

건청 아동과 인공와우이식 아동의 시각 및 청각 통계적 학습 능력과 언어능력의 관계

Visual and Auditory Statistical Learning and Language Performance
in Children With Normal Hearing and Children With Cochlear Implant

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< Abstract >

Purpose: The large individual differences in children with CI have been explained by age of implantation (AOI), duration of implant use (DOI), communication mode, social economic states (SES), parental education level, and gender. However, recent research has focused on neurocognitive factors such as statistical learning, which is critical for language development. The purpose of the current study was to investigate the relationship of visual and auditory statistical learning and language performance in children with CI. **Methods:** Fifteen children with NH and fifteen children with CI participated in the study. A visual statistical learning task (VSL) and an auditory statistical learning task (ASL) were used for experimental tasks and a receptive vocabulary and a degraded listening task (high vs. low predictable sentence) were used for language tasks. **Results:** The results showed that children with CI showed a defect in visual and auditory statistical learning ability compared to the children with NH. In the NH group, age significantly predicted receptive vocabulary with high predictability accuracy. However, in the children with CI, it was AOI that significantly predicted high predictability accuracy. Additionally, low predictability accuracy was predicted by AOI and visual statistical learning ability. **Conclusions:** The overall results suggest that AOI is an important factor of explaining the causal relationship between language processing ability in children with CI. Also, poor statistical learning ability may be an underlying reason of the language processing deficit in children with CI. Lastly, statistical learning in the visual domain represented the overall fundamental learning ability in children with CI.

Keywords: Cochlear implant, statistical learning, degraded listening task, language processing

I. Introduction

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Listening is one of the most important pathways in language acquisition. Person who have severe auditory sensory deficit may not reach normal language performance or language development will be delayed. With cochlear implants and consistent language therapy, over than 60% children with cochlear implant (CI) can reach the normal range of language development (Niparko et al., 2010).

However, despite advances in medical technology and the absence of other disorders, large individual differences in language ability are found in children with CI (Eisenberg et al., 2002; Geers, 2003; Geers et al., 2003; Geers et al., 2009; Hawker et al., 2008). It has been reported that the age of implantation (AOI), duration of implant use (DOI),

communication mode, social economic states (SES), parental education level, and gender are the contribution factors of large variations (Geers et al., 2007; Geers et al., 2009; Holt and Svirsky, 2008; Niparko et al., 2010; Peña et al., 2002; Pisoni et al., 2010). However, this point of view limits the understanding of the underlying cause of these issues. Thus, it is difficult to explain the magnitude of the individual differences in children with CI.

Several authors have argued the importance of the neurocognitive system in the overall cognitive and language learning (Pisoni et al., 2010; Ullman, 2004; Ullman & Pierpont, 2005). Ullman has explained the learning system dividing into declarative and procedural model.

The declarative model suggests that representation, episodic knowledge, and semantic knowledge are learned by the declarative memory system. To the contrary, the procedural model supposed that habits, skills, and procedural information are learned by the procedural memory system, without having explicit knowledge and information. Procedural memory plays an important role in learning information that is stored implicitly, whereas declarative memory system plays an important role in learning arbitrary information consciously (Ullman & Pierpont, 2005).

There are two development models for the spoken language. These models are divided according to the process of language learning. It can be classified into top-down approach and bottom-up approach. Top-down approach is defined as a long-term knowledge in one's memory which helps to process the information (Anderson, 1982). In contrast, bottom-up approach is a process in which the information is focused on each stimulus. Without the explicit knowledge, and with no rehearsals, complex cognitive skills can be learned in procedural learning (Reber, 1967). Procedural learning has been outlined in many studies to identify the underlying reason for language development, including children with CI and children with specific language impairment (SLI) since it is an implicit learning that is critical in infants when they first acquire language.

Implicit learning is used for one of procedural learning. There are different methods to measure implicit learning ability like statistical learning, artificial grammar learning, serial reaction time (Yim & Windsor, 2010). These tasks are

different superficially, but they have same mechanism (Perruchet & Pacton, 2006).

Statistical learning is an innate ability to detect intrinsic rules in serial stimuli. It can be identified within-word and between-word by its transitional probability (Yim & Windsor, 2010).

According to several studies, infants learn language by statistical learning ability they possess (Graf Estes et al., 2007; Kirkham et al., 2002; Lany & Saffran, 2010; Saffran et al., 1996; Saffran et al., 1999). Statistical learning ability was found in the group of 8 months old infants (Saffran et al., 1996) in which infants were exposed to the arrangement of 4 three-syllable nonwords in random order. Then, they learned the different degrees of interest in the partial new nonwords and completely new nonwords from the stimulus which has been exposed before. Results suggested that infants can distinguish familiar words from unfamiliar words. This is how infants learn language quickly and exactly is a natural inherent surroundings.

It has been argued that statistical learning ability is critical not only for infants but also for school age children as well as adults. (Conway & Christiansen, 2005; Conway et al., 2007; Conway et al., 2010a, 2010b; Yim & Windsor, 2010). Yim and Windsor (2010) examined the statistical learning using a visual stimulus and auditory stimulus of 20 school age children and 20 adults. Each subject was exposed to continuous 4 sets of triplet shapes and triplet tones. Then they were forced to choose exposed familiar one among the two options to find out whether participants have learned the rules implicitly. The results confirmed the importance of statistical learning in language skills above and beyond memory.

Statistical learning ability is associated with a diverse domain of language such as vocabulary and syntactic ability (Chambers et al., 2003; Cleeremans et al., 1998; Peña et al., 2002; Ullman, 2004; Ullman & Pierpont, 2005). If statistical learning is a fundamental learning mechanism that is important for infants to learn language, it will be directly related to language skills (Conway et al., 2010a).

