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Executive Function, Working Memory, Perceptual-Motor Skills, and Speech Perception in Normal-Hearing Children: Some Preliminary Findings[1]

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Abstract. Speech perception involves a number of complex cognitive processes. Previous work has suggested that executive function, working memory, and perceptual-motor skills play a role in children's language development. In order to further investigate this relationship, we evaluated the correlations between perception of degraded speech, which represents an approximation of the auditory signal received by a cochlear implant user, with several tasks involving executive function, working memory, and sensory-motor function. Our data revealed that age and performance on two tasks, one representing executive function and one representing perceptual-motor skills, were significantly correlated with children's perception of highly degraded speech. Moreover, correlations between each of these tasks and the perception of degraded speech remained strong and significant even when the effects of age were partialled out. These results suggest that processes attributed to executive function, such as attention, planning, motor control, hand-eye coordination, and problem solving, underlie spoken language processing and its development. The present findings with normal-hearing, typically-developing children provide an initial benchmark for more detailed investigation of individual differences in performance and audiologic outcome among profoundly deaf children who use cochlear implants.

Introduction

Profoundly deaf children who use cochlear implants (CIs) show a large degree of variability in terms of post-implantation audiologic outcomes. Children with very similar hearing losses and etiologies of deafness may obtain drastically different benefit from their CI (Pisoni et al., 2000). Variables such as age at onset of deafness, length of auditory deprivation, and age at implantation have been found to be associated with a wide range of outcome measures in implanted children (Fryauf-Bertschy et al., 1992; Osberger et al., 1991). Other language-related factors, such as mode of communication (Pisoni et al., 1997) and parents' knowledge of vocabulary (Stallings et al., 2000), also correlate with children's language outcomes after receiving a CI. Recently, several studies have shown that other neurocognitive measures, such as motor skills (Horn et al., 2006) and working memory span (Cleary et al., 2002b), also correlate with spoken language processing in children with implants. To better understand language outcome after cochlear implantation, it is important to further investigate these additional factors as possible predictors of language benefit. The current research investigates the relationship between spoken language processing, executive function, working memory, and perceptual-motor skills in normal-hearing children, with the motivation of applying our findings to the field of cochlear implantation. We hypothesize that performance on the executive function, working memory, and perceptual-motor tasks will be correlated with children's performance on a degraded speech perception task. Before describing the current project in more detail, we first review the findings associated with the role of executive function, working-memory, and perceptual-motor skills in speech perception and spoken language development.

Executive Function and Spoken Language Processing

Executive functioning is a term used to describe certain behaviors which are attributed to the functions of the frontal lobe (Stuss, 1992), such as attention, problem solving, planning, inhibiting reflexive behaviors, monitoring behaviors, and goal-directed behavior (O'Reilly & Munakata, 2000). Russell (1948) investigated the role of the frontal lobe in development and found that the frontal regions were of great importance in the childhood years in terms of conditioning behavior patterns for the rest of the brain. Because of this, it is not surprising that executive dysfunction is linked to a variety of developmental disorders including attention deficit hyperactivity disorder (ADHD), Tourette's syndrome, dyslexia, and autism (Chelune et al. 1996; Ozonoff & Jensen, 1999; Pennington & Ozonoff, 1996; Helland & Asbjørnsen, 2000).

One of the most well-known executive function tasks is the Stroop Color Naming task (Stroop, 1935), in which the subject must inhibit a reflexive response to read printed color words, while naming the color of ink in which the words are printed. For example, the word 'blue' would be printed in red ink, and the subject must say 'red' while inhibiting the reflex to read the word 'blue'. Deficits in the ability to perform the Stroop task have been found in children with dyslexia (Helland & Asbjørnsen, 2000).

The Wisconsin Card Sorting Task (WCST) is another common measure of executive functioning. In this procedure, the subject is given a stack of test cards and must sort them based on the shape, color, or number of stimuli on the cards. The experimenter tells the subject if he is right or wrong so that the subject can learn the rules for matching the cards. After a certain number of correct matches, the rules change without notice. Performance on this test measures the subject's ability to flexibly shift responses and inhibit the reflex to follow the previous set of rules. Liss et al. (2001) investigated autistic children's performance on the WCST and found that children with autism were less likely to inhibit perseverative responses when the rules changed than were children with developmental language disorders. Similar results have been found when comparing perseveration in children with autism to typically-developing controls (Bennetto, Pennington, & Rogers, 1996; Prior & Hoffman, 1990; Ozonoff & McEvoy, 1994; Rumsey, 1985). In addition to these studies in children, individual differences in executive function have been found in adults. Performance on frontal lobe tasks is correlated with a variety of other information processing tasks even in typical populations (Miyake et al., 2000).

