Comparing the semantic networks of children with cochlear implants and children with typical hearing: Effects of length of language access.

Michaela Socher^{1,2,3}, Ulrika Löfkvist^{4,5}, Malin Wass⁶

¹ Department of Behavioural Sciences and Learning, Linköping University, Linköping, Sweden

² Linnaeus Centre HEAD, Swedish Institute for Disability Research, Linköping University, Linköping, Sweden

³ Fraunhofer Institute for Building Physics IBP, Institute Stuttgart
Stuttgart, Germany

⁴ Department of Public Health and Caring Sciences, Uppsala University, Uppsala, Sweden

⁵ Department of Clinical Science, Intervention and Technology, Karolinska Institute, Stockholm, Sweden

⁶ Department of Business Administration, Technology and Social Sciences, Luleå University of Technology, Luleå, Sweden

Author note

Correspondence concerning this article should be addressed to Michaela Socher, Fraunhofer Institute for Building Physics IBP, Institute Stuttgart, Nobelstraße 12, 70569 Stuttgart. E-mail:

Michaela.Socher@ibp.fraunhofer.de

This paper has been published in the Journal of Communication Disorders

<https://doi.org/10.1016/j.jcomdis.2022.106247>

Acknowledgment

This research was supported by Riksbankens Jubileumsfond (P15-0442:1), the European Union Seventh Framework Program (FP7/2007–2013) under Grant Agreement FP7-607139 (iCARE); and the Swedish Research Council for Health, Working Life and Welfare (2013-01363).

We want to thank all the children and caregivers participating in the study, as well as Linn Hellgren, Elias Ingebrand, and Elisabet Östlund for helping with the data collection. In addition, we would like to thank the reviewers of the manuscript for their helpful comments and suggestions. A special thanks to Alexander P. Christensen for the support with the SemNet package!

Abstract

Purpose: Kenett et al. (2013) report that the semantic networks, measured by using an oral semantic fluency task, of children with cochlear implants (CI) are less structured compared to the semantic networks of children with typical hearing (TH). This study aims to evaluate if such differences are only evident if children with CI are compared to children with TH matched on chronological age, or also if they are compared to children with TH matched on hearing age.

Method: The performance of a group of children with CI on a verbal fluency task was compared to the performance of a group of chronological-age matched children with TH. Subsequently, computational network analysis was used to compare the semantic network structure of the groups. The same procedure was applied to compare a group of children with CI to a group of hearing-age matched children with TH.

Results: The children with CI perform on the same level on an oral semantic verbal fluency task as the children with TH matched on hearing age. There are significant differences in terms of the structure of the semantic network between the groups. The magnitude of these differences is very small and they are non-significant for a proportion of nodes included in the bootstrap analysis. This indicates that there is no true difference between the networks. Hearing age, but not age at implantation was found to be significantly positively correlated with semantic verbal fluency performance for the children with CI.

Conclusions: The results from the current study indicate that length of exposure to the tested language is an important factor for the structure of the semantic network and the performance on a semantic verbal fluency task for children with CI. Further studies are needed to

- 38 explore the role of the accessibility of the language input for the development of semantic
- 39 networks of children with CI.

Comparing the semantic networks of children with cochlear implants and children with typical hearing: Effects of length of language access.

Children with CI have been found to produce fewer words during a spoken language semantic verbal fluency task compared to peers with TH (Wechsler-Kashi et al., 2014) and similar results have been found for deaf and hard of hearing (DHH) children using sign-language, oral language with sign support, or oral language (Marshall et al., 2018). A study by Kenett et al. (2013) indicates that these results might in part be explained by differences in the semantic network structure for spoken language of children with CI compared to children with TH. However, it is currently unclear if most of the difference in the structure of the spoken language semantic networks of children with CI compared to children with TH can be explained by a later access to spoken language input for the children with CI.

Kenett et al. (2013) found differences in the semantic networks of children with CI and children with TH matched on chronological age. In order to measure the semantic networks the authors used an oral semantic verbal fluency task. In this task participants are asked to name as many words as possible from a specific taxonomic category (for example animals) within a time limit (often one minute). Previous research shows differences in the number of animals named during a semantic verbal fluency task between children with CI and children with TH (Wechsler-Kashi et al., 2014). Marshall et al. (2018) found that both executive function as well as vocabulary skills are associated with verbal fluency skills for DHH children who use CI, HA or both (CI+HA). This is in accordance with findings for children with TH (Kave et al., 2008; Tallberg et al., 2010). This suggests that the performance on verbal fluency tasks for both children with CI and children with TH is related to the size and structure of the tested taxonomic

category (for example animals) and the retrieval processes which are influenced by executive functioning.