Previous findings confirmed that there was a significant correlation between implicit learning ability and language processing skills in the normal hearing group (Fallon et al., 2002). The integration of sensory, linguistic, and cognitive processes is necessary to recognize spoken language

(Eisenberg et al., 2002). Other efforts such as controlling background noise are needed in noisy environments. The ability to use top-down knowledge is needed to process the high context of a sentence while the ability to use bottom-up knowledge is needed to process the low context of a sentence (Conway et al., 2010b; Klatt, 1979). It is possible to measure language processing skills using these two context conditions found in everyday life. These results indicate that statistical learning ability could be an underlying learning mechanism in language performance.

Many researchers claim that vulnerability in the procedural memory system results in deficits in cognitive and language development for children with language disorders (Evans et al., 2009; Ullman, 2004). Evans et al., (2009) found that children with SLI showed 52% ($SD=11\%$) performance on statistical learning (chance level), on the other hand normal children showed 58% ($SD=13\%$), statistically significant differences were found. However, there was no significant correlation between statistical learning performance and vocabulary ability, unlike normal children. When the exposure time increased to 42 min from 21 min, statistical learning performance increased. The study results suggested that language deficit in children with SLI may be influenced due to statistical learning ability.

Children with CI are likely to have difficulties with statistical learning ability compared to children with normal hearing (NH) (Conway et al., 2010b). According to the study of Conway et al., (2010b), visual statistical learning performance in children with CI appeared to be lower than in the group of children with NH. There were negative correlation between visual statistical learning ability and age of implantation (AOI) and positive correlation between visual statistical learning ability and duration of implant use (DOI). In other words, the longer period of auditory deprivation, the lower visual statistical learning performance and the longer period of experience to hearing sounds via devices, better visual statistical learning performance.

It is likely that innate statistical learning ability is influenced if there is little exposure to spoken language in the critical period due to auditory deprivation. Also, children with CI are affected by presented domains unlike other communication disorder populations (Cleary et al.,

2001; Conway & Christiansen, 2005).

An auditory and visual working memory of 8-9 years of children with CI was measured by Cleary et al., (2001). It analyzed the differences in two groups under three conditions, visual-spatial cues only, auditory cues only and visual-spatial cues with auditory signals. The performance of working memory in children with CI was lower than that with NH under all conditions. In particular, performance in multimodal condition was much higher than performance in unimodal condition unlike children with CI. It suggests that children with CI have a deficit on cognitive work regardless of which domain was presented.

Several sounds children have experienced is a major pathway for understanding the sequence of events. Even though they can hear the sounds from their device, there is possibility that the auditory deprivation period has impact on procedural and sequence learning (Conway et al., 2009). This emphasizes that it is related to not only processing auditory signals, but also cognition and language. This is called 'Auditory scaffolding hypothesis' (Conway et al., 2009). Statistical learning performance might be low due to the weakness of auditory sense according to this hypothesis. Due to the deprivation of one sensory modality, the nervous system changes and new encoding occurs (Finney et al., 2003; Kral & Tillein, 2006).

Therefore, there can be a lack of effective utilization of auditory cues and an improper strategy for processing information in children with CI. Based on the generalized information processing theory, auditory deprivation could have affected the visual domain which can result in limited statistical learning ability in visual domain (Conway & Christiansen, 2005). However, the nervous system can be reorganized to allow greater activation of the visual domain as compensation for the auditory deprivation (Bavelier & Neville, 2002; Bergeson et al., 2003). Thus, even if children with CI have deficit in statistical learning in auditory domain they may have compensated their innate ability in visual domain. Thus, we do not know whether children with CI have limited ability in visual statistical learning due to the cognitive generalization or good performance in visual statistical learning thanks to the brain plasticity.

In the Conway's study (2010a), not only vocabulary task but also degraded listening task consisting of two different sentence types (high predictability and low predictability

sentences) was used in order to measure language skills. It is important to measure vocabulary which heavily depends on explicit memory, but also language processing ability which depends more on procedural memory in daily life (Holt et al., 2012). Also, context may be an important factor for expressive vocabulary ability (Lee et al., 2009a) and syntax ability in children with CI (Yoon & Choi, 2009). Especially, language processing task measured in background noise in a test situation is more like a real life situations that children may be faced on a daily basis.

Based on the research described above, our goals were to determine whether statistical learning ability in children with CI is lower than in children with NH, to identify statistical learning ability as a neurocognitive factor that could explain language skills in children with CI, and to explore whether statistical learning ability is affected by different modalities in children with CI. It was hypothesized that children with CI will perform lower than children with NH on statistical learning on both domains and will be correlated with language skills especially with language processing measures.

II. Methods

1. Participants

All participants were recruited by advertisement or by Samsung Medical Center who have signed the consent form for study. This study abided by the Institute Review Board from Ewha Womans University and Samsung Medical Center.

Children with CI met the following criteria: (a) cochlear implants before the age of 4, (b) used cochlear implants for a minimum of 1 yr, (c) nonverbal IQ of 85 or greater measured by the Korean Kaufman Assessment Battery for Children (K-ABC, Moon & Byun, 1997) (d) word recognition measured by the Korean consonant-vowel-consonant (CVC) words list to ensure sufficient hearing acuity to perform the degraded listening and auditory statistical learning tasks. The Korean CVC words test had to be at least 80% for inclusion in this study (Lee et al., 2009b). (e) no additional disorder.

Parents provided information about their children's AOI

and DOI. Table 1 shows the demographic information for participant children with CIs.

표 1. 인공와우이식 아동 참여자 정보

Table 1. The children with CI participant demographic information

No.	Age (mo)	AOI (mo)	DOI (mo)	CVC phoneme score(%)	Device	Mode
1	48	23	25	95.4	Cochlear-Freedom	Bilateral
2	53	16	37	90.8	Cochlear-Freedom	Bimodal
3	58	29	29	95.4	Cochlear-Freedom	Unilateral
4	80	14	66	93.8	Cochlear-Freedom	Bilateral
5	82	30	52	89.2	Cochlear-Freedom	Bilateral
6	83	20	63	95.4	Cochlear-Freedom	Bimodal
7	83	47	36	81.5	Cochlear-Freedom	Bimodal
8	88	28	60	94.6	Advanced Bionics-Clarion	Bimodal
9	88	29	59	93.1	Cochlear-Freedom	Bimodal
10	92	33	59	99.2	Cochlear-Freedom	Bimodal
11	98	30	68	99.2	Cochlear-Freedom	Unilateral
12	101	20	81	81.5	Advanced Bionics-Clarion	Unilateral
13	108	18	90	96.5	Cochlear-Freedom	Unilateral
14	123	26	97	93.8	Cochlear-ESPrIt 3 G	Bilateral
15	129	46	83	92.3	Cochlear-ESPrIt 3 G	Bilateral

CVC phoneme score were presented as the percentage correctly identified phonemes (the number of correctly identified phonemes/total number of phonemes × 100). AOI=age of implantation; CVC phoneme score=consonant-vowel-consonant phoneme score; DOI=duration of implant use.

