promoting deaf children's improvement in WM scores and that this effect cannot be explained by previous differences between the children in the intervention and the comparison groups. The large effect size and the fact that the intervention was delivered by teachers after a single day of professional training make this intervention highly cost-effective. The use of the intention to treat design suggests that, if teachers of the deaf have access to the materials and professional development to support their work, they will be sufficiently motivated to use them with their deaf pupils. An intention to treat design does not require monitoring treatment fidelity and is more ecologically valid than a design in which treatment fidelity is closely monitored because monitoring might influence what happens during the study. It is a robust design in so far as no teacher or child is excluded from the analysis due to circumstances that could affect the quality or quantity of the program delivery. The inclusion of all children of participating teachers, with the exception of those with additional special educational needs, makes the sample more representative; variations in preferred mode of communication and type of amplification used by the children reflected the diversity within the classrooms.

The computer mode of delivery of the materials tightens several aspects of program delivery and what is left to vary is the number of games used and differences between teachers in how well they are capable of guiding the children in practicing rehearsal. Some teachers might more easily recognize when the children have become independent in rehearsing than others. This could result in some children being left to rehearse on their own too early, when they were not yet sufficiently independent, whereas other children might have the teachers still rehearsing with them past the point when they could have attained independence. This variation, and its possible implications for the children's learning, is well worth investigating in the future.

A limitation of this study is the use of a quasi-experimental design, with the assignment of teachers rather than children to the intervention and comparison group. Quasi-experimental designs require an attempt to control statistically for the pre-test differences between the groups and the interval between the pre- and the post-test, a requirement which was met in the present study. However, it could still be argued that a randomized control design would be the ideal one for testing the effectiveness of the WM intervention. Although we recognize the advantages of randomized control trials, it is important to note that this would not necessarily produce clear results if the intervention was delivered in school, as the possibility of children allowing their friends to have access to the computer games cannot be discarded, and therefore there would be contamination between the groups.

Strength of this study is the use of three measures combined into a single factor score at post-test. Shipstead *et al.* [1], in a review of the literature on WM training, urged researchers to use the structural equation approach to WM measurement adopted here. They argued that if a single task is used, which is closely related to the tasks that form the training program, improvement in this outcome measure may be due to the learning of procedures for dealing with the task at hand, particularly if the content of the training and the post-test measure are the same. In the present study, the training program involved the children in the recall of letters, digits, colors, number of different animals, and words whereas the post-test measures involved digits, number of dots and pictures. Although there is a similarity in content in the digits post-test measure and one of the training tasks, the training task presented the digits on a 3x3 grid with an underlying organization (digits increased from left to right and top to bottom) whereas the digits in the post-test were presented in a linear arrangement. A good procedure for recall in the training task would draw on the digits' positions, but this procedure would not be useful when the digits were presented in linear arrangement with no underlying organization. Shipstead *et al*. further argue that training in complex tasks could result from improvements in attention control, and thus the improvement in WM measures would be influenced by attention. We do not dispute this possibility, which was part of our hypothesis regarding the effectiveness of the intervention for deaf children, because many perform poorly in attention measures. Thus we recognize that the improvement in WM observed in this study may not be independent of improvement in attention control.

A second limitation is that the design of this study does not allow for an analysis of the mechanisms of transfer nor for an analysis of what specific components of the training are crucial for improvement. The development of research applications, such as this WM training program, often suffers from this weakness, because the aim in applications is to maximize benefits by combining components that might not be effective in isolation. Camos, Lagner, and Barrouillet [51] have found that articulatory rehearsal and attention refreshing are two independent mechanisms that operate in the maintenance of information in WM and might affect different features. The present study cannot provide information on the role of rehearsal separately from binding of information between sensory modalities to facilitate recall. Nevertheless, it is important to find out in the future whether some aspects of the program are crucial as well as whether the effects of the different components are cumulative, and further research is necessary. This study can be seen only as a first demonstration of the effectiveness of a WM training program with deaf children.

WM is hypothesized by many researchers to be a cognitive resource that has an impact on learning. Research with hearing as well as deaf children shows that WM is an important factor for word learning and language processing [9, 52], reading comprehension [12, 53] and mathematical achievement [13, 48, 54, 55]. Because deaf children underperform in comparison to hearing children in WM tasks even after cochlear implants, it is important to attempt to improve their WM.

Contrary to what was previously thought, it is now accepted that WM is plastic and can be enhanced by training [40]. Two recent meta-analyses [1, 56] confirm the effectiveness of WM interventions in improving WM scores. These meta-analysis also underscore the need to analyze both near and far transfer. Shipstead *et al.* [1] concluded that the evidence even for near transfer is ambiguous, because many studies have used single WM tasks as outcome measures and it is possible that participants only learned procedures to deal with that particular task. Melby-Lervåg and Hulme [56] concluded for the lack of transfer between improvements in WM and academic achievement i.e. a lack of far transfer. All the studies reviewed in this latter meta-analysis attempt to improve WM without rehearsal training. It can be speculated that children who do not recognize the importance of rehearsal might show transfer to academic contexts if the WM intervention helps them to realize that rehearsal helps input information into long term memory; for example, they could realize that by practicing number facts, they are more likely to retrieve these number facts from memory later on. It is quite possible that different approaches to WM intervention leads to different results in transfer to academic skills and further research is needed to analyze the outcomes of different interventions.

Because transfer to academic learning was not assessed in the present study, one cannot say whether this transfer occurred. However, we conjecture that, if such transfer does occur, it is not an immediate but a medium term effect. WM is part of the acquisition process, which must be distinguished from retrieval [57]. Academic skills may rely on retrieval of stored knowledge, which would be influenced by acquisition processes only after the children have had some time to use their stronger WM skills acquired through training. This conjecture also has implications for further research: it is urgent that further intervention studies should be carried out in which different approaches to WM intervention are used. These studies would be stronger if they had longer term follow up and controlled for practice with academic materials to be learned. It could turn out that similar amount of practice with the academic materials and in the WM program are equally or more effective in improving retrieval and promoting performance in academic achievement tests.

Nevertheless, the implications of the results of the present study for education are exciting: it is possible to promote deaf children's WM through cost-effective techniques that teachers can learn in a relatively small amount of time and implement with their children.

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