Taxonomic categories have been found to develop through statistical learning (Unger, 2020; Lany & Saffran, 2010) as well as through labeling (Unger, 2020). Labeling means explicitly telling a child which category a word belongs to (for example in school), while statistical learning means the child uses recurring co-occurrences in the language input to infer categories (Unger, 2020). Additionally, research with bilingual's shows that the duration of language input plays an important role for the size and complexity of a taxonomic category (Borodkin et al., 2016). This is in accordance with the Conceptual Framework of Change in the Aging Lexicon by Wulff et al. (2019) in which they argue that the environment plays an important role for the semantic network structure. Depending on the language input a person receives the semantic network (of which taxonomic categories are a part) will develop differently. Wulff et al. (2019) further argue that retrieval processes are of importance. In their framework they emphasize that differences in cognitive control and/or search strategies can contribute to the observed differences in semantic networks.

Using the Conceptual Framework of Change in the Aging Lexicon by Wulff et al. (2019) it could be argued that the results found by Kenett et al. (2013) could be explained either by differences in the structure of the tested taxonomic category (animal) or by differences in retrieval processes between children with CIs and children with TH. The general difficulties in the distinction between the structure of the semantic network and the processes operating on the structure have recently been discussed by Kumar et al. (2021) and Castro and Siew (2020). Previous research shows that children with CI tend to name fewer words on a semantic verbal fluency task than children with TH, but the groups seem not to differ significantly in terms of

word retrieval strategies and pattern of responses (Löfkvist et al., 2012; Wechsler-Kashi et al., 2014). Therefore it could be argued that differences in the structure of the semantic network, rather than differences in the processes operating on the structure, are likely the reason for the differences found by Kennett et al. (2013).

In research, children with CIs are often tested using spoken language measures (such as an oral semantic verbal fluency task). However, prelingually deaf children with CI do not have full access to intelligible spoken language until their CI is activated for the first time. If they are compared to children with TH who are matched on chronological age, they are compared to peers who had access to spoken language for a longer time (on average). Differences between children with CI and children with TH in terms of the size and complexity of their taxonomic categories of spoken language would then not be surprising. One way of estimating the structure of a taxonomic category is by analyzing the results of a semantic verbal fluency task by using semantic network analysis. This kind of analysis is based on the theory that words that are named in temporal proximity in a verbal fluency task are more closely associated with each other (Zemla & Austerweil, 2018). Correspondingly Kenett et al. (2017) found that success in free- and cued recall decreases with increased path length between word pairs. An association between the network structure and word recall has also been found for phonological networks (Vitevitch et al., 2012) for typically developing first language speakers. How activation spreads through the network (from word to word) might influence how well words are recalled. Words that are closely connected with each other can activate each other, while words with no connection or a longer path length are less likely to do so. How easily activation spreads through the semantic network might influence higher order language skills. Kenett et al. (2013) hypothesize that language skills for which several semantic meanings of words need to be activated at the same

time, such as in figurative language, might be negatively affected if the activation does not spread easily through the semantic network.

Different measures have been used to evaluate the structure of semantic networks (Siew et al., 2019). The average shortest path length (ASPL) measures the average length of the shortest path between every pair of words in the network. A larger ASPL indicates that the network is more spread out. The clustering coefficient (CC) measures the extent to which neighbors of a node are also neighbors of each other. A larger CC indicates a higher interconnection of the words in a network. The modularity (Q) of a network is a measure for how much the network is divided into subsections. For a graphical representation of the network measures see Figure 1. When evaluating the structure of a network the task used to estimate the network as well as the ASPL, CC, and Q combined need to be taken into consideration. In case of a semantic fluency task, it would be assumed that every taxonomic category, for example animals, is divided into different subcategories, such as farm animals or animals in the home. A clearly divided and spread-out network might be beneficial for the performance on a verbal fluency task as its structure would lead to a directed activation rather than to a random spread of activation. The network would be characterized by a long ASPL (spread out) and a high Q (high modularity). In addition, the CC would be expected to be of medium size as the nodes in the subsections would be closely interconnected while the nodes between subsections would be expected to have a fewer and longer connections. Kenett et al. (2013) found that the semantic network of children with CI has a smaller diameter, while having a significantly shorter ASPL and a significantly larger CC in comparison to peers with TH. This indicates a higher density of the semantic network of children with CI, which might lead to activation spreading more randomly through the network. However, Kenett et al. (2013) did not investigate the Q value of the networks. Adding

131 this value could help to investigate if there is also a difference in terms of organization into
 132 subsections.