7 of 22 children with CI were excluded and 11 of 26 children with NH due to criteria. A total of 30 children, 15 children with CI (mean=87.6 mos, SD=23.1) and 15 with NH (mean=87.8 mos, SD=23) ranging in age from 4 to 10 yr, participated in the study. The mean nonverbal IQ (Moon & Byun, 1997) for the children with CI was 111.2 (SD=11.6) and the mean for the children with NH was 115.8 (SD=11.1). There were no significant differences between the two groups in age and nonverbal IQ (Table 2).

표 2. 건청 아동과 인공와우이식 아동의 생활연령과 비언어 성 지능 차이에 대한 분산분석

Table 2. Difference between age and nonverbal IQ in children with NH and children with CI

Variable	Children with NH (n=15)	Children with CIs (n=15)	Comparison	
	Mean (SD)	Mean (SD)	F	p
Age (mo)	87.8 (23.0)	87.6 (23.1)	0.001	0.981
Nonverbal IQ	115.8 (11.1)	111.2 (11.6)	1.228	0.277

2. Stimulus Materials

1) Visual Statistical Learning (VSL)

The stimulus was composed of the 9 non-namable shapes presented in Fig. 1. Seven of the nine shapes were used by Yim and Windsor (2010) and two shapes were created specifically for this study.

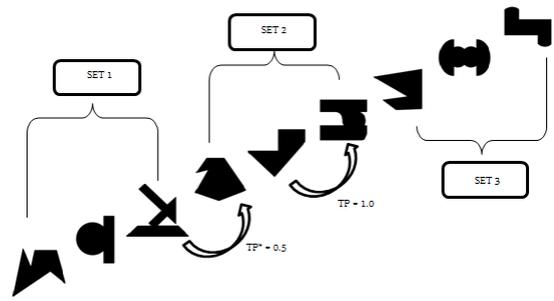
In the learning phase, three sets of triplets were used. Each set was composed of three shapes. The transitional probability (TP) of the shapes within a set was 1.0 and the TP between 3 sets of triplets was 0.5. The presentation duration for each shape was 1 s. Both groups of children were shown 3 sets of triplets consecutively for 4 m 50 s. Each set of triplets appeared 12 times and the same set of triplets was not presented consecutively.

The only way to segment the set pattern was by TP because there was no pause or auditory index between each set of triplets. A black vertical bar was positioned in the middle of the computer monitor. Each shape appeared to the left or right of the bar and passed to the other end of the monitor. Afterward, the shape returned behind the bar.

In the test phase, both groups of children were shown two sets of triplets and asked to select which sequence was more familiar based on the sets presented during the learning phase. One of the two sets of triplets was chosen from the sequences presented during the learning phase while the other was unfamiliar. A total of 24 pairs were presented (see Appendix 1).

2) Auditory Statistical Learning (ASL)

Based on research by Yim and Windsor (2010), the



TP (transitional probability) means the emerging probability from any stimuli to next stimuli.

그림 1. 시각 통계적 학습 과제에 사용된 3개 세트
Figure 1. Three sets of triplet were used for visual statistical learning tasks

auditory stimuli used in the present study consisted of nine pure tones within an octave presented in Fig. 2 (set 1: 440Hz, 370Hz, 349Hz / set 2: 330Hz, 493.9Hz, 261.6Hz / set 3: 294Hz, 277Hz, 392Hz). As with the VSL task, there were two phases. In the learning phase, children heard streaming sounds while they were coloring or drawing pictures. Three sets of triplet tones were presented. Four graduate students confirmed that each tone was different.

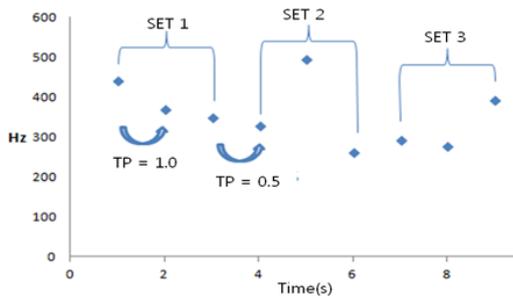
Each set was composed of three tones. The TP within 1 set was 1.0 and the TP between the three sets was 0.5. The presentation duration of each tone was 250 ms. Both groups of children heard the streaming sounds for 2 m 50 s. Each pattern was presented 21 times and the same set of patterns was not presented consecutively. The only way to segment a set was by TP because there was no pause or auditory index between each set.

After the learning phase, both groups of children heard two sets of triplet tones and were asked to select the more familiar set based on the sounds heard during the learning phase. One set was from the learning phase and the other was unfamiliar. Twenty-four pairs were presented (see Appendix 2).

3. Language Tasks

Language knowledge was measured by a standardized test (Receptive Vocabulary Test: REVT, Kim et al., 2009) and language processing ability was measured by the degraded listening task developed for the current study.

The degraded listening task (DLT) was adapted from



TP (transitional probability) means the emerging probability from any stimuli to next stimuli.

그림 2. 청각 통계적 학습 과제에 사용된 3개 세트
Figure 2. Three sets of triplet were used for auditory statistical learning tasks

Hyun and Yim's study (Conway et al., 2010a; Fallon et al., 2002; Shi, 2011). The degraded listening task (DLT) consists of two different sentences by its predictability. One is high predictable (HP) sentences, and the other is low predictable (LP) sentences.