From these findings we can infer that executive functions may also play a role in the development of other cortical processes. In particular, children who show delays in the development in executive functions may also show delays in spoken language processing. Very little research has been conducted on the topic of executive function and language. Luria (1961) proposed a close interaction between language and executive function. Singer and Bashir (1999) described a case study of a 16-year-old boy with language-learning disorder, which involved problems with speech production, word finding, and language formulation. They found that their subject struggled with several domains of executive function including attention, inhibition, maintenance, adaptation and self-regulation. Similarly, patients with frontal lobe damage also show deficits in both written and verbal fluency (Kimberg et al., 1996). Because of the lack of research in the field of frontal lobe functions and language development, one of our goals was to investigate these factors in typically-developing children, ultimately applying our findings to children who use cochlear implants.

Working Memory and Spoken Language Processing

Working memory (for review, see: Conway, et al., 2005) has been identified as being involved in complex cognitive behaviors including reasoning and problem solving (Engle, 2002). The two most common tasks used to assess verbal working memory are digit span and nonword repetition. The digit span task is a common component of intelligence testing, which requires the subject to remember and repeat a sequence of digits either forwards (forward span) or backwards (backward span). Forward digit span (FDS) taps into the subject's ability to phonologically encode and verbally rehearse sequential materials. Backward digit span (BDS), on the other hand, involves not only encoding and rehearsal, but also mentally manipulating the series of digits, which involves executive function and cognitive control.

Nonwords are novel, phonologically possible words that have no meaning or semantic representation in long-term memory. In a nonword repetition task, the subject is asked to repeat back spoken nonwords one at a time. Nonword repetition is a complex task which requires phonological encoding, memory, articulatory planning, and speech production. The relationship between speech perception, digit span, and nonword repetition tasks has been investigated in adults as well as in typically-developing children (for reviews, see Baddeley, 2003; Baddeley, Gathercole, & Papagno, 1998; Gathercole, 1999; 2006; Gupta & MacWhinney, 1997). Several studies have found that digit span and nonword repetition are correlated with children's vocabulary development (Adams & Gathercole, 1996; Edwards, Beckman, & Munson, 2004; Gathercole & Baddeley, 1989; Gathercole et al., 1999; Gathercole, Willis, Emslie, & Baddeley, 1992; Marjerus et al, 2006; Michas & Henry, 1994).

Digit span and nonword repetition have also been investigated in profoundly deaf children who use CIs. More importantly, several measures of working memory have been linked to language outcome measures (Pisoni & Geers, 2000, Burkholder & Pisoni, 2003; Burkholder & Pisoni, 2006), as well as other measures of working memory and spoken language processing (Cleary et al., 2002a; Dillon et al., 2004) in these children. However, the relationship between working memory and speech and language abilities still only accounts for about twenty percent of the variance in language outcomes of children with CIs. Therefore, it is necessary to investigate other cognitive factors that may affect language outcome in deaf children by assessing the correlations between spoken language processing, working memory, and other related tasks that draw on processes associated with frontal lobe function.

Perceptual-Motor Skills and Spoken Language Processing

In typically developing children, motor and language milestones tend to occur in synchrony (Lenneberg, 1967; Siegel, 1992), leading researchers to wonder if delays or deficits in one domain may also show up in the other. In fact, motor control and coordination have been found to be empirically linked with language abilities in both children and adults. For example, sequential fingertip tapping skill is correlated with phonological decoding (i.e., reading) abilities in normal adults (Carello, 2002). This finding implies that the processes which underlie difficulties in reading may be related to motor and coordination development. Children with specific language impairment (SLI) have been found to perform more poorly than age-matched controls on tasks involving motor control and visual discrimination (Powell & Bishop, 1992). Similarly, twin studies in which one or both twins have SLI, revealed a genetic link between language, motor, and working memory impairment (Bishop, 2000).

Following these earlier studies, investigators have recently begun to consider the role of motor development in language outcomes in children with CIs. Several longitudinal studies were completed, in which motor assessments made before the child received an implant were compared to the child's audiologic outcome measures post-implantation. These studies have found that children who present with higher motor scores on the Vineland Adaptive Behavior Scales (Sparrow et al., 2005) do better on assessments of language, vocabulary, and spoken word recognition than children with lower motor scores (Horn et al., 2005). Specifically, Horn et al. (2006) found that fine, but not gross, motor abilities were highly correlated with the expressive and receptive language abilities of children with cochlear implants. Similarly, the ability to correctly reproduce geometrical designs has been found to be predictive of implant success in children (Horn et al., 2004, in press; Fagan et al., in press). These studies suggest that relations between children's motor performance and their speech perception abilities warrant more detailed investigation.

