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Phonological Short term memory in deaf children fitted with a cochlear implant: effects of phonological similarity, word lenght and lipreading cues

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Abstract

Phonological short-term memory (pSTM), or the ability to hold information in mind for a few seconds, is investigated in deaf children fitted with a cochlear implant (CI children) before the age of 3 years, in the framework of Baddeley's model. Results show that, compared to their age-matched hearing controls, CI children are delayed in the development of their pSTM capacity, and exhibit reduced effect of phonological similarity (PSE) and word length (WLE). However, when CI children are matched for pSTM capacity with younger NH children, the difference regarding PSE and WLE disappear. The CI children do not produce more order errors than NH children. Taken together, the results indicate normal resources of *functioning* of pSTM. The reasons for the shorter pSTM span in CI children are discussed.

Key words: Cochlear implant, auditory perception, phonological short-term memory, phonological similarity effect, word length effect, memory span.

La memoria fonológica a corto plazo en niños sordos con implante coclear: efectos de la similitud fonológica, la longitud de la palabra y la lectura labial

En este trabajo se investigó, en el marco del modelo de Baddeley, la memoria fonológica a corto plazo (MfCP), o habilidad para mantener información en la mente durante unos segundos, en niños sordos que han recibido un implante coclear (IC) antes de los 3 años. Los resultados muestran que, comparados con un grupo de niños oyentes de igual edad, los niños con IC presentan un retraso en el desarrollo de su capacidad de MfCP, y muestran un efecto reducido de similitud fonológica y de longitud de la palabra. Sin embargo, cuando se empareja a los niños con IC con niños oyentes jóvenes por su capacidad de MfCP, desaparece la diferencia en similitud fonológica y longitud de la palabra. Los niños con IC no producen más errores de orden que los niños oyentes. Tomados conjuntamente, estos resultados indican unos recursos normales de *funcionamiento* de la MfCP. Se discuten las razones del lapso más bajo de MfCP de los niños con IC.

Palabras clave: Implante coclear, percepción auditiva, memoria fonológica a corto plazo, efecto de similitud fonológica, efecto de longitud de la palabra, memoria retentiva.

Introduction

Working memory refers to the capacity to maintain and manipulate information during an ongoing task. Working memory seems an important factor in explaining changes in language skills in hearing adults and children (Baddeley, Gathercole and Papagno, 1998; Cowan, 1996), even in very young children aged 13 to 20 months. Apparent changes in vocabulary development may emerge out of incremental changes in capacity such as working memory and experience with individual words (Mills, Conboy and Paton, 2006). Given the relationship between language development and working memory capacity, the question of the development of this capacity in deaf children fitted with a cochlear implant is a very important one.

Phonological short term memory (pSTM) is the part of the working memory allocated to the short-term maintenance of linguistic information. In the

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case of speech, pSTM mechanisms have been best described by the phonological loop model of Baddeley et al. (1984). This model includes two components: a phonological buffer (or store) that holds memory traces for approximately 2 seconds, and a subvocal rehearsal process used to refresh the memory traces.

According to Jacquemot and Scott (2006), phonological short-term memory (pSTM) is related to speech processing in two ways. First, the performance of the phonological buffer which store verbal information transiently, is affected by the phonological nature of speech stimuli. Normally-hearing adults and children show the *phonological similarity effect* (PSE): stimuli that are phonologically dissimilar (non-rhyming words) are recalled better than stimuli phonologically similar (rhyming words). In the case of rhyming words, the candidate representations for a particular serial recall position are similar on the vowel. Maintaining a sequence of such representations in correct order is more difficult than maintaining a sequence of dissimilar representations. The locus for the phonological similarity effect is the *phonological store,* a component sensitive to native phonological properties that are processed by the speech perception mechanisms. For instance, the recall performance of French subjects worsens with sequences of stimuli that differ in stress location, whereas Spanish subjects perform well. Unlike Spanish, stress location in French is predictable and French speakers need not code stress in their phonological representations (Dupoux, Peperkamp and Sebastian-Gallés, 2001; Thorn and Gathercole, 2001). This suggests that native phonological properties influence recall performance and that the code used to store the stimuli is phonological in nature.

Second, the pSTM also interacts closely with the speech production system. The pSTM performance is highly affected by the length of the stimuli, in terms of duration of articulation (Baddeley, Thompson and Buchanan, 1975). The *word length effect* (WLE) refers to the fact that words that take more time to articulate and subvocally rehearse (long words) provoke a reduced span compared to words that are shorter to articulate and subvocally rehearse. The WLE is abolished under articulatory suppression, suggesting that this effect is linked to the subvocal rehearsal component of pSTM (Baddeley, et al., 1984). The pSTM performance depends on how quickly speech stimuli can be produced subvocally (i.e. internally produced without any spoken output). For instance, digit span are larger in languages whose digits are fast to pronounce, an effect even observed in bilingual subjects (Murray and Jones, 2002).

While the pSTM can been conceived as involving processes overlapping with both *speech* perception and *speech* production, it is more appropriate to conceive it as encompassing processes involved in the perception and production of any *language*, be it signed, cued, or spoken. As a matter of fact, the PSE, the WLE and the articulatory suppression effect have been observed in participants congenitally deaf belonging to different linguistic backgrounds (Sign Language, oralism, Cued Speech). Studies have suggested that in sign languages, as in spoken languages, information is stored in a phonological code (hand configuration, movement, place of articulation and hand orientation are the phonological primitives in sign languages). Tested with sequences of signed stimuli, deaf signers show a PSE: recall performances is lower for sequences composed of similar signs than for those composed of dissimilar signs (Wilson and Emmorey, 1997). As in spoken language, deaf signers' performance is lower when signed stimuli to be remembered are long rather than short to articulate (Wilson and Emmorey, 1998). This sign length effect (SLE) is similar to the WLE found in hearing subjects: under manual articulatory suppression the SLE is abolished suggesting that it originates from the rehearsal process. These results suggest that the signed pSTM consists of a buffer that stores information using the phonological structure of the sign language, and a submanual rehearsal process that seems to operate like a subvocal rehearsal process described in hearing subjects (Wilson, 2001).