1. 칫솔로 이를 닦다.
2. 아저씨가 종이를 불다.

The first sentence is an example of HP sentence, because we can guess the last word easily by using our knowledge. The second sentence is an example of LP sentence, because it is hard to find the last word by guessing. All sentences were created in Korean version.

Each sentence was composed of three phrases and the number of syllables per phrase was from 2 to 5. All verbs were in the present tense and 「subject, object, and verb」, 「subject, adverb, and verb」, 「adverb, object, and verb」, and 「subject, subject, verb or adjective」 was the order of the sentence.

To control the vocabulary difficulty, high frequency vocabulary was selected from among the vocabulary that 75 % of 30-month old children could express in their daily lives based on Choi (2000)' study. For the sentences composed of verbs with an auxiliary verb, metaphors and personification expressions were excluded. Ambiguous adjective tenses were also excluded.

A total of 130 sentences composed of 63 high predictability (HP) and 67 low predictability (LP) sentences were developed. Afterwards, 21 normal adults, graduate

students from A university, were asked to fill in the blanks (the last word) within each sentence. All sentences were presented in a random order.

The predictability of each sentence was scored as 1 when the participant provided an accurate response to the last word. If not, it was scored as 0. The raw score per sentence was divided by 100%. A total of 14 HP sentences (predictability ranging from 86 to 100%) and 14 LP sentences (predictability ranging from 0 to 0.95%) were selected as the final version of the degraded listening task (see Appendix 3).

All sentences were recorded by a female speaker through the TASCAM US-122MK II USB 2.0 Audio/MIDI interface (TEAC Corporation). Recorded materials were edited using the segmentation program developed by a professional at SiTEC (Sound information technology center).

Babble noise was then added to the last word in each sentence using ITU-T P.56 Speech Voltmeter from the ITU Software Tools Library (G. 191 Annex A, ITU). The length of the last words and the babble noise were identical.

The signal to noise ratio (SNR) was modulated on the basis of speech loudness for each of the last words. Modulated noise was added to every last word in an identical time domain which was an English babble noise from NOISEX-92 (Varga & Steeneken, 1993).

Pilot testing was conducted to determine the appropriate SNR. Two children with NH were tested at 2dB, 0dB, -2dB, -5dB, -6dB, -8dB, and -10dB SNR. In the results of previous study, mean score of high predictability sentence was 74%, mean score of low predictability sentence was 55% for normal adult (Conway et al., 2010a). -5dB was selected because mean score of high predictability sentence was 80%, low predictability sentences was 50% in the pilot test.

4. Procedure

The children with NH and CI were tested by trained research assistants at the Ewha Womans University. Both groups of children were tested in 2 phases, screening and experimental. The children with NH were given a nonverbal IQ test (Moon & Byun, 1997) and a brief pure tone hearing test as a screening test. These tests were used to ensure that the children were within the normal range. Nonverbal

IQ (Moon & Byun, 1997) had to be at least 85.

Children with NH who passed the screening were given 4 different experimental tests: VSL, ASL, receptive vocabulary test, and DLT. The experimental tests related to hearing, ASL and DLT took place in a sound-attenuated booth. Experimenters presented the materials through speakers at an average level of 67dB HL (ranged from 62.5 to 73 dB HL).

In order to control the loudness of speech sounds, we measured the loudness of each sentence using a sound level meter and the average was presented. Speakers were placed at ± 45 degrees azimuth relative to the listener.

An experimenter scored and recorded responses beside the children to provide reinforcement through verbal praise and to help keep the children's attention on the task. Three experimental tasks were conducted individually in a quiet room. The children with CI were given a nonverbal IQ test (Moon & Byun, 1997) and a Korean CVC words test for screening. The nonverbal IQ test was used to ensure that the children were within normal nonverbal IQ. The Korean CVC words test was scored as the percentage of correctly recognized phonemes to ensure that children with CI had sufficient hearing acuity to perform the experimental tasks related to hearing. Children with CI who passed the screening were given identical experimental tests as the children with NH.

The directions for visual, auditory statistical learning tasks and degraded listening task are below.

1) Visual Statistical Learning Task:

(1) learning phase: "You will see some shapes that you have never ever seen before. Just pay attention and look at the shapes on the computer screen."

(2) test phase: first, check if the child knows the meaning of the word 'familiar', "which word is more familiar to you, computer or putercom?" then, we give a direction, "You will choose the familiar set. You saw the several shapes on the screen. Then tell me which set is more familiar to you, 1 or 2."

2) Auditory Statistical Learning Task:

(1) learning phase: "You will hear some tones that you have never ever heard before. Just listen to the sounds and color the picture on the paper"

(2) test phase: same with visual statistical learning task. If a child didn't understand the word 'familiar', change to 'heard lots of time' or 'seen lots of time'.

3) Degraded Listening Task:

The tester asked the child, "Can you hear the speech sounds where many people are talking?" The child responded "No. Then we give the direction, "It is hard to hear the speech sounds when there are many people. Now you will hear some sounds. But there is last word of the sentence is covered with a noise in the speech sound. Listen carefully and tell me the last word." Two sentences were given for practice before the test phase.

III. Results

To address the potential of a practice effect across modalities, accuracy was calculated separately for the VSL and ASL tasks, depending on the presentation order involved. Participants who performed the VSL task first had equivalent accuracy in ASL performance as those that performed the ASL task first, $F(1, 29)=0.076, p>.05$. There was no order advantage.

Our research question was whether children with CI have deficits in statistical learning compared to children with NH. The one-way ANOVA was used to compare group differences in the two domains. Table 3 shows the mean and SD of both groups for the VSL, ASL performance, vocabulary, DLT HP and LP scores.