Degraded Speech Perception as a Measure of Spoken Language Processing

The use of CI simulated speech as a measure of spoken language processing has become a common experimental tool over the last decade. This method allows researchers to use normal-hearing, typically-developing subjects and provide them with an auditory simulation of a cochlear implant in order to study perceptual learning and adaptation to spectrally-degraded speech (e.g., .Rosen et al., 1999; Fu & Galvin, 2003). Effects of context on understanding degraded speech stimuli have also been reported, showing that context plays an important role in sentence perception (Conway et al., 2007; Kalikow, et al., 1977; Miller & Selfridge, 1950; Rubenstein, 1973). Little research, however, has been conducted concerning the perception of degraded speech by children, especially for degradations simulating the effects of cochlear implants.

Eisenberg et al. (2002) studied the perception of degraded lexically-easy and lexically-hard sentences by normal-hearing children and profoundly deaf children who used cochlear implants. Lexically-easy sentences contained keywords that were high in word frequency (i.e., more common in the language) and low in neighborhood density (i.e. have few similar-sounding neighbors and therefore are less confusable). Lexically-hard sentences contained keywords that were low in word frequency (i.e., less common in the language) and high in neighborhood density (i.e. have more similar sounding neighbors and are therefore more confusable). Research has shown that word frequency and neighborhood density have an effect on speech perception under degraded conditions (Meyer & Pisoni, 1999; Luce & Pisoni, 1998). Eisenberg et al. (2002) found that normal-hearing children performed better on the perception of lexically-easy words and sentences under cochlear implant simulation than on lexically-hard words and sentences, demonstrating that word frequency and neighborhood density influence spoken language processing under degraded listening conditions. In addition, the children were more likely to correctly perceive degraded sentences than degraded isolated words, suggesting a benefit from the presence of contextual cues when listening to degraded speech.

Eisenberg et al. (2002) also presented these same lexically-balanced words and sentences in the clear to children who use CIs. Similar trends were observed. The children who used CIs performed better on lexically-easy sentences and words than on lexically-hard sentences and words. These findings replicated and extended earlier work by Kirk et al. (1995), who found that word frequency, neighborhood density, and context play a role in CI users' performance on speech perception tasks.

Except for the recent study by Eisenberg et al. (2002), there has been no research on perception of CI-simulated speech in children. It is important to continue the research in this field in order to investigate the degree to which children show individual differences in degraded speech perception, and to determine what other behavioral measures might be used to predict differences in spoken word recognition. Research on this problem has a direct clinical application to the field of cochlear implantation because the electrical signal received by CI users is highly degraded. In this study, we want to know if the same mechanisms that predict normal-hearing children's speech perception performance for CI-simulated speech also predict deaf children's audiologic and speech perception outcomes following implantation.

The present study was carried out to assess predictors of spoken language processing performance in children by investigating the relationship between spoken language processing and other cognitive processes. Specifically, we measured the speech perception of normal-hearing children listening to degraded (CI-simulated) sentences, and compared their performance on this task with measures of executive function, working memory, and perceptual-motor skills.

Method

Each of the participants in this study completed ten tasks in one session that lasted between sixty and ninety minutes, with breaks provided as needed. All testing was completed in a sound-proof booth. This paper summarizes performance on five of these tasks. For tasks involving published materials, the tests were administered as described in the testing manuals. All testing was completed at Indiana University by the first author. The specific materials and set-up for each task are described below.

Participants

Fifteen normal-hearing children were tested in the Speech Research Laboratory at Indiana University-Bloomington. The children were all monolingual English speakers who ranged in age from five years, five months (5;5) to eight years, eleven months (8;11) of age (mean 7;5). Children were recruited from the LEARN Home Schooling Network in Bloomington, IN as well as from the Department of Psychological and Brain Sciences KID Information Database.

Materials and Procedure

A brief pure-tone audiometric screening was administered to each child at 250, 500, 1000, 2000, and 4000 Hz using a portable audiometer (Maico Hearing Instruments, Model MA27A). Responses were required at 20 dB HL for each frequency. Each ear was tested separately, and all children passed the screening at all frequencies and in both ears.

Degraded Sentence Perception. Speech perception abilities were measured using lexically-controlled sentences which were degraded using a cochlear implant simulator. The sentences consisted of twenty lexically-easy (i.e., high word frequency, low neighborhood density) and twenty lexically-hard (i.e., low word frequency, high neighborhood density) sentences. Each sentence contained three keywords. Audio recordings of the sentences in the clear were obtained from Laurie Eisenberg, and are the same as in Eisenberg et al. (2002).

We degraded the sentences to four spectral channels using a sine wave vocoder cochlear implant simulator (www.tigerspeech.com), and presented them to each child through a loudspeaker (Advent AV570) at 65 dB SPL. The children were instructed to listen closely to each sentence and then repeat back what they heard, even if they were only able to perceive one word of the sentence. Two practice sentences were presented before testing. Children were given feedback after they made their responses to the practice sentences, but received no feedback during testing. All 40 of the test sentences (20 'easy' and 20 'hard') were presented to the children. The order of presentation of the test sentences was randomized for each child, and each sentence was presented only once. The child's responses were recorded onto digital audio tape (DAT), and were later scored off-line based on number of keywords correctly repeated for each sentence.