134 *Figure 1.* Graphical representation of the clustering coefficient, the shortest path, and the
 135 modularity of a network. The ASPL is calculated by taking the average of all SPLs. This graph is
 136 reprinted from Nilsson et al. (2021) with permission from the authors.

137

138 The aim of this study was to replicate the findings by Kenett et al. (2013) and to
 139 investigate if differences in length of accessibility to intelligible spoken language input explains
 140 differences in the structure of the semantic network for spoken language for children with CI and
 141 children with TH. In addition, the aim was to investigate if individual differences in length of
 142 accessibility of intelligible spoken language input are associated with verbal fluency performance
 143 for children with CI. We assume that length of access to a language influences the size and
 144 topology of taxonomic categories. This assumption is based on research on second language
 145 speakers (Borodkin et al., 2016). In addition, it is based on research showing that statistical
 146 learning is used to build taxonomic categories (Unger, 2020; Lany & Saffran, 2010). If a child
 147 receives language input for a longer time they will likely be exposed to more words (and also
 148 animal names) as well as to more recurring co-occurrences which they can use for building

taxonomic categories. Therefore, we expect that the length of access to the tested language (here spoken Swedish) will positively influence size and topology of the taxonomic category animal of children with CI. In the current study, length of accessibility of intelligible spoken language input was conceptualized by the hearing age of the children measured as the time since they received their CI. We are aware that the term hearing age is controversial. In the current study, we define hearing age as the time the children had access to intelligible spoken language. Thereby we do not consider spoken language input to be necessary for cognitive development or general language development of DHH children. However, as only two children in the study group were using sign language, for most of the children included in the current study no or very limited accessible language input was available before implantation. In addition, the focus of the study is the structure of the semantic network of spoken language. We argue that for every language the structure of the semantic network depends on how long the children had access to this specific language. In the current study the language we are investigating is spoken Swedish. The sample of children with CI included in the current study first had access to intelligible spoken Swedish when they received their CI. The results cannot be generalized to the structure of the semantic network for sign language, or any other language used by the children.

Methods

Participants

For this study, data from two research projects was combined. The merging of the results was approved by a local ethics committee (Ref:2019-05044). Both original research projects were approved by a local ethics committee (Ref: 2015/308-31 and 2011/295-31). Written consent was obtained from all participating children's caregivers. In the group of children with CI, children with a progressive hearing loss, or for whom hearing loss was detected when the child was older

than six months, were excluded (excluded $n = 17$). This was done to ensure that only prelingually deaf children are included in the study. In addition, children with additional developmental disabilities were excluded from the study (excluded $n = 6$). This was done, as developmental disabilities often influence language development. One additional child with CI and one child with TH were excluded due to missing data. Children with CI who received their implant after 4 years of age were excluded (excluded $n = 2$). Children receiving their CIs after 4 years of age are likely to have a progressive hearing loss which would explain the later implantation. If the children have a congenital hearing loss, they are likely to have missed both the critical/sensitive period of phonological and syntactical development (Ruben, 1997), which is likely to lead to a more heterogenous group in terms of language skills. This led to a group of 36 children with CI and 39 children with TH who were included in the matching process. For the first comparison the children were matched on chronological age. If no direct match could be found for a child with CI, the next best match was used. The largest difference accepted was 4 months. This led to a sample of 18 children with CI and 18 children with TH in the chronological age matched groups. For the rest of the children with CI no children with TH could be matched on chronological age (with a tolerance of 4 months). The groups were well matched ($\Delta M = -0.25$, 95% CI [-4.34, 3.84], $t(34) = -0.12$, $p = .902$, $d = -0.04$) on chronological age. The descriptive data of the two groups is presented in Table 1. The groups did not differ significantly in terms of their complex verbal working memory span as measured with a sentence completion and recall task (see [removed for blinded review] for a description of the task), $W = 107.5$, $p = .213$, $r = .217$. Two children with CI had missing data for the complex verbal working memory task.

Table 1

Descriptive data on chronological and hearing age for the children with CI and the children with TH. Age in the format Years;Months.