There was a statistically significant difference by group for the VSL task, $F(1, 29)=4.105, p<.05$: children with NH had a mean of 59.7% ($SD=16.1$) and those with CI had a mean of 49.4% ($SD=11.1$). In the auditory domain, there was a statistically significant difference between the two groups, $F(1, 29)=9.485, p<.01$: children with NH had a mean of 62.5% ($SD=15.4$) and those with CI had a mean of 48% ($SD=7.5$). In both domains, there were statistically significant differences in statistical learning.

There was a statistically significant difference by group for the receptive vocabulary score, $F(1, 29)=4.487, p<.05$: children with NH had a mean of 93.2 ($SD=31.6$) and those with CI had a mean of 69.5 ($SD=29.8$). Also there was a statistically significant difference by group for the degraded

표 3. 일반 아동과 인공와우이식 아동의 시각 및 청각 통계적 학습 수행력

Table 3. Visual and auditory statistical learning performance for children with NH and children with CI

Variable	Children with NH (n=15)	Children with CIs (n=15)	Comparison	
	Mean (SD)	Mean (SD)	F	P
Visual statistical learning ^a	59.7 (16.1)	49.4 (11.1)	4.105*	0.052
Auditory statistical learning ^a	62.5 (15.4)	48.9 (7.5)	9.485**	0.005
Receptive vocabulary ^b	93.2 (31.6)	69.5 (29.8)	4.487*	0.043
DLT-HP ^b	26.3 (2.0)	18.5 (4.3)	40.730***	0.000
DLT-LP ^b	13.6 (2.2)	2.8 (1.8)	214.863***	0.000

^a The value is percentage; ^b The values are raw score.
* $p < .05$, ** $p < .01$, *** $p < .001$

listening task (high predictability sentence score), $F(1, 29)=40.730$, $p < .001$ and the degraded listening task (low predictability sentence score), $F(1, 29)=214.863$, $p < .001$. Children with NH had each mean of 26.3 ($SD=2.0$), 13.6 ($SD=2.2$) and those with CI had each mean of 18.5 ($SD=4.3$), 2.8 ($SD=1.8$).

Another research question was to determine how much of the variance in children’s statistical learning could explain language performance. Additional factors such as age, nonverbal IQ (Moon & Byun, 1997), AOI, CVC phoneme score, and DOI were examined. Stepwise multiple regression analysis was conducted for the two separate

groups on the two different tasks.

For the children with NH, age was significantly correlated with receptive vocabulary ($p < .001$, Table 4). Age was a significant predictor of their receptive vocabulary, $F(1, 14)=82.275$, $p < .001$, $R^2=0.864$, accounting for 86.4% of the variance in receptive vocabulary.

Age was significantly correlated with the high predictability DLT ($p < .01$) (Table 4). Age was also the only predictor that significantly explained the variance, $F(1, 14)=11.530$, $p < .01$, $R^2=0.47$, accounting for 47% of the variance in DLT HP sentences.

Table 5 shows the results of correlation among variables in children with CI. DOI was positively correlated with receptive vocabulary ($p < .01$). DOI was a significant predictor of receptive vocabulary, $F(1, 14)=12.211$, $p=.004$, $R^2=0.484$, accounting for 48.4% of the variance in receptive vocabulary.

AOI was negatively correlated with DLT HP sentences ($p < .05$). AOI was a statistically significant predictor that explained the variance, $F(1, 14)=5.294$, $p < .05$, $R^2=0.289$, accounting for 28.9% of the variance in DLT HP sentences.

VSL performance was positively correlated with DLT LP sentences and AOI ($p < .05$). VSL performance was a significant predictor of DLT LP sentences, $F(1, 14)=6.962$, $p < .05$, $R^2=0.349$, accounting for 34.9% of the variance.

In addition, AOI was another significant predictor of DLT LP sentences. The full regression model accounted for 55.2% of the variance in LP sentence, $F(1, 14)=7.385$, $p < .01$, $R^2=0.552$.

표 4. 일반 아동의 통계적 학습 수행력과 언어 능력간의 상관관계 분석

Table 4. Intercorrelations among statistical learning performance and language ability in children with NH

	Age		VSL		ASL		Receptive Vocabulary		DLT-HP	
	r	p	r	p	r	p	r	p	r	p
VSL	-0.251	0.367								
ASL	0.270	0.330	-0.181	0.518						
Receptive vocabulary	0.929	0.000***	0.307	0.266	-0.294	0.287				
DLT-HP	0.686	0.005**	0.268	0.333	-0.325	0.237	0.674	0.006**		
DLT-LP	0.094	0.738	-0.132	0.638	-0.227	0.416	0.253	0.364	0.225	0.420

VSL=visual statistical learning; ASL=auditory statistical learning; DLT-HP=degraded listening task-high predictability sentence; DLT-LP=degraded listening task-low predictability sentence.

** $p < .01$, *** $p < .001$

표 5. 인공와우이식 아동의 통계적 학습 수행력, AOI, DOI, 언어능력간의 상관관계 분석

Table 5. Intercorrelations among statistical learning performance, AOI, DOI, and language ability in children with CI

	Age		AOI		DOI		VSL		ASL		Receptive vocabulary		DLT-HP	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p
AOI	0.331	0.228												
DOI	0.909	0.000***	-0.093											
VSL	0.207	0.459	0.579	0.024*	-0.037	0.895								
ASL	0.097	0.731	0.009	0.975	0.099	0.726	0.318	0.248						
Receptive vocabulary	0.681	0.005**	0.051	0.856	0.696	0.004**	-0.027	0.925	-0.017	0.925				
DLT-HP	0.231	0.408	-0.538	0.039*	0.481	0.069	-0.202	0.469	0.191	0.469	0.358	0.190		
DLT-LP	-0.038	0.894	-0.025	0.929	-0.029	0.919	0.591	0.020*	0.288	0.297	0.040	0.887	0.285	0.303

AOI=age of implantation; DOI=duration of implant use; VSL=visual statistical learning; ASL=auditory statistical learning; DLT-HP=degraded listening task-high predictability sentence; DLT-LP=degraded listening task-low predictability sentence.
* $p < .05$, ** $p < .01$, *** $p < .001$

IV. Discussion

1. Statistical Learning Performance in Children with NH and Children with CI

There were significant differences in VSL and ASL between children with NH and those with CI. Children with CI were less proficient than those with NH at segmenting the three combinations in the sequential order presented. Children with CI had difficulties with identifying information presented in sequential order. The results confirmed that not only auditory domain but also in visual domain were affected by auditory deprivation in this group (Conway et al., 2010b).