WISC-III Forward and Backward Digit Span. The forward and backward digit span portions of the WISC-III intelligence scale (Wechsler, 1991) were administered to the children to obtain a measure of verbal immediate memory span. The testing materials were prerecorded by a young adult female talker, and were presented to the child through a loudspeaker (Advent AV570) at 65 dB SPL. Number sequences for both the forward and backward span tasks ranged from two to ten digits in length, with two strings of digits presented at each sequence length. For the forward span test, the child was asked to repeat the digits in the same order in which they were presented. The backward span task required the children to repeat the digits in the opposite order. The children's responses were recorded on digital audio tape (DAT). Responses were scored on-line, using the tape as a scoring crosscheck. Testing was terminated when the child missed two sequences of the same length.

Memory for Dot Patterns. The memory for dot locations subtest of the Children's Memory Scale (CMS; Cohen, 1997) was used as a measure of both immediate and delayed recall of a spatial pattern. The children were shown a picture of six blue dots inside a large white background. The dot pattern was presented to the child for five seconds before being taken out of sight. The child was then asked to replicate the dot pattern by placing six blue chips onto a 3x4 grid. The child was allowed to place the chips on the grid in any order with no time restriction. The final pattern produced by the child was recorded and no feedback was given on the child's performance. The chips were then cleared from the child's grid, and the same dot pattern was shown to the child again for five seconds and then taken out of view. The child was then asked to replicate the dot pattern. This process was repeated a third time, resulting in a total of three learning trials in which the same dot pattern was used. Next, a trial of red dots was presented and the child was asked to replicate it. The red dot trial was not scored, but rather served as a distracter. The child was then asked to recall from memory the initial blue dot pattern that had been presented three times (immediate recall trial). At the conclusion of the experiment (after a delay of approximately 30 minutes), the child was again asked to replicate the blue dot pattern from memory (delayed recall trial). The child's replications were scored based on total number of chips placed correctly on the grid. Therefore, a child could receive a total raw score of up to twenty-four points for the three learning trials plus the immediate recall trial, and up to six points for the delayed recall portion of the task. These raw scores were then converted into scaled scores, taking into account the age of the child.

NEPSY – A Developmental Neuropsychological Assessment. The NEPSY (Korkman et al., 1998) is a clinical neuropsychological test battery designed to assess children's development in the following five domains: Attention/Executive Functions, Language, Visuo-spatial Processing, Sensorimotor, Memory and Language (for review, see Ahmad & Warriner, 2001). Results from two subtests of the NEPSY, described below, will be reported in this paper.

The Design Copying subtest of the NEPSY is part of the visuo-spatial processing domain, which includes a battery of tests aimed to assess the child's non-verbal visuo-spatial skills such as body movement and hand-eye coordination. The children were given eighteen geometric designs and asked to copy each design. All eighteen designs from the subtest were copied by each child. The child was not allowed to erase any mistakes made, and was not allowed to turn the paper while drawing. Each design was scored on a four-point scale taking into consideration things such as angle, completeness, and proportion. The scoring criteria differed for each design. The child's pencil grip and the presence or absence of hand tremors were also noted by the experimenter.

The Knock and Tap subtest of the NEPSY was administered to assess the child's attention and executive functioning, specifically, their ability to coordinate motor responses, inhibit reflexive responses, and shift responses when a rule change was introduced (i.e. inhibit perseveration). First, the experimenter demonstrated that when she knocked on the table the child was to tap on the table with his preferred hand (the child's non-preferred hand rested on the table at all times). She also demonstrated that if she tapped on the table, the child was to knock on the table. Four practice trials were carried out with this set of rules as many times as necessary until the child understood the rules. All children required only one practice session. A total of fifteen test trials were then completed under this set of rules. Then, a new set of rules was introduced to the child. Now, if the experimenter hit the side of her fist on the table, the child was to knock on the table, and if she knocked the child was to hit the side of his/her fist on the table. However, if the experimenter tapped on the table, the child was to do nothing. Six practice trials were administered with the new set of rules as many times as necessary until the child understood the rules. All children required only one practice session. Fifteen test trials were then administered under the new rule set. The child's response was recorded for each trial. The number of correct responses out of a total possible raw score of thirty points was then converted into a percentile ranking based on the child's age.

Results and Discussion

Mean performance on the degraded sentence perception task is shown in Table 1, which reports the average number of target words correctly perceived by the children. Examination of this table reveals that children performed numerically better on the lexically-easy sentences (41% correct) than on the lexically-hard sentences (36% correct). However, this difference was not statistically significant: Easy vs. Hard, t(14)=2.02, *p*=.06.