In deaf participants educated orally or with Cued Speech(1), the pSTM consists of a buffer that stores information using the phonological structure of spoken or cued languages, and a submanual rehearsal process sensitive to the WLE as described in hearing subjects. The performance of deaf youngsters is sensitive to the PSE and the WLE: better recall is obtained for non-rhyming words than for rhyming words, and also better for short words than for long words (Campbell and Wright, 1990; Conrad, 1979, Hanson, 1990; Leybaert and Charlier, 1996; Leybaert and Lechat, 2001; Lichtenstein, 1998). Interestingly,

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(1) Cued Speech (CS) is a system of manual cues which disambiguate speech reading. Children raised early and intensively with CS show a rate of language development similar to that of age-matched hearing children (see Leybaert et al., 1998).

the performance is also better for written syllables that are dissimilar on the lips than for syllables which are similar on the lips, suggesting that the phonological properties conveyed by speechreading influence recall performance in deaf participants (Campbell and Wright, 1990).

Despite these strong similarities in the functioning of the components of the phonological loop (i.e., phonological store and rehearsal loop), studies have nearly systematically revealed a shorter STM capacity for deaf than for hearing age-matched participants (see e.g. Boutla, Supalla, Newport and Bavelier, 2004; Conrad, 1979, Campbell and Wright, 1990; Lichtenstein, 1998; Marschark and Meyer, 1998; Waters and Doehring, 1990; but see Wilson and Emmorey, 2006 for a different view). The reasons why deaf participants have shorter pSTM span than hearing participants are not entirely clear up to now. One hypothesis is that deaf participants are less prone than hearing ones to encoding information about temporal order. This explanation is based on evidence showing that deaf participants who exhibit a shorter span in the classical serial order recall task, perform equally well to hearing ones in memory tasks requiring order-irrelevant recall (Hanson, 1982; Boutla, Supalla, Newport and Bavelier, 2004).

Another factor that could determine limited STM capacity could be that most of deaf children experience difficulties to get a full, well-specified access to the language input. This is traditionally the case for children who rely on speechreading and residual hearing to perceive spoken language. Speechreading does not provide an input sufficiently detailed and robust as to permit the storage of phonologically distinct words. The development of vocabulary is in tight relation with the development of serial order maintenance in normally-hearing children (Gupta, 2003). If deaf children experience a strong delay in the development of their phonological lexicon, they also may experience a lack of incremental change in their pSTM capacity and a delay in their use of spontaneous rehearsal. As a matter of facts, spontaneous rehearsal seems to emerge at least 2 years later in deaf than in hearing children, and is predicted by the automatization of language skills (rapid naming of colors, numbers, animals and objects) rather than by age (Bebko, 1984; Bebko, Bell, Metcalfe-Haggert and McKinnon, 1998). This situation will leave deaf children with important delay of the pSTM capacity. Evidence supporting this explanation is given by the fact that deaf children who have been exposed early and intensively to Cued Speech develop a memory span equivalent to age-matched hearing children, which is quite rare among deaf children (Leybaert and Charlier, 1996; Leybaert and Lechat, 2001).

The fact that the development of capacity of pSTM is related to both language perception and language production systems is an incentive to investigate whether deaf children fitted early with a cochlear implant develop the same processes as the normally-hearing children. Cochlear implants (CI) permit better access to spoken language to profoundly deaf children and have a huge impact on language development, especially when children are fitted early, i.e. before the age of 2 years (Svirsky, Teoh and Neuburger, 2004). The available studies on pSTM in CI children indicate on average a shorter immediate auditory digit span in this clinical population than in the normally hearing (NH) age-matched peers (Burkholder and Pisoni, 2003; 2006; Dawson, Busby, McKay and Clark, 2002; Pisoni, Cleary, Geers and Tobey, 2000; Pisoni and Cleary, 2003; Pisoni and Geers, 2000). However, huge variability exists between children with CI. Those children who use oral communication methods have longer forward digit spans than children who use total communication (i.e., oral + signs), suggesting that the quantity and quality of phonological exposure can have a systematic effect on the pSTM capacity for sequences. In addition, the performances of children with CI in pSTM is related both to their speech perception abilities and to their verbal speaking rate, which is indicative of their subvocal rehearsal (Burkholder and Pisoni, 2003, 2006; Dillon et al., 2004). For instance, forward digit span is positively correlated with measures of speaking rate and negatively correlated with average sentence duration for utterances produced in an intelligibility test (Pisoni, Cleary, Geers and Tobey, 2000).

Speechreading information may contribute to the phonological encoding of stimulus information, even more in children with cochlear implants than in normally-hearing children. Indeed, the auditory information delivered by the cochlear device is not as precise as that perceived through normal audition, leading children with CI to poor perception of voicing and place of articulation features through audition alone. Audio-visual integration reflects the perceiver's ability to use different sources of sensory information to recover the underlying articulations of the talker's vocal tract (Fowler and Deckle, 1991; Liberman and Mattingly, 1985). NH adults and children make use of both auditory and visual information in speech perception, especially in poor listening conditions (Sumby and Pollack, 1954). Children with a hearing impairment are able to make use of the complementary information provided by the visual modality, increasing their speech perception scores in audio-visual presentation relative to the score obtained in the auditory-alone condition (Erber, 1972). CI children also show an ability to combine the acoustic information provided by electrical stimulation and the visual information about speech articulators (Lachs, Pisoni and Kirk, 2001). For most of the children with implants, perception is dominated by vision when visual and auditory speech information conflicted (Schorr, van Wassenhove and Knudsen, 2005; Colin, Deltenre, Radeau and Leybaert, 2007; Leybaert and Colin, 2008). However, no direct comparison of the pSTM capacity for auditory and audio-visual speech stimuli has been realized up to now on CI children.