	Group	Chronological age				Hearing age			
		Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max
Chronological age matched	CI	6;6 (0;7)	6;6	5;6	7;2	5;4 (0;11)	5;5	3;3	6;3
	TH	6;6 (0;5)	6;6	5;7	7;1	6;6 (0;5)	6;6	5;7	7;1
Hearing age matched	CI	7;10 (1;2)	7;9	6;6	11;0	6;5 (0;7)	6;3	5;6	7;5
	TH	6;5 (0;6)	6;4	5;7	7;4	6;5 (0;6)	6;4	5;7	7;4

For the second comparison the children were matched on hearing age. Hearing age was calculated by subtracting age at implantation from chronological age. If no direct match could be found the next best match was used. The largest difference accepted was 4 months. This led to a sample of 20 children with CI and 20 children with TH in the hearing age matched groups. For the rest of the children with CI no children with TH could be matched on hearing age (with a tolerance of 4 months). The groups were well matched ($\Delta M = -0.25$, 95% CI [-4.22, 3.72], $t(38) = -0.13$, $p = .899$, $d = -0.04$) on hearing age. The descriptive data of the two groups is presented in Table 1. The groups did not differ significantly in terms of their complex verbal working memory span as measured with a sentence completion and recall task, $W = 242$, $p = .147$, $r = .235$. One child with CI had missing data for the complex verbal working memory task. It is important to note that the groups had some overlap, with some children being both in the chronological age matched and the hearing matched groups. For detailed information on chronological age, hearing age, age at implantation, language modalities and schooling see Table X (supplemental material).

Material

An oral semantic verbal fluency task (Animals, by Benton and Hamsher, 1976) was used as an outcome measure for this study. The children were asked to say as many animals out loud as possible within one minute. Real animals, but not figures from movies were scored as correct answers and the children received one point for each correct answer. If a child named the same animal several times, they only received a point the first time.

Procedure

The children with CI were tested one-to-one by a speech and language pathologist. The children with TH were also tested one-to-one by a speech and language pathologist or by an experienced test leader with a background in cognitive science. All children were tested in a quiet room at school, at home, or at the hearing clinic. All test sessions were recorded, and the recordings were used to transcribe the responses for the oral semantic verbal fluency task. The testing was part of two larger research projects [removed for blinded review] and the children were tested on more tasks than are reported here. The results from the oral verbal fluency task from the project by [removed for blinded review] have previously been used in another paper on pragmatic language ability [removed for blinded review]. In that study, the oral verbal fluency scores have been correlated with pragmatic language ability. The results from the oral verbal fluency task from the project by [removed for blinded review] have previously been reported in an article on orthographic learning [removed for blinded review]. In that study, a composite measure of the animal semantic verbal fluency task scores, the FAS letter fluency task scores, and the scores from the Boston Naming test were found to be correlated with orthographic learning.

Data analysis

To analyze differences between the groups both inference statistics on the total number of words, the number of switches, the average cluster size, as well as network analysis has been used. The network analysis used in this study is a replication of the method used by Kenett et al. (2013). To count the number of switches as well as the average cluster size the program Semantic Network and Fluency Utility (SNAFU, Zemla et al., 2020) has been used. This program makes it possible to automatize this kind of scoring which is less error prone and less time consuming than hand-coding (Zemla et al., 2020). Correlation analysis was used to investigate the association between age at implantation, hearing age and oral semantic fluency performance (total score, switches, and cluster size) for the children with CI. We used R (R Core Team, 2020) with the package stats (R Core Team, 2020), car (Fox, Weisberg, & Price, 2020), rstatix (Kassambara, 2020), dplyr (Wickham et al., 2020), tidyr (Wickham & Henry, 2020), purrr (Henry & Wickham, 2020), ggplot2 (Wickham, 2016), flextable (Gohel, 2021), SemNetDictionaries, SemNetCleaner, SemNeT (Christensen & Kenett, 2021) and papaja (Aust & Barth, 2020). The alpha value was set to 0.05.

Score comparison and Correlation Analysis.

All data was checked for normality and homogeneity of variance. Only the data for the total score comparison of the performance of the hearing age matched group was normally distributed. The condition of homogeneity of variance was also met for this data. Therefore, a student's t-test was used. For all other comparisons Wilcoxon tests were used. Spearman correlations were used for the correlation analysis.

Network comparison.