Table 1: Degraded Speech Perception Scores

Task	Mean	SD
Easy Sentences	24.7	10.07
Hard Sentences	22.3	10.4
Total	47	19.9

Table 1. Means and standard deviations for number of keywords correct on the lexically-easy and lexically-hard sentences (total possible keywords correct = 60 for each sentence type), and for the total number of keywords correct across sentence type (total possible keywords correct = 120).

The children's scores on the other experimental tasks are summarized in Table 2. For the forward digit span (FDS) task, the children produced an average of 7.1 correct sequences (2 of length 2, 2 of length 3, 2 of length 4, and 1 of length 5). The children produced fewer correct sequences on backward digit span (BDS; mean of 4.1 correct sequences: 2 of length 2, and 2 of length 3). The difference between children's performance on FDS and BDS was statistically significant: FDS vs. BDS, *t*(14)=7.25, *p*<.001. The total digit span performance (TDS = FDS+BDS) had a mean of 11.4 correct sequences.

The CMS Learning scaled scores (total of the children's replications on the first 3 exposures) had a mean of 10.1 (50th percentile). The CMS Total scaled scores (CMS Learning score + Immediate Recall score) had a mean of 11.0 (63rd percentile). The CMS Delay scaled scores (Delayed Recall score) had a mean of 11.3 (63rd percentile).

The NEPSY Design Copying Subtest scaled scores had a mean of 12.8. There are no percentile conversions available for this individual score, because it is part of a larger battery of tests which comprise the visuo-spatial processing domain of the NEPSY. Therefore, only standardized data for the sum of scaled scores in the entire domain were available. Since the Design Copying was the only visuo-spatial processing domain task of the NEPSY that we completed, we are unable to report percentile rankings for this scaled score. The NEPSY Knock and Tap raw scores had a mean of 28.5 and a standard deviation of 1.06. This translates to the 26th to 75th percentile, which is considered to be the expected level of performance for typically developing children.

Table 2: Means and Standard Deviations of Experimental Subtests

Task	Mean	SD
FDS	7.1	2.1
BDS	4.1	1.2
TDS	11.4	3.1
CMS-Learn	10.1	3.65
CMS-Total	11.0	3.85
CMS-Delay	11.3	2.38
Design Copy	12.8	2.73
Knock&Tap	8.5	1.06

Table 2. Means and standard deviations for various tasks including: forward digit span (FDS), backward digit span (BDS), total digit span (TDS = FDS+BDS), CMS-Learning scaled scores (CMS-Learn = replications of first 3 exposures), CMS-Total scaled scores (CMS-Total = CMS-Learn + Immediate Recall), CMS-Delay scaled scores (Delayed Recall), Design Copying scaled scores, and Knock and Tap raw scores (total possible = 30).

To investigate the relations between working memory and degraded speech perception, we ran a series of correlations comparing performance on the speech perception task with performance on the digit span and CMS tasks. The results of this analysis are summarized in Table 3. The only significant correlation that emerged from this analysis was the correlation between the total digit span score (TDS) and the scores on lexically-hard (Hard Sent., r=.53, p<.05) and total sentence perception (Total Sent., r=.52, p<.05). FDS was also correlated with scores on lexically-hard sentences (r=.50, p=.06) and total sentence perception (r=.46, p=.09) although both correlations were only marginally significant.

However, when we performed a partial-correlation analysis controlling for age, both correlations became non-significant (Table 4), indicating that younger children have more problems with both digit span and speech perception than older children. The fact that digit span correlates with speech perception only when age is not controlled for suggests that any association between performance on these two tasks is largely accounted for by a single common source of variance having to do with chronological age.

Table 3: Correlational Analysis Between Working Memory and Speech Perception Tasks

Task	Easy Sent.	Hard Sent.	Total Sent.
FDS	r = .387 p = .154	r = .498 p = .059	r = .456 p = .088
BDS	r = .427 p = .112	r = .315 p = .253	r = .380 p = .126
TDS	r = .508 p = .053	r = .526 p = .044*	r = .523 p = .041*
CMS-Learn	r = .109 p = .698	r = .110 p = .696	r = .113 p = .689
CMS-Total	r = .221 p = .429	r = .207 p = .460	r = .219 p = .432
CMS-Delay	r = -.079 p = .778	r = -.053 p = .852	r = .-068 p = .810

* = sig. to .05

Table 3. Correlational analysis of digit span and CMS: dot location memory tasks with degraded speech perception scores. Age is included as a variable.

Table 4: Partial-Correlation Analysis Between Digit Span and Speech Perception (Controlling for Age)

Task	Easy Sent.	Hard Sent.	Total Sent.
FDS	r = .040 p = .893	r = .254 p = .380	r = .162 p = .580
BDS	r = .140 p = .633	r = -.007 p = .980	r = .066 p = .823
TDS	r = .155 p = .597	r = .224 p = .441	r = .203 p = .487

Table 4. Partial-correlation analysis of digit span and speech perception scores, controlling for age.