The results of significant difference in visual statistical learning performance between children with NH and children with CI are consistent with previous research (Conway et al., 2010b). It is challenging to directly compare the study results with a previous study on auditory statistical learning in children with CI.

Evans et al., (2009) reported children with SLI had statistically significant lower scores compared to normal. Auditory statistical learning performance in language delayed group is lower than normal children; it can be also explained similar to difference between children with CI and NH. Statistical learning has been suggested as domain general ability from previous studies (Conway et al., 2010b;

Yim & Rudoy, 2013). Thus it makes sense that children with CI have lower performance on both auditory and visual statistical learning.

The segmentation ability of sequential stimulus is an important skill in language acquisition (Graf Estes et al., 2007; Lany & Saffran 2010). It has been suggested that statistical learning ability is an underlying factor in infants' ability to learn language quickly (Saffran et al., 1996, 1999; Kirkham et al., 2002). Since language units have probabilistic relationships with one another, it is possible to detect the probability within a sentence and to understand implicit rules within a spoken language (Kirkham et al., 2002). Thus, detrimental effect on this learning mechanism may influence normal language development.

The statistical learning interacts with the auditory stimuli that children are exposed to which is not the strongest feature that children with CI possess. Consequently, this may be the reason why it is difficult to reach normal performance even after CI implantation. Children with CI may be affected by the nerve reorganization and complex plasticity of the brain (Pisoni et al., 2010). However, their statistical learning ability in visual domain was still lower compared to children with NH. Thus, this study presents meaningful results confirming deficits in the statistical learning ability of children with CI regardless of the presented domain.

2. Predictor of Language Performance in children with NH

There are interesting results from data involving children with NH. First, there was no correlation between statistical learning and age. Statistical learning performance did not improve with age. These results suggest that statistical learning ability may be not related to development. As revealed in several studies, statistical learning ability has been found in all ages, from infants to adults (Conway & Christiansen, 2005; Conway et al., 2007, 2010a, 2010b; Kirkham et al., 2002; Saffran et al., 1996, 1999; Yim & Windsor, 2010).

Second, there was a high positive correlation between age and HP sentence score. Age accounted for 45.1% of the variance in the HP sentence score. These results are consistent with previous reports that age predicts HP sentence score (Benichov et al., 2012). The results of this study show that older children with NH are better at using top-down knowledge.

The results also showed that the group with more learning experience performed better in predicting the last word in sentences and in identifying words logically related to each other. This suggests that top-down processing ability requires not only procedural knowledge, but also explicit knowledge including vocabulary acquired through many years of experience.

Third, there was positive correlation between receptive vocabulary score and language processing score (DLT-HP) in NH group. According to Ullman(2004), explicit memory and learning is related to the mental lexicon, procedural memory and learning is related to learn skills and information which is included order or sequence.

However, CI group in our study has shows no difference between receptive vocabulary score and language processing score, that is why normal children can reach similar level, but we predict there will be difference between receptive vocabulary and language processing score in the group of language deficit.

We did not have syntactic language tasks but language processing task and vocabulary task represented children's language skills. Even though there was no significant correlation between receptive vocabulary and statistical learning, there was a significant correlation between

degraded listening task and statistical learning.

3. Predictor of Language Performance in Children with CI

Remarkable results were obtained involving children with CI. First, HP sentence score was negatively correlated with AOI and AOI accounted for 28.9% of the variance in HP sentence score in which early implanted children had better performance with HP sentences. Recall that age was a significant predictor for HP sentence score in children with NH.

These results suggest that children who hear from a younger age will be able to process high context sentences more accurately because they were exposed to language earlier. The HP sentences in DLT were designed to tap the ability to use top down knowledge and emphasized language processing ability which was somewhat different from vocabulary knowledge. Although it has been suggested that the amount of language experience is an important factor which can be represented via DOI, language experience at a right timing, represented by AOI, is more important for HP sentence accuracy shown in children with CI.

This may be the reason why age was a sole predictor of vocabulary and HP in children with NH whereas it was DOI for vocabulary (which represents language knowledge) and AOI for HP sentence accuracy (which represents language processing). As was already revealed by many studies, AOI is a critical predictor for language ability after implantation in children with CI. It is a common theory that surgery at an earlier age yields positive results (Geers et al., 2007; Holt & Svirsky, 2008; Tomblin et al., 2005).

Thus, exposing a sound within sensitive period may have a significant effect on the central auditory system, which allows children with CI process linguistic information as well as NH group (Sharma et al., 2002; Szagun & Stumper, 2012).

Second, the LP sentence score was positively correlated with VSL ability and VSL performance accounted for 34.9% of the variance in the LP sentence score. Additionally, AOI accounted for 20.3% of the variance in the LP sentence score. AOI and VSL performance accounted for 55.2% of the variance in the LP sentence score.

LP sentence score was better with younger AOI. AOI predicts language processing skills in everyday life, with both HP sentences using top-down knowledge and LP sentences using bottom-up knowledge, acoustic-phonetic knowledge (Conway et al., 2010b; Klatt, 1979).

To develop the ability to process sequential sentences, one must be exposed to speech sounds as early as possible, with or without high context. This is because regular and predictable exposure to the stimulus plays a positive role in the development of speech processing ability through brain plasticity. Exposure to speech sounds at the right time results in the ability to identify regularity and sequence learning opportunities. Thus, earlier exposure to speech sounds may have a positive impact on language processing skills in children with CI.

However, it should be noted that LP sentence accuracy requires VSL ability, unlike HP sentences. LP sentence performance represents ability to process information which rely less on experience compared to HP. Thus, fundamental learning ability which was measured by statistical learning predicted LP performance significantly whereas HP was predicted by AOI only. Interesting results were that it was VSL which predicted LP rather than ASL.