The general goal of the present study was to determine the capacity and the processing components of pSTM in CI children who were fitted before the age of 3 years, in the framework of Baddeley et al.'s (1984) model. A first aim is to compare the pSTM capacity in auditory lists for CI children and age-matched NH children. We predict a lower pSTM capacity in CI children. Given that children with a CI are a very heterogeneous group, an additional question is whether *some children* fitted early with a CI reach a pSTM span equivalent to that of their hearing peers of the same chronological age.

A second aim is to compare the PSE and the WLE in the two groups. We predict a delay in the use of the rehearsal strategy indexed by WLE in CI children compared to age-matched NH children. An additional aim was to determine whether the PSE and the WLE could be of similar magnitude in CI children and in NH children *matched for pSTM capacity.*

A third aim of the experiment was to directly compare the pSTM capacity in audio-alone and audio-visual modalities. We predict that the benefit taken from the speechreading cues will be larger in the CI children than in the NH group.

Finally, we were interested in the comparison of the errors made by the CI children and those made by the NH children. Order errors are of particular relevance because they result from the loss of temporal order information during encoding or spoken recall due to inefficient rehearsal. By contrast, item errors result from the replacement of an individual item (word or digit) in the list with an item that was not presented in the original list. Item errors seem to indicate encoding problems rather than inefficient rehearsal.

Method

Participants

Twenty-two deaf 4- to 11-year-old children (M = 6.85, SD = 1.93) fitted with a cochlear implant were recruited. Two subjects were disregarded from the analyses because in the rhyme condition they only responded /wa/. For example, when given the 2 words sequence «bras, roi», one child responded «bras, oi». When given another 2 words trial: «toit, bras», he answered «oi, bras». His answers could not be scored reliably.

Among the 20 remaining CI children, 13 were fitted with the implant before the age of 37 months (mean = 30 months, SD = 5 months), and 7 others were fitted at a later age (mean = 50 months, st.dev. 12 months)(2). Ten children were male and ten were female. These children were followed by four different centers of the French speaking part of Belgium. Most of them had a congenital profound hearing loss larger than 100dB at the better ear. The average age of diagnosis of deafness for all children was between 0 and 42 months (M = 16.22, SD = 10.93), and coincides generally with their first hearing device. Implantation of the 20 CI children occurred between 20 months and 71 months (M = 37.55, SD = 12.73), and the duration of implant use ranged from 23 to 106 months (M = 44.70, SD = 20.02). All children were tested for (nonverbal) intelligence by their psychologists, and only children who fell within limits for their age range were included in the present study.

A comparison group of 20 NH children strictly matched with the CI participants for age- and gender was selected among a larger group of 51 NH children who participated the experiment (3) (Mean age:

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(2) We only had access to children's age of implantation after they passed the experiment. All our analyses were completed with and without the children fitted with a later age than 36 months. Because no difference was observed, we decided to include the late-implanted children in our group.

(3) Although we first compared our 20 deaf children to these 51 hearing children, we prefer to report here the comparison between two groups of equivalent size N = 20). The two comparisons gave similar results.

Tabla 1 *Mean memory span (standard deviations in brackets) for spoken monosyllabic words (auditory alone condition) as a function of hearing status and age group*

	Deaf children	Hearing children
Age group 1 (N = 5)	2.40 (0.55)	3.80 (0.83)
Age group 2 (N = 8)	3.13 (1.46)	4.38 (0.92)
Age group 3 (N = 7)	3.14 (0.90)	5.14 (1.07)

6 years 8 months). An independent sample test showed no difference between the age of the CI children and the NH children. All NH children were reported by their parents to be monolingual native speakers of French, and had no known hearing, speech, or intellectual disorders at the time of testing.

In order to compare age effects, three subgroups were distinguished among the CI and the NH children: group 1 (N = 5 in each population; 42 to 64 months), group 2 (N = 8; 68 to 78 months) and group 3 (N = 7; 91 to 130 months). For CI children, the mean age of implantation varied between the three groups, F(2,17) = 6.31; $p < 0.001$. The older children were fitted later than the children of the two other subgroups (mean age of implantation in group 1: 29 months, group 2: 33 months, group 3: 48 months).

Stimuli and materials

The experimental task was a word span task (Van Reybroeck, 2003) (4). It consisted of three conditions: control, rhyme, and long words. The control condition consisted of seven monosyllabic words phonologically dissimilar : *poule, verre, sac, pied, chien, lit, dent*. The rhyme condition consisted of seven words ending with the vowel /a/: *bras, toit, roi, doigt, noix, chat, rat*. The long words condition consisted of seven tri-syllabic words phonologically dissimilar: *pantalon, parapluie, chocolat, fenêtre, téléphone, crocodile, kangourou*.

Selections were made from the 7 words in each condition in order to form lists of the different lengths (from two words to seven words). A given word appeared only once in a list. Each word occupied a different position across the different lists of a same length. Care was also taken that words very close phonologically (like *toit* and *doigt*, or *rat* and *roi*) or words close semantically (like *poule* and *chien*, or *rat* and *chat*) did not appear in succession in the context of one list.

Children were first familiarized with the material. Pictures representing the words used in the three conditions were selected from databases (Bonin, Peereman, Malardier, Méot, and Chalard, in press; see http://leadserv.u-bourgogne.fr/bases/pictures/) and presented on 10 cm × 15 cm cards. Children were asked to name each picture aloud. This allows the experimenter to be sure that the children know the words, and permits also to become familiar with the child's pronunciations. The experimenter then pronounced each name and asked the child to repeat it so that the child became used to the experimenter's pronunciation and voice. Then the pictures were removed.