To assess the relationship between speech perception, executive function, and perceptual-motor skills, we performed a correlational analysis comparing the two NEPSY subtests with scores from the speech perception task. The results of this analysis are summarized in Table 5. Both the Design Copying and the Knock and Tap scores were significantly correlated with the speech perception measures (*r*>.59, *p*<.02).

Table 5: Correlations Between EF and P-M skills and Speech Perception

Task	Easy Sent.	Hard Sent.	Total Sent.
Design Copy	r = .663 p = .007**	r = .653 p = .008**	r = .676 p = .006**
Knock & Tap	r = .593 p = .020*	r = .386 p = .156	r = .501 p = .057

* = sig. to .05, ** = sig. to .01

Table 5. Correlational analysis of executive function and perceptual-motor tasks (NEPSY: Design Copying scaled scores and NEPSY: Knock & Tap percentile rankings) with speech perception. Age included as a variable.

Strong positive and significant correlations (*r*'s >.6, *p*'s<.01) between scores on the Design Copying task and all of the degraded sentence perception measures were observed. Children who were better able to perceive speech under degraded conditions also performed better at copying geometric designs. A scatterplot of the individual scores is shown in Figure 1. These results suggest that executive function and perceptual-motor skills which are involved in copying geometric designs are associated with speech perception, word recognition, and spoken language processing.

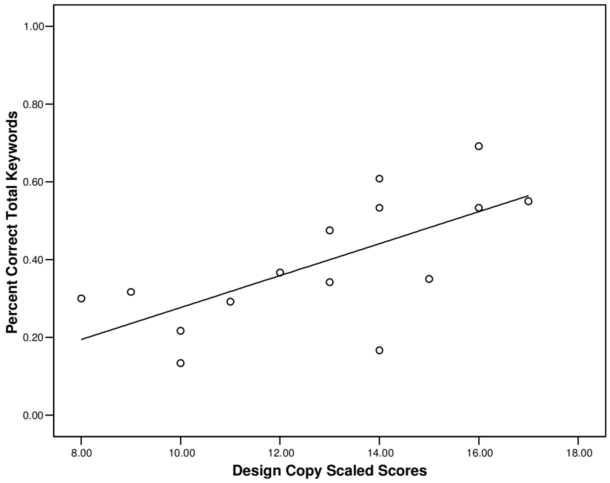

Figure 1. Scatterplot of performance on the Design Copying task and percent correct total keywords (easy + hard sentences) on the sentence perception task.

Scores on the Knock and Tap test were also positively correlated ($r=.59$, $p<.05$) with speech perception, but only for the perception of lexically-easy sentences. Children who were better at perceiving lexically-easy sentences under degraded conditions also performed better on the Knock and Tap task. A scatterplot of the scores on these two tasks is shown in Figure 2. This indicates that the perception of high-frequency, low-density words is linked to the executive function and perceptual-motor skills involved in completing the Knock and Tap task.

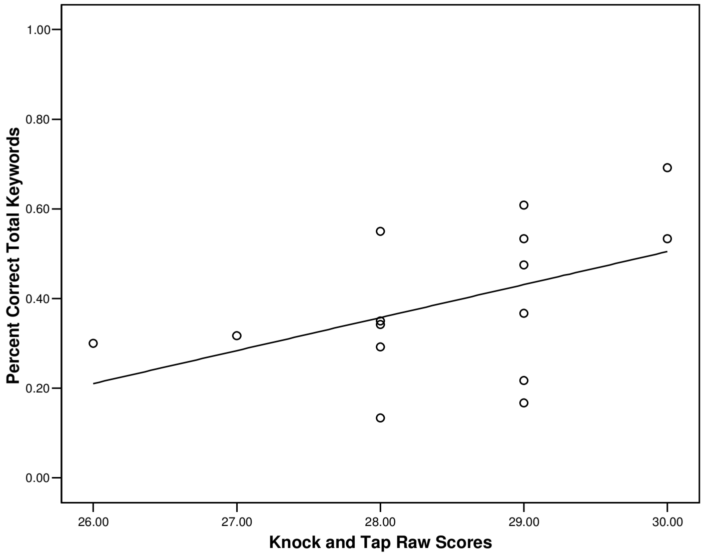

Figure 2. Scatterplot of performance on the Knock and Tap task and percent correct total keywords (easy + hard sentences) on the sentence perception task.

In order to evaluate the effect of age on these correlations, we performed a partial-correlation analysis controlling for age. The results of this analysis are summarized in Table 6. When age is partialled out of the correlation, the Design Copying test scores are still significantly correlated (r’s>.59, p’s<.05) with all three speech perception measures. This indicates that the link between the abilities used on Design Copying and those used in degraded speech perception is not a result of age. In other words, the association between these two tasks cannot be explained simply due to younger children performing more poorly than older children.