The networks used in this study are based on mathematical graph theory (Siew et al., 2019). They are mathematical structures representing associations between entities. In the case of the current study the entities of interests are words. First, a binary response matrix was created with each column representing one unique animal named by at least one of the children in the sample and each row representing a participant. The number 1 was used to represent that a participant named an animal and 0 was used to represent that a participant did not name an animal. Only words produced by at least two participants in each group were kept leading to so-called word-matched networks. Comparing word-matched networks ensures that the structure is not influenced by the size of the network. This can be the case if one group produced more words than the other did. The Triangulated Maximally Filtered Graph method based on Pearson's correlations was used to estimate the networks (see Kenett et al., 2013). This means that Pearson's correlations between the semantic verbal fluency responses were calculated, and the results were used to estimate the relation between the words. To estimate the networks the functions provided by the SemNeT package were used (Christensen & Kenett, 2021). The method used for the current study was the same as has been used by Kenett et al. (2013) and a more detailed description can be found in their paper.

All networks were first validated using a bootstrapped random network comparison (see Kenett et al. (2013) with 1000 runs. This means it was compared if the networks had significantly different structures than 1000 randomly created networks with the same number of nodes. The network of the two chronological age matched groups, as well as the networks of the two hearing-age-matched groups were visually compared, investigating if any structural differences were evident from the graphs. In a last step a node-drop bootstrap analysis (2000 runs) was used to statistically compare the ASPL, CC, and Q of the networks of the two chronologically age matched groups and the two hearing-age-matched groups. This means 2000 networks were

created based on 50% of the nodes for both the children with CI and the children with TH and then statistically compared. The same was subsequently done for 60%, 70%, 80%, and 90% of the nodes. For the Bootstrap analysis and the random network comparison the functions provided by the SemNeT package were used (Christensen & Kenett, 2021).

Results

Chronological age matched groups

Comparison of score, switches, and clusters.

A significant difference in terms of total number of words was found between the groups $W = 81, p = 0.01, r = 0.43$. In Figure 2 the individual data, median, first quartile, and third quartile for each group is presented. No significant difference between the groups was found in terms of their number of switches ($Mdn_{CI} = 5.06, Range_{CI} = [1, 8], Mdn_{TH} = 5.44, Range_{TH} = [1, 11], W = 144, p = .570, r = .097$, and the average cluster size ($Mdn_{CI} = 1.65, Range_{CI} = [1, 3], Mdn_{TH} = 1.85, Range_{TH} = [1, 2.67], W = 125, p = .247, r = .247$).

Figure 2. Comparison of the total semantic verbal fluency score of children with CI and children with TH matched on chronological age.

Network analysis. The children with CI as a group named in total 64 unique words.

The children with TH as a group named in total 81 unique words. Forty-seven of these animals were the same in both groups and 25 of them were named by two children in each group. These 25 words were included in the word-matched correlation networks. A random network comparison showed a significant difference between randomly created networks and the network for the children with CI for all three network measures. The comparison showed a significant difference between the randomly created networks and the network for the children with TH for all three network measures (see Table 2). This indicates that both the network of the children with

CI and the children with TH had significantly different topological properties than randomly created networks of the same size and the networks were considered to be validated.

Table 2

Random Network comparison for the networks of the children with CI and the children with TH.

	CI (p-value)	M.rand	SD.rand	TH (p-value)	M.rand	SD.rand
ASPL	< 0.001	1.9640	0.0260	< 0.001	1.9726	0.0259
CC	< 0.001	0.3097	0.0375	< 0.001	0.2811	0.0375
Q	< 0.001	0.2509	0.0194	< 0.001	0.2553	0.0202

The word-matched correlation networks are presented in Figure 3. Both networks are small. They both include 25 nodes. The network of the children with CI includes 138 edges and the network of the children with TH includes 137 edges. Forty of the edges are the same in the two networks (between the same words). Visually, the subsections of both networks are not clearly divided yet. This might be due to the age of the children. The network of the children with TH seems to have developed more subsections than the network of the children with CI. This makes the network more spread out.

Figure 3. Graphical representation of the semantic network of the children with CI and the children with TH matched on chronological age.

Comparison of ASPL, CC and Q using a Bootstrap analysis.

A significantly

larger average shortest path length was found for the children with TH compared to the children with CI (see Table 3).

Table 3

Summary of the bootstrap analysis of the average shortest path length of the network of the children with CI and children with TH. The numbers in the first column indicate the proportion of nodes used for the Bootstrap analysis.

	df	t	p	Lower ci	Upper ci	d	Mean CI	SD CI	Mean TH	SD TH	Direction
0.50	1998	-6.569	< .001	-0.018	-0.01	0.294	1.611	0.045	1.625	0.05	CI < TH
0.60	1998	-12.157	< .001	-0.041	-0.029	0.544	1.749	0.056	1.784	0.072	CI < TH
0.70	1998	-15.993	< .001	-0.057	-0.045	0.715	1.832	0.064	1.882	0.078	CI < TH
0.80	1998	-25.538	< .001	-0.096	-0.082	1.142	1.936	0.065	2.025	0.089	CI < TH
0.90	1998	-27.468	< .001	-0.098	-0.085	1.228	2.005	0.066	2.097	0.082	CI < TH

A significantly larger clustering coefficient was found for the children with CI compared to the children with TH (see Table 4).