It is an unexpected result that there was no correlation between auditory statistical learning performance and language task which is different from previous studies. We assume that if auditory domain is more affected by auditory deprivation, it may be visual domain which better represent the ability to detect statistical regularity.

Another explanation for these results is that ASL had smaller standard deviation compared to VSL. When predicting a variable, there has to be a certain amount of variation. In CI group, ASL had a mean of 48.9% and *SD* of 7.5% in which VSL had a mean of 49.4% and *SD* of 11.1% similar to that of NH group for the VSL. However, as data shows the *SD* in ASL was limited compared to VSL and this may be the reason why ASL did not have enough variation to explain language performance compared to VSL in this group

However, this study suggests that the capability to cognize regularities in everyday lives is interpreted, with significance, to be related with linguistic competence. Everyday life is full of rules, and these rules apply to more than sounds. Traffic lights flashing and plates on display in

stores are all determined by an order that depends on certain properties. There is some inherent regularity in visual stimulus. Interestingly, the ability to identify and use these regularities could predict the rules for matching acoustic-phonetics.

Lastly, there was a positive correlation between VSL ability and AOI ($r=0.579$, $p=.024$). AOI was examined with stepwise regression analysis to determine whether it predicts VSL ability. The results showed that AOI accounted for 33.6% of the variance in VSL ability.

An interpretation of this result is that children who received cochlear implants late rely on procedural learning of visual stimuli as a compensatory mechanism because of auditory deprivation during a critical period. This result confirms once again that children with CI are more affected by the presented domain than children with other communication disorders.

Based on the results presented above, language processing ability that required acoustic-phonetic knowledge was associated with earlier AOI and good performance in VSL. VSL ability may also be affected by auditory deprivation prior to implantation. Children with NH performed significantly better under multimodal conditions than both visual and auditory stimuli (Evans et al., 2009). However, children with CI responded slower to auditory stimuli and had difficulty utilizing all available clues (Evans et al., 2009).

Neurological findings imply that VSL ability may be enhanced during auditory deprivation in children with CI. Brain plasticity results in a change in the brain due to sensory deprivation. When processing visual stimuli, there is greater recruitment in the posterior-superior-temporal sulcus in the auditory deprivation group (Bavelier & Neville, 2002).

In addition, different patterns were observed in visual stimulus processing between the auditory deprivation group and the normal hearing group. The primary auditory cortex of the right hemisphere in the auditory deprivation group is involved in processing visual rather than auditory stimuli (Finney et al., 2003). This result indicates that the nervous system is reorganized and the compensatory mechanism is developed after auditory deprivation. These findings suggest that children with CI employ a different system in the processing of stimulus due to the auditory deprivation.

In summary, children with CI show a deficit in VSL and ASL ability compared to those with NH. Secondly, AOI is a critical factor explaining the causal relationship for language processing ability in children with CI. Thirdly, in the present study, VSL ability was found to play an important role in language processing ability.

Follow-up longitudinal studies should examine whether the magnitude of increase in statistical learning by time is similar across groups and across domains and further investigate the relationship between overall language performance and fundamental learning mechanism.

The limitations of this study were as follows.

First, a total of 15 children with NH and 15 children with CI participated in this study. It is difficult to generalize the results of this study due to a limited subject number. Therefore, further research should be recruited much more participation.

Also, we presented auditory stimulus to children before experimental task to ensure perception of the sound. However, pitch discrimination may have been very weak for some children with CI depends on their mapping statuses.

Finally, children were exposed to only visual stimulus in the visual statistical learning task, but exposed to auditory stimulus while coloring the picture in the auditory statistical learning task. In addition, we use the same paradigm for visual and auditory statistical learning tasks with previous studies. There remains differences in exposure time of visual stimulus (1s, 4m 50s) and auditory stimulus (250ms, 2m 50s). It is difficult to match the both stimulus identically. In the future study, attention shall be considered when creating the task.

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부록 1. 시각 통계적 학습 과제 문항

Appendix 1. Test phase in visual statistical learning task

Test phase	A	B
1	Set 3	BGE
2	FHB	Set 2
3	HCF	Set 1
4	Set 2	BDI
5	DAG	Set 1
6	Set 3	ADH
7	IDC	Set 2
8	Set 1	EIB
9	FAI	Set 3
10	GEA	Set 1
11	GCD	Set 2
12	Set 3	HFB
13	Set 1	IAF
14	DCG	Set 3
15	AFH	Set 2
16	Set 3	CEH
17	CHD	Set 1
18	Set 2	EBG
19	Set 3	IBF
20	Set 2	HAD
21	FBI	Set 1
22	Set 2	CEI
23	EAH	Set 3
24	Set 1	BDG

부록 2. 청각 통계적 학습 과제 문항

Appendix 2. Test phase in auditory statistical learning task

Set 1	440Hz (A), 370Hz (B), 349Hz (C)
Set 2	330Hz (D), 493.9Hz (E), 261.6Hz (F)
Set 3	294Hz (G), 277Hz (H), 392Hz (I)

Test phase	A	B
1	Set 1	GBF
2	BEI	Set 3
3	GEA	Set 2
4	DGC	Set 1
5	Set 2	HAF
6	Set 3	DIB
7	BDG	Set 2
8	Set 1	EGA
9	CFH	Set 3
10	Set 2	CDI
11	AEG	Set 3
12	HEA	Set 1
13	Set 3	FGC
14	Set 2	AEH
15	Set 1	CHF
16	IDA	Set 3
17	Set 1	IDB
18	EIC	Set 2
19	Set 3	EBH
20	FAI	Set 1
21	Set 2	FGB
22	BGE	Set 1
23	ICF	Set 2
24	Set 3	HAD

부록 3. 소음상황듣기 검사 기록지

Appendix 3. Degraded listening task sheet

아동 번호:

높은 예측성 원점수 (DLT-HP score):

검사 일시:

낮은 예측성 원점수 (DLT-LP score):