List lengths began with two words, then three words, ... up to seven words if appropriate. Four words lists of a given length were administered in the control conditions, then in the rhyme condition, then in the long words condition. Instructions emphasized that the child had to orally repeat the words in the order in which they were presented as soon as the experimenter gave him/her a manual signal. The experimenter read one word per second from the list. Each list was given only once, apart from the cases where there was an obvious perturbation (noise or child's inattention), in which case the list was repeated only once more. When the child incorrectly recalled or did not attempt to recall more than two lists of the same length in one of the conditions (e.g. rhyming), testing was concluded for that condition. Testing was pursued until the child failed in all of the three conditions.

This task was administered in two modalities by the first author: using live voice presentation, without lip reading cues available (audio-alone), and with lip reading cues available (audio-visual). For the audio-alone condition, a white sheet was placed at the half bottom of the experimenter's face so that only the experimenter's eyes were visible for the child. Half of the children began with the audio-visual modality, and the other half with the audio alone modality. The two modalities were administered in the same session, for time and organisation reasons. However, a short pause was respected between the two modalities.

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(4) Although this test has not yet been published, complete material and protocols are available from the second author.

Tabla 2 *Mean number of trials correctly recalled (standard deviations in brackets) as a function of modality (auditory alone versus audio-visual), conditions (control, rhyme, length) for deaf children with CI and hearing children matched for gender and age (N = 20 in each group)*

	Deaf children with CI	Hearing children
Auditory/control	7.65 (3.45)	12.80 (3.87)
Auditory/rhyme	4.85 (2.91)	7.55 (2.74)
Auditory/length	5.95 (2.09)	9.20 (2.73)
Audio-visual/control	8.50 (3.79)	12.40 (3.87)
Audio-visual/rhyme	5.60 (3.11)	7.80 (2.53)
Audio-visual/length	6.35 (1.79)	9.55 (2.84)

Tabla 3 *Mean number of trials correctly recalled (standard deviations in brackets) as a function of modality (auditory alone versus audio-visual), conditions (control, rhyme, length) for deaf children with CI and hearing children matched for accuracy in the control auditory condition (N = 11 in each group)*

	Deaf children with CI	Hearing children
Auditory/control	9.82 (3.06)	9.64 (3.26)
Auditory/rhyme	6.82 (2.36)	6.55 (2.62)
Auditory/length	7.09 (1.87)	7.46 (2.73)
Audio-visual/control	10.91 (3.42)	9.36 (3.20)
Audio-visual/rhyme	7.73 (2.28)	6.55 (2.58)
Audio-visual/length	7.36 (1.50)	7.36 (1.50)

Scoring

Four dependent variables were calculated for each child in each condition. *pSTM span* represents the highest list length for which at least two on the four trials were correctly recalled. *Number of correct trials* represents the sum of all trials correctly recalled until the conclusion of the test for that condition. *Number of items correctly reported in order* represents the sum of the individuals words correctly reported in their right order until the conclusion of the test for that condition. *Number of items correctly reported independent of the order* represents the sum of the individual words reported from the lists presented, independently of their order.

Results

pSTM span in the control condition (audio-alone modality)

Differences of the pSTM span previously reported between CI children and NH children were replicated here. The CI children displayed shorter word span in the control condition in the audio-alone modality than their age-matched NH peers (see table 1). Quantitatively, the word span of groups 2 and 3 of CI users was just below that of age group 1 of NH children, thus indicating a delay of more than 20 months. In addition, while the memory span of the NH children increased linearly with age group, this increase also appears between groups 1 and 2 in the CI users, but not between groups 2 and 3.

Tabla 4 *Number of children reaching a memory span of 2, 3, 4, 5, 6 or 7, as a function of age and hearing status*

Deaf children with CI Hearing children																
	4y	5y	6y	7y	8y	9y	10y	11y	4y	5y	6y	7y	8y	9y	10y	11y
2		3	4			1										
3	1	1		1	1	1	1	2	1	1	2					
4			2							2	1			1	1	
5						1			1		5		1	2		
6			1										1			
7															1	

Tabla 5 *Mean number of items correctly recalled (standard deviations in brackets) in their position of presentation (order) and independently of their position of presentation (no order) as a function of modality, conditions, and hearing status (N = 11 in each group)*

	Deaf with CI	Hearing
Auditory/control		
Order	35.45 (15.06)	34.91 (19.74)
No order	43.73 (18.05)	45.18 (23.01)
Auditory/rhyme		
Order	23.18 (8.75)	21.45 (11.77)
No order	28.73 (12.33)	27.27 (11.23)
Auditory/length		
Order	23.73 (8.43)	23.82 (11.89)
No order	30.55 (9.97)	31.45 (11.88)
Audio-visual/control		
Order	39.82 (16.80)	33.64 (16.86)
No order	48.82 (19.64)	42.73 (18.79)
Audio-visual/rhyme		
Order	27.64 (8.89)	23.09 (11.04)
No order	33.82 (10.49)	28.82 (12.42)
Audio-visual/rhyme		
Order	24.55 (6.12)	24.09 (14.02)
No order	32.27 (5.48)	31.27 (15.79)

An univariate ANOVA on this score with hearing status (NH vs. CI) and age group (1, 2 or 3) as between-subjects factor yielded a significant effect of hearing status, $F(1, 34) = 21.55$; $p < 0.001$. The effect of age group just failed to reach the significance level, $F(2,34) = 2.97$; $p < 0.067$. The interaction between hearing status and age group was not significant, $F < 1$. Similar results were obtained from the univariate ANOVAs on the other three dependent variables, i.e., number of lists correctly recalled, number of items correctly recalled in order, and number of items correctly recalled independently of order, except for the fact that the effect of age group reached a significant level ($p < 0.05$) for the two scores involving number of items recalled. In the following analyses, we will use the number of lists correctly recalled as dependent variable, because this score offers more variance than the memory span score.

PSE, WLE, and modality effect

According to Baddeley's model, NH children's should show the PSE (lower performances in the rhyme condition than in the control condition) and the WLE (lower performance for long words compared to the control condition). The question is whether this is also the case for the CI children. Regarding the effect of modality, one could expect an advantage for audio-visual presentation, especially in the group of CI children.