Table 4

Summary of the bootstrap analysis of the clustering coefficient of the network of the children with CI and children with TH. The numbers in the first column indicate the proportion of nodes used for the Bootstrap analysis.

	df	<i>t</i>	<i>p</i>	Lower ci	Upper ci	d	Mean CI	SD CI	Mean TH	SD TH	Direction
0.50	1998	12.889	< .001	0.011	0.015	0.576	0.754	0.009	0.741	0.031	CI > TH
0.60	1998	16.037	< .001	0.011	0.014	0.717	0.746	0.009	0.734	0.022	CI > TH
0.70	1998	17.767	< .001	0.01	0.012	0.795	0.742	0.01	0.731	0.016	CI > TH
0.80	1998	24.126	< .001	0.012	0.014	1.079	0.739	0.01	0.726	0.014	CI > TH
0.90	1998	29.472	< .001	0.013	0.015	1.318	0.738	0.01	0.724	0.011	CI > TH

A significantly larger modularity was found for the children with TH compared to the children with CI (see Table 5).

Table 5

Summary of the bootstrap analysis of the modularity of the network of the children with CI and children with TH. The numbers in the first column indicate the proportion of nodes used for the Bootstrap analysis.

	df	<i>t</i>	<i>p</i>	Lower ci	Upper ci	d	Mean CI	SD CI	Mean TH	SD TH	Direction
0.50	1998	-5.268	< .001	-0.012	-0.005	0.236	0.218	0.036	0.227	0.038	CI < TH
0.60	1998	-10.588	< .001	-0.019	-0.013	0.474	0.274	0.033	0.29	0.035	CI < TH
0.70	1998	-12.449	< .001	-0.022	-0.016	0.557	0.305	0.034	0.324	0.033	CI < TH
0.80	1998	-15.122	< .001	-0.024	-0.019	0.676	0.347	0.032	0.369	0.031	CI < TH
0.90	1998	-17.922	< .001	-0.025	-0.02	0.801	0.371	0.03	0.394	0.026	CI < TH

Hearing age matched groups

Comparison of score.

No significant difference in terms of total number of words was found between the groups $\Delta M = -0.20$, 95% CI $[-2.58, 2.18]$, $t(38) = -0.17$, $p = .866$, $d = -0.05$ (see Figure 4). In Figure 4 the individual data, mean and standard deviation for each group is presented. No significant difference between the groups was found in terms of their number of switches ($Mdn_{CI} = 6.5$, $Range_{CI} = [3, 11]$, $Mdn_{TH} = 5.75$, $Range_{TH} = [1, 11]$), $W = 236.5$, $p = .324$, $r = .158$, and the average cluster size ($Mdn_{CI} = 1.87$, $Range_{CI} = [1.17, 1.33]$, $Mdn_{TH} = 1.76$, $Range_{TH} = [1, 2.67]$), $W = 198.5$, $p = .978$, $r = .158$.

Figure 4. Comparison of the total semantic verbal fluency score of children with CI and children with TH matched on hearing age.

Network analysis.

The children with CI as a group named in total 81 unique words. The children with TH as a group named in total 78 unique words. Forty-eight of these animals were the same in both groups and 30 of them were named by two children in each group. These 30 words were included in the word-matched correlation networks. A random network comparison showed a significant difference between randomly created networks and the network for the children with CI for all three network measures. The comparison showed a significant difference between the randomly created networks and the network for the children with TH for all three network measures (see Table 6). This indicates that both the network of the children with CI and the children with TH had significantly different topological properties than randomly created networks of the same size and the networks were considered to be validated.

Table 6

Random Network comparison for the networks of the children with CI and the children with TH.