Table 6:
Partial-Correlation Analysis Between EF and P-M skills and Speech Perception (Controlling for Age)

Task	Easy Sent.	Hard Sent.	Total Sent.
Design Copy	r = .631 p = .015*	r = .597 p = .024*	r = .648 p = .012*
Knock & Tap	r = .677 p = .008**	r = .349 p = .221	r = .533 p = .050*

* = sig. to .05
** = sig. to .01

Table 6. Partial-correlation analysis of executive function and perceptual motor tasks (NEPSY: Design Copying scaled scores and NEPSY: Knock & Tap percentile rankings) with speech perception, controlling for age.

The correlation between the Knock and Tap test and the perception of lexically-easy sentences actually became stronger when age was controlled for (*r*=.68, *p*<.01). The correlation between Knock and Tap scores and the total keywords perceived was also significant (*r*=.53, *p*=.05). This pattern suggests that the association between the Knock and Tap task and the degraded speech perception task also are not due to age-related factors.

We also found that both the Knock and Tap and Design Copying scores were strongly correlated with one another (*r*=.64, *p*=.01) even when age was partialled out of the correlation (*r*=.62, *p*<.05). This result suggests that both tasks share a common source of variance that is independent of age, and some overlap exists between the resources need to complete these tasks, even though they were placed in separate domains in the NEPSY test battery.

Overall, our results indicate varying degrees of correlation between working memory, executive function, perceptual-motor skills, and speech perception abilities in normal-hearing children. While the correlations between speech perception and measures of working memory (Digit Span and CMS: Memory for Dot Locations) reflect age related factors at this stage in our analysis, the executive function and perceptual-motor tasks were found to correlate with speech perception regardless of age. Therefore, it is likely that some aspects of motor and frontal lobe functioning may play a role in spoken language processing and perception.

General Discussion

We originally predicted that measures of executive function, working memory, and perceptual-motor skills would be correlated with children's performance on a degraded speech perception test, based on earlier empirical evidence that spoken language processing is associated with attention, memory, and motor functions. The present findings provide insight into the relationship between speech perception, executive function, and perceptual-motor skills in typically-developing children. These findings are particularly interesting because, not only are executive function and perceptual-motor tasks correlated with a measure of spoken language processing, they are also correlated with each other. This indicates that the development of attention, coordination, and speech perception and production develop at similar rates in children, and that these abilities may reflect common organizational processes.

It is important to consider the following observations regarding our results. First, the correlation we initially found between digit span and degraded speech perception was expected, based on earlier studies showing that spoken language processing and verbal working memory measures are linked in typically-developing children and in children who use CIs. However, this correlation became weaker when age was controlled for in the analysis. Whereas previous studies have shown a link between working memory and vocabulary development (e.g., Baddeley, 2003; Baddeley et al., 1998), our data suggest that verbal working memory may not be related to the perception of spoken language under degraded listening conditions, at least for the current set of stimuli.

Second, we found no significant correlations between memory for dot locations and children's speech perception abilities. Previous research has shown that cochlear implant children perform more poorly on measures of spatial memory span than normal-hearing children (Cleary, et al., 2001). However, in a study using the same CMS dot locations test with children who use cochlear implants, their overall performance was comparable to the published norms for the task, but was still slightly lower than scores obtained from a normal-hearing control group (Cleary & Pisoni, 2007). It is possible that visuo-spatial memory is not closely linked to speech perception when compared to phonological working memory. Further examination of these tasks in typically-developing children is warranted.

Third, the Design Copying and Knock and Tap tasks were found to strongly correlate with the degraded speech perception task. Previous studies have shown that non-verbal cognitive development is highly predictive of language development in children as young as 2 to 4 years of age (Oliver, Dale, & Plomin, 2004), and that children who show deficits in language development also show deficits in non-verbal domains (Viding et al., 2003). Korkman and colleagues (2001) found that the subtests of the NEPSY are highly correlated with age, especially in younger children (ages 5 to 8). Their findings not only indicate that the NEPSY is a developmentally sensitive test, but also magnify the importance of our findings, because the correlations we found between these tasks were not a function of age. The development of executive function, speech perception, and perceptual-motor abilities apparently varies from child to child, with children's performance on one task being highly predictive of their performance on the others.

The finding that frontal lobe functions are related to language development is not surprising when framed in the theory of embodied cognition (for review, see Wilson, 2002). This approach suggests that cognitive and sensory processes do not function independently of one another, but rather are controlled by a complex, integrative system which encompasses brain, body, and world (Clark, 1997). Developmental research has shown that milestones in both language and motor development follow a similar timetable, and that motor development successfully predicts later language development in children (Lenneberg, 1967; Siegel, 1982). In line with this view, it has been found that there are distinct developmental periods for frontal lobe functions during which children's attentional and self-regulational abilities are developed and organized (Case, 1992). In fact, some researchers believe that the frontal lobe is directly responsible for guiding the actions of other perceptual, cognitive, and physical systems, such as language (Stuss 1992; Thatcher, 1992).