The mean number of lists correctly recalled for control, rhyme, and long words conditions, in the audio-alone and the audio-visual modalities are reported in table 2. A three-way ANOVA examined the between-subjects effect of group (NH versus CI) and the within-subjects effects of condition (control, rhyme, long words) and modality (audio versus audio-visual) on the number of lists correctly recalled.

The effect of hearing status was significant, $F(1,38) = 16.08$; $p < 0.001$, with a lower performance of CI children than that of NH children (mean number of lists correctly recalled for NH children : 9.88; for CI children: 6.48). The effect of modality was also significant, $F(1,38) = 4.37$; $p < 0.05$, and did not interact with any other factor (mean number of lists correctly recalled in the audio-alone condition: 8.00, in the audio-visual condition: 8.37). The effect of conditions was highly significant, $F(2, 76) = 74.48$; $p < 0.001$ (mean number of lists correctly recalled: 10.34 in the control, 6.45 in the rhyme, and 7.76 in the long words conditions). A significant interaction between conditions and hearing status was obtained, $F(2,76) = 5.23$; $p < 0.01$. The mean number of lists correctly recalled for control, rhyme and long words conditions was 12.6, 7.68, and 9.38 for the NH children, and 8.1, 5.2, and 6.2 for the CI children. No other interaction was significant.

This analysis was completed by two contrasts. The contrast between rhyme and control conditions was highly significant, $F(1,38) = 127.13$; $p < 0.001$, and interacted significantly with hearing status, $F(1, 38) = 9.06$; $p < 0.01$. The contrast between long words and control conditions was highly significant too, $F(1,38) = 57.47$; $p < 0.001$, and interacted marginally with hearing status, $F(1,38) = 3.66$; $0.05 < p < 0.10$; exact $p = 0.063$).

The results of these analyses indicate that CI children have reduced PSE and WLE. Does this mean that CI children are less sensitive to rhyme and to word length in an absolute sense? Is their phonological loop less efficient? Not necessarily. It is also possible that the reduced PSE and WLE in CI children are related to their limited STM capacity. The next section deals with this question.

PSE and WLE for CI and NH children matched on pSTM span in the audio-alone condition

Here we tested the null hypothesis: CI children show similar PSE and WLE as those found in NH children matched for general auditory memory capacity.

Eight of the 20 CI children with a word span of 2 items were eliminated from this analysis because there were no corresponding NH children. Compared to the 8 excluded children, the 12 remaining did not differed significantly by age at implantation (remaining: 39 months; excluded: 35 months), nor by duration of stimulation with CI (mean duration of stimulation : 50 months vs. 39 months . The remaining children were older than the excluded (88 months versus 72 months), and they were at elementary school for a longer time (4 years versus 2 years 4 months, F(1,22) = 4.2; $p = 0.055$).

The 12 CI children were strictly matched with 12 NH children regarding their performance in the control condition of the audio-alone modality. An effort was made to equalize the two sub-groups on pSTM span (meanpSTM span: 3.58, for both hearing and deaf children, SD = 1.00), mean number of lists correctly recalled (NH children: 9.42; SD = 3.20; CI children: 9.67; SD = 2.96), mean number of items correctly recalled in order (NH children: 33.92; SD = 19.13; CI children : 34.25; SD = 14.95). The cost of this forced matching procedure was that the CI children were significantly older than the NH children (88 months versus 68 months, F(1, 22) = 4.89; $p < 0.05$), and had a significant longer schooling experience (4 years vs. 2 years 6 months, F(1,22) = 4.35; $p < 0.05$).

We considered the mean number of lists correctly recalled as the dependent variable (as in the previous analyses). An ANOVA with repeated measures on conditions and modalities, with hearing status as between subjects factor, yielded a significant condition effect, F(2,44) = 47.62; $p < 0.001$. Neither the hearing status, nor the interaction between conditions and hearing status were significant, which indicates the success of our matching procedure. The effect of modality, and the interaction between modality and hearing status were not significant either.

This analysis was completed by two contrasts, one comparing the rhyme and the control conditions, the other comparing the long words and the control condition. Both contrasts were highly significant : Rhyme: F(1,22) = 76.91; $p < 0.001$; Long words: F(1,22) = 37.97; $p < 0.001$). The interaction between these contrasts and hearing status were not significant ($p > 0.10$).

To sum up, this analysis shows that when CI children were strictly matched with older NH children for the performance in the audio-alone control condition, the two groups exhibit similar PSE and WLE. CI children are NOT more «deaf» to phonological similarity and word length than are NH children.

Do CI children made more order errors than the NH children?

It is therefore of interest to examine whether, when matched for level of performance, CI children and NH children made the same kind of errors. For this analysis, we used the number of items correctly reported at their position of presentation, and the number of items correctly reported independently of their position of presentation. Table 5 shows that the difference between mean number of items correctly recalled in order and mean number of items correctly recalled independently of order is very similar in CI children and in NH children. A difference score (mean number of items independently of order minus mean number of items recalled in order) was computed for each subject in each condition. This score was submitted to an ANOVA with conditions and modalities as within-subjects factor, and group as between-subjects factor. Only the effect of condition was significant, F(2,40) = 5.78; $p < 0.01$): indeed, the difference between the two scores was larger in the control condition, intermediate in the long words condition, and lower in the rhyme condition. Neither the group factor, nor the interactions involving group were significant.