	CI (p-value)	M.rand	SD.rand	TH (p-value)	M.rand	SD.rand
ASPL	< 0.001	2.0717	0.0271	< 0.001	2.0627	0.0241
CC	< 0.001	0.2587	0.0362	< 0.001	0.2435	0.0346
Q	< 0.001	0.2717	0.0187	< 0.001	0.2764	0.0193

The word-matched correlation networks are presented in Figure 5. From a first visual investigation it seems that the networks show developing subsections, with the nodes in the subsections more closely connected than the nodes between the subsections. This is supported by the modularity values for the networks, which are larger for both the network of the children with CI and the children with TH compared to the networks from the chronological age matched

comparison group. Both networks include 30 nodes. The network of the children with CI includes 168 edges and the network of the children with TH includes 167 edges. Twenty-seven of the edges are the same in the two networks (between the same words).

Figure 5. Graphical representation of the semantic network of the children with CI and the children with TH matched on hearing age.

Comparison of ASPL, CC and Q using a Bootstrap analysis. A significantly

larger average shortest path length was found for the children with TH compared to the children with CI when including 70%, 80% and 90% of the nodes into the bootstrap analysis (see Table 7). When including only 50% and 60% of the nodes no significant difference was found. The effect size was smaller than for the chronological age matched groups. This indicates that no or only very small differences in terms of ASPL exist between the compared networks.

Table 7

Summary of the bootstrap analysis of the average shortest path length of the network of the children with CI and children with TH. The numbers in the first column indicate the proportion of nodes used for the Bootstrap analysis.

	df	<i>t</i>	<i>p</i>	Lower ci	Upper ci	<i>d</i>	Mean CI	SD CI	Mean TH	SD TH	Direction
0.50	1998	-1.027	0.305	-0.008	0.003	0.046	1.763	0.062	1.766	0.064	CI = TH
0.60	1998	-1.517	0.129	-0.012	0.002	0.068	1.897	0.078	1.902	0.079	CI = TH
0.70	1998	-3.13	0.002	-0.02	-0.005	0.14	2.013	0.088	2.025	0.091	CI < TH
0.80	1998	-7.064	< .001	-0.038	-0.021	0.316	2.127	0.093	2.157	0.094	CI < TH
0.90	1998	-15.19	< .001	-0.064	-0.05	0.679	2.228	0.089	2.285	0.079	CI < TH

388

389 A significantly larger clustering coefficient was found for the children with CI compared
 390 to the children with TH (see Table 8) for the 80% and 90% bootstrap analysis. For all other
 391 proportions of nodes, no significant difference was found between the groups. The effect size was
 392 smaller as for the chronological age matched group. This indicates that no or only very small
 393 differences in terms of CC exist between the compared networks.

394 **Table 8**

395 Summary of the bootstrap analysis of the clustering coefficient of the network of the children
 396 with CI and children with TH. The numbers in the first column indicate the proportion of nodes
 397 used for the Bootstrap analysis.

	df	<i>t</i>	<i>p</i>	Lower ci	Upper ci	<i>d</i>	Mean CI	SD CI	Mean TH	SD TH	Direction
0.50	1998	-1.805	0.071	-0.002	0	0.081	0.741	0.016	0.742	0.013	CI = TH
0.60	1998	-0.617	0.538	-0.001	0.001	0.028	0.735	0.014	0.736	0.012	CI = TH
0.70	1998	1.306	0.192	0	0.002	0.058	0.732	0.012	0.731	0.012	CI = TH
0.80	1998	8.537	< .001	0.003	0.005	0.382	0.728	0.01	0.725	0.01	CI > TH
0.90	1998	19.763	< .001	0.007	0.008	0.884	0.725	0.009	0.718	0.008	CI > TH

398

A significantly smaller modularity was found for the children with CI compared to the children with TH when including 70%, 80%, and 90% of the nodes into the bootstrap analysis. When including only 50% and 60% of the nodes, no significant difference between the compared networks was found (see Table 9). The effect size was smaller than for the chronological age matched groups. This indicates that no or only small differences in terms of Q exist between the compared networks.

Table 9

Summary of the bootstrap analysis of the modularity of the network of the children with CI and children with TH. The numbers in the first column indicate the proportion of nodes used for the Bootstrap analysis.

	df	<i>t</i>	<i>p</i>	Lower ci	Upper ci	<i>d</i>	Mean CI	SD CI	Mean TH	SD TH	Direction
0.50	1998	-0.704	0.481	-0.004	0.002	0.032	0.278	0.034	0.279	0.035	CI = TH
0.60	1998	-1.022	0.307	-0.005	0.001	0.046	0.327	0.034	0.328	0.034	CI = TH
0.70	1998	-3.888	< .001	-0.008	-0.003	0.174	0.364	0.032	0.37	0.032	CI < TH
0.80	1998	-5.346	< .001	-0.009	-0.004	0.239	0.399	0.029	0.406	0.028	CI < TH
0.90	1998	-6.229	< .001	-0.008	-0.004	0.279	0.433	0.025	0.439	0.021	CI < TH