	문장	대답		문장	대답
P1	연필로 글씨를 <u>써요</u>		28	쌀로 떡을 <u>만들어요</u>	
P2	할머니는 딸기를 <u>좋아해요</u>		29	기린은 목이 <u>길어요</u>	
1	할머니가 택시에서 <u>자요</u>		30	친구의 인형이 <u>커요</u>	
2	모자를 머리에 <u>써요</u>		31	고모가 서랍을 <u>닫아요</u>	
3	할아버지가 베개를 <u>잡아요</u>		32	종이에 동그라미를 <u>그려요</u>	
4	친구와 놀이터에서 <u>놀아요</u>		33	다친 곳에 약을 <u>발라요</u>	
5	병원에서 주사를 <u>맞아요</u>		34	아기가 그림을 <u>꺼내요</u>	
6	시장에서 빵을 <u>만들어요</u>		35	계단에서 바나나를 <u>잘라요</u>	
7	돈으로 과자를 <u>사요</u>		36	비행기는 하늘을 <u>날아요</u>	
8	이모가 쓰레기를 <u>차요</u>		37	밭로 공을 <u>차요</u>	
9	종이를 가위로 <u>잘라요</u>		38	소는 음매하고 <u>울어요</u>	
10	폴로 종이를 <u>붙여요</u>		39	아기가 침대에서 <u>노래해요</u>	
11	아빠가 기차를 <u>타요</u>		40	방에서 텔레비전을 <u>봐요</u>	
12	삼촌이 껌을 <u>붙여요</u>		41	바깥에 바람이 <u>불어요</u>	
13	수건으로 손을 <u>닦아요</u>		42	아줌마가 수건을 <u>덮어요</u>	
14	하마는 입이 <u>커요</u>		43	아빠의 신발이 <u>더러워요</u>	
15	아저씨가 종이를 <u>붙여요</u>		44	선생님이 풍선을 <u>안아요</u>	
16	토끼가 깡충깡충 <u>뛰어요</u>		45	선생님이 의자에 <u>앉아요</u>	
17	의사가 가방을 <u>열어요</u>		46	코끼리는 코가 <u>길어요</u>	
18	엄마가 양말을 <u>취요</u>		47	칫솔로 이를 <u>닦아요</u>	
19	아저씨가 자동차를 <u>찾아요</u>		48	가게에서 그릇을 <u>봐요</u>	
20	나무에서 감이 <u>떨어져요</u>		49	화장실로 열쇠를 <u>던져요</u>	
21	의사가 약을 <u>사요</u>		50	친구의 얼굴이 <u>무서워요</u>	
22	엄마가 포도를 <u>버려요</u>		51	친구에게 선물을 <u>취요</u>	
23	아빠가 안경을 <u>넣어요</u>		52	학교에서 풀을 <u>그려요</u>	
24	빗으로 머리를 <u>빗어요</u>		53	원숭이의 얼굴이 <u>길어요</u>	
25	원숭이가 나무에 <u>앉아요</u>		54	엄마가 구두를 <u>신어요</u>	
26	냉장고에서 우유를 <u>꺼내요</u>		55	고모가 놀이터에서 <u>뛰어요</u>	
27	할머니의 고양이가 <u>아파요</u>		56	주머니에 손을 <u>넣어요</u>	

건청 아동과 인공와우이식 아동의 시각 및 청각 통계적 학습 능력과 언어능력의 관계

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목적: 인공와우이식 아동의 언어능력 예측인자로 인공와우이식 연령, 인공와우 사용기간, 부모의 경제력과 교육력, 성별 등이 밝혀져 있지만, 최근 연구들에서 통계적 학습 능력과 같은 신경인지적 요인들도 언어발달에 중요한 역할을 한다는 결과가 보고되고 있다. 본 연구의 목적은 통계적 학습 능력이 인공와우이식 아동에게 결함이 나타나는지 알아보고, 인공와우이식 아동의 통계적 학습 능력과 언어 능력과의 관계를 살펴보고자 하였다. **방법:** 본 연구에 참여한 아동은 생활연령을 일치시킨 만 4~10세의 인공와우이식 아동과 건청 아동 각 15명씩, 총 30명이었다. 모든 아동은 감각 제시 양식(시각과 청각)에 따른 통계적 학습 능력 과제를 수행하였고, 언어과제로는 수용어휘력 검사와 일상생활의 언어처리능력을 측정하는 과제로 소음상황듣기 검사(높은 예측성 및 낮은 예측성 문장)를 수행하였다. **결과:** 첫째, 청각 및 시각 통계적 학습 능력은 인공와우이식 아동이 건청 아동보다 통계적으로 유의하게 더 낮은 수행력을 나타냈다. 둘째, 시각 통계적 학습 능력과 언어처리능력(낮은 예측성 문장)의 정적 상관성이 나타났다. 인공와우 관련 변인인 인공와우이식 연령과 시각 통계적 학습 능력간의 정적 상관성이 나타났으며, 인공와우이식 연령과 언어처리능력(높은 예측성 문장)간의 부적 상관성이 나타났다. 셋째, 건청 아동의 경우, 생활연령이 수용 어휘력과 높은 예측성 문장 점수를 유의하게 예측해주는 것으로 나타났으나, 인공와우이식 아동의 경우, 인공와우 사용기간이 수용 어휘력을 유의하게 예측해주고, 인공와우이식 연령이 높은 예측성 문장 점수를 유의하게 예측하였다. 시각 통계적 학습 능력과 인공와우이식 연령이 낮은 예측성 문장 점수를 유의하게 예측하였다. **결론:** 인공와우이식 연령은 언어처리능력의 예측인자이며, 낮은 통계적 학습 능력은 인공와우이식 아동의 낮은 언어처리능력의 기저요인의 하나가 될 수 있다. 그러므로 인공와우이식 아동의 시각 통계적 학습은 근본적인 학습 능력의 하나임을 밝혔다.

<검색어> 인공와우, 통계적 학습, 소음상황듣기, 언어처리

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