Inter-individual differences

The findings so far reported suggest that CI children have lower pSTM span on average than age-matched NH children. Is this true for every single child? We look at how many children aged from 4 to

11 years reached a memory span of 2 to 7 words in the groups of CI children and NH children matched for chronological age. The results of this cross-tabulation (see table 4) revealed three interesting points. First, none of the NH children had a span as low as 2 words, while 8 CI children did. Second, none of the CI children reached a 7 pSTM span, while one NH child, aged 10 years, did. Third, 5 CI children out of 20 (i.e. 25% of the sample) reached a memory span equivalent or higher to that of age matched NH peers : one 5-years-old (memory span = 3), two six-years-old (memory span = 4), one six-years-old even reached a memory span of 6 words, which was larger than the memory span displayed by our NH children and one nine-years-old (memory span of 5 words). Conclusively, the delay in phonological working memory is NOT generalized across all CI children. Although we did not obtained measures of the language development of all the CI children, the two 6-years-old children had a very good level of language. They reached a score of 7 on the Category of Auditory Performance scale (O'Donoghue, et al., 2000), meaning that they could communicated by phone with an unknown person. Efficiency in working memory thus seems to be related to language development, at least in these two good performing CI children.

We also looked whether age at implantation and duration of stimulation with the cochlear implant were related to pSTM span or number of lists correctly reported in the control condition of audio-alone modality. None of the four correlations reached significance.

Discussion

The present study is the first one that has looked at pSTM in the framework of Baddeley's model, i.e. by examining PSE and WLE in addition to pSTM span for words. The results point to four interesting conclusions.

First, there is a 20 months delay in the development of the capacity of pSTM when CI children (as a group) are compared to age-matched NH children. To be fitted with a CI before the age of 3 years is not sufficient to ensure the normal development of pSTM (Burholder and Pisoni, 2003, 2006). Several of our observations support this point of view. Eight of the CI children had an pSTM span of only two, suggesting an absence of rehearsal. Additionally, while the pSTM span progress regularly with age in the NH children, there was a slow progression between CI children from the group 1 and 2, and a total absence of progression between children of group 2 and 3. CI children from group 3 were fitted at a later age than those of the other two groups. Late fitting result in significant delay in language development (Svirsky et al., 2004), and in poorer auditory perception of syllables without context (Colin et al., 2007). These two factors could explain the poor development of pSTM in the older group.

How to interpret the fact that 5 CI children from our sample reached memory performances comparable (or even better in one case) to those of NH children of the same age? These children, fitted between two and three years of age, could have benefited from residual hearing during the first two years of life, so that their brain was already trained to process the speech sounds. Future research should take into account the pre-operative hearing level as a possible predictor of the effect of CI on the development of phonological working memory (see Szagun, 2004 for an effect of pre-operative hearing level on the acquisition of spoken morphology).

Second, the functioning of pSTM is similar in NH children and older CI children when the two groups are matched for span for monosyllabic non-rhyming words in the audio-alone condition. The components of the pSTM, the phonological input store (indexed by the PSE) and the rehearsal loop (indexed by the WLE) function similarly in CI children as in NH children. These data extend the literature in the domain of pSTM in deaf children. Indeed, it was already known that deaf children educated with Cued Speech showed similar PSE and WLE than hearing children (Leybaert and Charlier, 1996), but these children had developed their phonological representations mainly from visual input (speechreading + manual cues). The present data now suggest that it is possible for deaf children who have been fitted with a CI around the age of three years, and who have had auditory training and experience for more than four years to develop similar sensitivity to word length and phonological similarity than younger hearing children.

Third, our data do not show support for the contribution of speech reading to the improvement of the performance of CI children, which surprises us, given the fact that CI children rely more than NH children on visual speech information in speech perception (Colin et al., 2007; Leybaert and Colin, 2008; Schorr et al., 2005). Given that the auditory input delivered by the cochlear implant is not well-specified, we thought that the addition of speechreading would improve the intelligibility of the speech signal, particularly of the place of articulation feature. This could reduce the cognitive cost of word identification for children with CI, and leave more cognitive resources for the processing of the speech information in the phonological working memory. This was not observed. It is possible that pSTM is more influenced by rehearsal speed than by encoding in children with CI (Dillon et al., 2004). Unfortunately, we did not measured speaking rate, which prevents us of testing the contribution of this variable to the pSTM capacity.

Fourth, CI children do not seem to experience more problems for memorizing order information than younger NH children matched for overall memory performance.

Together, our data suggests that the efficiency of the storage and of the rehearsal components is related to efficiency of the pSTM, in CI children, as it is in hearing children. Assessment of pSTM might be important for evaluating the effects of cochlear implants, for both theoretical and practical reasons. In further studies, children fitted earlier than 3 years of age should be tested (such a research program becomes possible now that children are implanted around the age of one year). Earlier implantation would provide the brain structures with adequate information at the time they are maximally responsive, and result in a significant advantage in language development (Svirsky et al., 2004). As language development is related to the efficiency of pSTM in children with CI (as it is in normally-hearing children), one may thus predict that children fitted before the age of two years would display a significantly larger pSTM capacity for spoken words than children fitted later.

Future research also should be devoted to investigate the abilities that depend upon working memory, for example rhyming judgements. Deaf youngsters without CI could decide whether two written words, or two picture names, rhyme (Dodd and Hermelin, 1977; Campbell and Wright, 1988; Charlier and Leybaert, 2000). However, both behavioural studies (D'Hondt and Leybaert, 2003) and neuroimaging studies (Aparicio, Gounot, Demont and Metz-Lutz, 2007) have concluded that the neural resources recruited for rhyme judgement are less lateralised in deaf people than they are in hearing people. One possible reason could be that the deaf persons without CI have developed their phonological representations from visual and articulatory inputs rather than from auditory input. Now that a new generation of deaf children is growing up hearing the sounds of language through CI, this hypothesis could be directly tested. It would be no surprise if the restoration of auditory function through early use of CI would entail the development of a more coherent network of processing phonological information within the left temporo-parietal region associated with phonological working memory (Paulesu et al., 2001).

pSTM experiments should be assessed in different languages, in order to assess whether deaf children with CI are sensitive to the native language contrasts. For instance, it would be interesting to know whether Spanish children with CI are sensitive to stress location, and code stress in their phonological representations in pSTM (contrary to French speakers with a CI who need not code stress in their representations).