Fourth, we found a strong relationship between the Design Copying and the Knock and Tap tasks. Although the NEPSY test battery places Design Copying and Knock and Tap in separate domains (visuo-spatial processing, and attention/executive function, respectively), children may actually be using similar neural and cognitive resources to complete these tasks. For example, replicating a drawing of a geometric design involves, at a minimum: visuo-spatial processing, attention, planning, and precise fine-motor coordination. Likewise, performing the Knock and Tap task involves, at a minimum: attention, inhibition, motor coordination, and restraining perseveration. It is apparent that some overlap occurs in the cognitive functions required to complete these two tasks, all of which have been attributed to the functioning of the frontal lobe (i.e. executive function).

Finally, we found that Design Copying was correlated with both lexically-easy and lexically-hard sentence perception (and overall performance on the speech perception task), while Knock and Tap was correlated with lexically-easy sentence perception but not with lexically-hard sentence perception. This pattern is particularly interesting because no significant difference was found between children's performance on the two types of sentences. It has been reported that there is a difference between the perception of lexically-easy and lexically-hard words under adverse listening conditions. Because lexically-hard words are used less frequently and are more easily confusable than lexically-easy words, lexically-easy words are generally perceived better than lexically-hard words under degraded conditions. Therefore, the perception of lexically-hard words is a more cognitively challenging task, which requires the listener to encode and discriminate fine phonetic distinctions in the speech signal (especially when the signal is degraded) in order to perceive the words correctly. The reason why Design Copying correlates with lexically-hard sentence performance while Knock and Tap correlates with lexically-easy sentence performance is unclear at this point. The two tasks correlate with each other, indicating that they may overlap in some executive function domain. It is possible that there are different dimensions to the various executive functions such as attention. For example, Knock and Tap and lexically-easy sentence perception may involve a form of general attention, while Design Copying and lexically-hard sentence perception may involve attention for fine details.

To summarize, we found no relationship between degraded speech perception and verbal or spatial working memory tasks in typically-developing children. However, we did find strong positive relations between speech perception and both a test of visuo-spatial processing (Design Copying) and a test of attention/executive function (Knock and Tap). The Design Copying and Knock and Tap tasks correlated with one another, indicating that while they are placed in different NEPSY domains, there may be some overlap in the cognitive functions (such as attention, planning, and motor coordination) required to complete these tasks. Upon further investigation of this relationship, we found that these two tasks were correlated with different speech perception measures in terms of the lexical content of the sentences. This suggests that executive function is not a homogenous psychological construct and may reflect different subskills and processing domains.

Finally, the sample size of the present study (N=15) is small and these results require confirmation with a larger sample of children. In addition, caution should be exercised when generalizing the results obtained for the degraded speech used in this study to other forms of spoken language perception tasks. In this study, we were interested in a fairly severe form of degradation that closely mimicked CI speech. The results for this form of degradation, however, may not generalize to other forms of degradation examined previously such as background noise, reverberation, or filtering. One could argue that, the more severe the stimulus degradation, the greater the role to be played by higher level cognitive processing used for deciphering the distorted input. The use of CI simulated speech as a performance measure has been criticized because subjects are acutely exposed to this type of degradation. The argument has been made that measures obtained from normal-hearing subjects under CI simulation may not be directly comparable to the measures obtained from CI users who are chronically exposed to acoustic degradation and therefore experience an effect of learning with continued exposure. In addition, the children assessed in this study already had typically developing spoken language abilities.

Their ability to make use of context or to make sense of degraded input may differ from that in children without typically developing language systems, such as many profoundly impaired children who receive cochlear implants.

Conclusions

Spoken language processing is a complex task that involves the processing and encoding of fine acoustic details. Motor and memory abilities have been found to be linked to children's ability to perceive language under highly degraded conditions. We found that executive function and perceptual-motor tasks strongly correlated with typically-developing children's ability to perceive degraded speech signals. These findings indicate that the development of certain aspects of executive function, such as attention, planning, motor control and coordination, visuo-spatial processing, and inhibition are closely linked with the development of spoken language processing in children. All of these executive functions are attributed to the frontal regions of the brain, indicating an important role of frontal lobe development and coordination in language development. Aside from their general theoretical impact in terms of the role of cognitive control in language processing, the present findings have implications for the study of individual differences in deaf children who have received CIs. Research on this unique clinical population in our lab is focused on discovering factors that may help predict profoundly deaf children's outcome and benefit achieved after receiving an implant. Understanding the contribution of such factors will allow for advancements in clinical protocols, ultimately improving the techniques used for aural habilitation and rehabilitation of children and adults who receive cochlear implants as a treatment for profound deafness.

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