On a more practical level, working memory has been repeatedly shown to be related to efficiency in reading and in spelling. Delay in reading and spelling acquisition have been documented among deaf children with CI both in French (Leybaert, Bravard, Sudre, and Cochard, 2009) and in English (Archbold, Harris, O'Donoghus, Nikolopoulos, White and Richmond, 2008). Future research should be devoted to assess the link between the limited pSTM and the efficiency of phonological processes in word and pseudoword reading and spelling.

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Bibliografía

Aparicio, M., Gounot, D., Demont, E. and Metz-Lutz, M. N. (2007). Phonological processing in relation to reading: An fMRI study in deaf readers. *Neuroimage*, *35*(3), 1303-16.

Archbold, S., Harris, M., O'Donoghue, G., Nikolopoulos, T., White, A. and Richmond, H. (2008). Reading abilities after cochlear implantation: The effect of age at implantation on outcomes at 5 and 7 years after implantation. *International Journal of Pediatric Otorhinolaryngology, 72*, 1471-8.

Baddeley, A., Lewis V. and Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology, A Human experimental psychology*, *36*, 233-52.

Baddeley, A., Gathercole, S. and Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158-73.

Baddeley, A. D., Thompson, N. and Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Behavior, 14*(6), 575-89.

Bavelier, D., Newport, E., Supalla, T. S., Hall, M. and Boutla, M. (2008). Short-term memory for order differs in signers and speakers: Implications for models of short-term memory. *Cognition, 107*(2), 433-59.

Bebko, J. M. (1984). Memory and rehearsal characteristics of profoundly deaf children. *Journal of Experimental Child Psychology, 38*, 415-28.

Bebko, J. M., Bell, M. A., Metcalfe-Haggert, A. and McKinnon, E. (1998). Language proficiency and the prediction of spontaneous rehearsal in children who are deaf. *Journal of Experimental Child Psychology, 68*, 51-69.

Bonin, P., Peereman, R., Malardier, N., Méot, A. and Chalard, M. (in press). A new set of 299 pictures standardized in French for name agreement, image agreement, conceptual familiarity, visual complexity, image variability, age of acquisition, and naming latencies.

Boutla, M., Supalla, T., Newport, E.L. and Bavelier, D. (2004). Short-term memory sapn : insights from sign language. *Nature neuroscience, 7,* 997-1002.

Burkholder R. A. and Pisoni, D. B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology, 85,* 63-88.

Burkholder, R. A. and PIsoni, D. B. (2006). Working memory capacity, verbal rehearsal speed, and scanning in def children with cochlear implants. In: P. Spencer and M. Marschark (Eds.). *Advances in the spoken language development of deaf and hard-of-hearing children.* New York: Oxford University Press; pp. 328-59.

Campbell, R. and Wright, H. (1988). Deafness, spelling and rhyme: how spelling supports written word and picture rhyming skills in deaf subjects. *The Quarterly Journal of Experimental Psychology, 40,* 771-88.

Campbell, R. and Wright, H. (1990). Deafness and immediate memory for pictures: Dissociations between «unner speech» and «inner ear». *Journal of Experimental Child Psychology, 50,* 259-86.

Charlier, B. L. and Leybaert, J. (2000). The rhyming skills of deaf children educated with phonetically augmented speechreading. *Quarterly Journal of Experimental Psychology, 53A*(2), 349-75.

Colin, C., Deltenre, P., Radeau, M. and Leybaert, J. (2007). La perception audiovisuelle de la parole chez les enfants munis d'un implant cochléaire: premières données. In: L. Collet, C. Corbé, M. Doly, M. Imbert and Christen (Eds.): *Percevoir et Protéger*, Edition Solal: Neurosciences sensorielles et cognitives; pp. 193-207.

Conrad, R. (1979). *The deaf school child.* London: Harper and Row.

Cowan, N. (1996). Short-term memory, working memory, and their importance in language processing. *Topics in language disorders, 17*, 1-18.

Cowan, N., Keller, T., Hulme, C., Roodenrys, S., McDougall, S. and Rack, J. (1994). Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. *Journal of Memory and Language, 33*, 234-50.

Dawson, P. W., Busby, P. A., McKay, C. M. and Clark, G. M. (2002). Short-term auditory memory in children using cochlear implants and its relevance to receptive language. *Journal of Speech, Language, and Hearing Research, 45,* 789-901.

D'Hondt, M. and Leybaert, J. (2003). Lateralization effect during semantic and rhyme judgement tasks in deaf and hearing children. *Brain and Language, 87*, 227-40.

Dillon, C. A., Burkholder, R. A., Cleary, M. and Pisoni, D. B. (2004). Nonword repetition by children with cochlear implants : accuracy ratings from normal-hearing listeners. *Journal of Speech, Language and Hearing Research, 47*, 1103-16.

Dodd, B. and Hermelin, B. (1977). Phonological coding by the prelinguistically deaf. *Perception and Psychophysics, 21,* 413-7.

Dupoux, E., Peperkamp, S. and Sebastian-Gallès, N. (2001). A robust method to study stress 'deafness'. *Journal of the Acoustical Society of America*, *110*, 1606-18.

Fowler, C. A. and Deckle, D. J. (1991). Listening with eye and hand: cross-modal contributions to speech perception. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 816-28.

Gupta, P. (2003). Examining the relationship between word learning, nonword repetition and immediate serial recall in adults. *Quarterly Journal of Experimental Psychology, 56A,* 1213–36.

Hanson, V. L. (1982). Short-term recall by Deaf signers of American Sign Language: implications of encoding strategy for order recall. *Journal of Experimental Psychology: Learning, Memory and Cognition, 8*, 572-83.

Hanson, V. I. (1990). Recall of order information by def signers: phonetic coding in temporal order recall. *Memory and cognition, 18,* 604-10.

Jacquemot, C. and Scott, S. K. (2006). What is the relationship between phonological short-term memory and speech processing? *Trends in Cognitive Sciences, 10*, 480-6.

Lachs, L., Pisoni, D. B., Kirk, K. I. (2001). Use of audiovisual information in speech perception by prelingually deaf children with cochlear implants: a first report. *Ear and Hearing, 22*(3), 236-51.

Leybaert, J., Alegria, J., Hage, C. and Charlier, B. (1998). The effect of exposure to phonetically augmented lipspeech in the prelingual deaf. In R. Campbell, B. Dodd and D. Burnham (Eds.). *Hearing by eye (II), The psychology of Speechreading and Auditory-visual Speech.* Psychology Press; pp. 281-99.

Leybaert, J. and Lechat, J. (2001). Phonological Similarity Effects in Memory for Serial Order for Cued Speech. *Journal of Speech, Language, and Hearing Research, 44,* 949-63.

Leybaert, J. and Charlier, B. (1996). Visual speech in the head: The effect of Cued Speech on rhyming, remembering, and spelling. *Journal of Deaf Studies and Deaf Education, 1,* 234-48.

Leybaert, J., Bravard, S., Sudre, S. and Cochard, N. (2009). La adquisicion de la lectura y la orthographia en ninos sordos con implante coclear: Efectos de la Palabra Complementada. In: M. Carillo and A. B. Dominguez (Eds). Líneas actuales en el estudio de la lengua escrita y sus dificultades: dislexia y sordera. Libro de lecturas en honor de Jésus Alegria. Malaga: Aljibe.

Leybaert, J. and Colin, C. (2008). Perception multimodale de la parole dans le développement normal et atypique : premières données. In: M. Kail, M. Fayol and M. Hickman (Eds). Apprentissage des langues. Paris: CNRS Editions; pp. 529-47.

Leybaert, J., Colin, C., Willems, P., Colin, S., Nouelle, M., Schepers, F. et al. (2007). Implant cochléaire, plasticité cérébrale, et développement du langage. In: J. L. Krahé (Ed.). *Surdité et langage: Prothèses, LPC et implants cochléaires.* Saint-Denis : Presses Universitaires de Vincennes; pp. 13-67.

Liberman, A. and Mattingly, I. (1985). The motor theory revised. *Cognition, 21*, 1-36.

Lichtenstein, E. H. (1998). The Relationships Between Reading Processes and English Skills of Deaf College Students. *Journal of Deaf Studies and Deaf Education, 3*, 80-134.

O'Donoghue, G., Nikolopoulos; T., Archbold, S. (2000). Determinants of speech perception in children after cochlear implantation. *The Lancet, 356,* 466-8.

Marschark, M. and Meyer, T. S. (1998). Mental representation and memory in deaf adults and children. In: M. Marschark and M. D. Clark (Eds.), *Psychological perspectives on deafness* (vol 2, pp. 53-77). Mahwah, NJ: Lawrence Erlbaum.

Mills, D. L., Conboy, B. and Paton, C. (2006). Do changes in brain organization reflect shifts in symbolic functioning ? In: L. Namy (Ed.) *Symbol Use and Symbolic Representation* (pp. 123-53). Mahwah, NJ: Lawrence Erlbaum Associates.

Murray, A. and Jones, D. M. (2002). Articulatory complexity at item boundaries in serial recall: the case of Welsh and English digit span. *Journal of Experimental Psychology: Learning, Memory and Cognition, 28*, 594-8.

Paulesu, E., Démonet, J.-F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N. et al. (2001). Dyslexia: cultural diversity and biological unity. *Science, 291*, 2165-7.

Pisoni, D. B. (2000). Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. *Ear and Hearing, 21*, 70-8.

Pisoni, D. B. and Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear and Hearing 24*, 106S-120S.

Pisoni, D. B. and Geers, A. (2000). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. *Annals of Otology Rhinology, and Laryngology, 185*, 92-3.

Pisoni, D. B., Cleary, M., Geers, A. and Tobey, E. (2000). Individual differences in effectiveness of cochlear implants in children who are prelingually deaf: New process measures of performance. *Volta Review, 101*, 111-64.

Schorr, E. A., Fox, N. A., van Wassenhove, V. and Knudsen, E. I. (2005). Auditory-visual fusion in speech perception in children with cochlear implants. *Proceedings of National Academy of Sciences, 102*(51), 18748-50.

Sumby, W. and Pollack, I. (1954). Visual contributions to speech visibility in noise. *Journal of Acoustic Society of America, 26,* 212-5.

Svirsky, M.A., Teoh, S.-W. and Neuburger, H. (2004). Development of language and speech perception in congenitally, profoundly deaf children as a function of age at cochlear implantation., *Audiology and Neuro-otology, 9,* 224-33.

Thorn, A. S. and Gathercole, S. E. (2001). Language differences in verbal short-term memory do not exclusively originate in the process of subvocal rehearsal. *Psychonomic Bulletin Review, 8,* 357-64.

Van Reybroeck, M. (2003). Elaboration d'une batterie d'épreuves évaluant les compétences phonologiques. Université libre de Bruxelles, DEA en Sciences Psychologiques et de l'Education, pp. 63.

Waters, G. S. and Doehring, D. G. (1990). Reading acquisition in congenitally deaf children who communicate orally: Insights from an analysis of component reading, language, and memory skills. In: T. H. Carr and B. A. Levy (Eds.), *Reading and its development: Component skills approaches* (pp. 323-373). San Diego, CA: Academic Press.

Wilson, M. (2001). The case for sensorimotor coding in working memory. *Psychological Bulletin and Review, 8,* 44-57.

Wilson, M. and Emmorey, K. (1997). A visuospatial «phonological loop» in working memory: evidence from American Sign Language. *Memory and Cognition, 25*, 313-20.

Wilson, M. and Emmorey, K. (1998). A «word length effect» for sign language: further evidence for the role of language in structuring working memory. *Memory and Cognition, 26,* 584-90.

Wilson, M. and Emmorey, K. (2006). Comparing sign language and speech reveals a universal limit on short-term memory capacity. *Psychological Science, 17*, 682-3.

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