Correlation Analysis

For the correlation analysis the data from the children with CI in the chronologically age matched group and the data from the children with CI in the hearing age group was combined. Children being part in both groups were only included once. This led to a sample of 29 children with CI for the correlation analysis. The total score, $r_S = .723$, $p < .001$, as well as the number of switches, $r_S = .607$, $p < .001$, were significantly positively correlated to hearing age. The

correlation between average cluster size and hearing age was non-significant, $r_s = -.051$, $p = .794$. Age at implantation was not significantly correlated to total score, $r_s = .192$, $p = .318$, number of switches, $r_s = .107$, $p = .580$, or average cluster size, $r_s = .244$, $p = .203$.

Discussion

The aim of this study was to investigate the role of the length of exposure to intelligible spoken language input for the development of the semantic network for spoken language of children with CI. The results showed that children with CI perform on the same level and show a comparable network topology as children with TH matched on hearing age. The hearing age of the children with CI, but not their age at implantation was found to be positively correlated with their oral semantic verbal fluency performance. These results in sum indicate that differences between children with CI and children with TH in terms of their structure and size of the taxonomic category animal are explained by differences in length of exposure to the language the children are tested in – in this case: spoken Swedish.

For the chronological age matched groups, the result showed a significantly poorer performance on the oral semantic verbal fluency task as well as significant difference in the network topology of the children with CI in comparison to children with TH. However, no significant differences in terms of number of switches or average cluster size were found. This is in accordance with previous studies showing that children with CI in the tested age group employ the same strategies as children with TH when performing a semantic verbal fluency task (Wechsler-Kashi et al., 2014; Marshall et al., 2018; Löfkvist et al., 2012). Wechsler-Kashi et al. (2014) argue that the differences in performance on a verbal fluency task might be due to less efficient word retrieval strategies of the children with CI. A study by Marko and Riečanský

(2021) shows that the semantic network structure influences semantic control functions. Highly connected networks make semantic inhibition more demanding (Marko & Riečanský, 2021), possibly because activation spreads easily between closely connected nodes (Zemla & Austerweil, 2018; Kenett et al., 2017). In the current study as well as in the study by Kennett et al. (2013), the semantic network of the animal category of children with CI has been found to have a shorter ASPL, a higher CC, and a lower Q than the network of chronological age matched children with TH. This result is similar to results found for second language speakers who had a shorter exposure to the tested language than the first language speaker comparison group (Borodkin et al., 2016). The network of the children with CI is more densely connected, less spread out, and less connected into subsections. This might make semantic inhibition more cognitively demanding, which might slow down word recall. More studies are needed to investigate if verbal fluency tasks are more cognitively demanding and depend more on top down processes such as semantic inhibition for groups with shorter exposure to the tested language, such as children with CI being tested in spoken language or second language speakers. Results by Perani et al. (2003) show that a verbal fluency task leads to more extensive brain activation for second language speakers even if they had access to the language from an early age (3 years). This indicates that the task is indeed more cognitively demanding if it has to be performed in a second language. However, for children with CIs this has not yet been tested. An alternative explanation for the results for the chronological age matched comparison could be that the size of the taxonomic category of children with CIs is smaller than that of children with TH matched on chronological age. Previous research shows that children with CI have a significantly smaller vocabulary for spoken language than their peers with TH (Lund, 2016). This might influence both their performance on the verbal fluency task and the network estimation and could therefore explain the differences seen in the current study. Also, differences in cognitive

functioning between the children with CI and the children with TH might influence the performance on the semantic verbal fluency task and the semantic network estimation.

The ability to retrieve information has been suggested to be an important cognitive component of verbal fluency tasks (Kavé & Sapir-Yogev, 2020). Wulff et al. (2019) emphasize in their framework of the aging lexicon that retrieval processes can play a role for differences seen in semantic network analysis. It could therefore be argued, that the differences found in the network measures for children with CI and children with TH in the current study are not due to differences in the structure of the memory representation of the taxonomic category animal but due to differences in the retrieval process. In the current study, the children with CI and the children with TH did not differ significantly in terms of their verbal working memory, which is an important cognitive prerequisite for word retrieval. However, the groups were not matched and the same was the case for participants in the study by Kennett et al. (2013). It could be the case that some of the differences in the network topology are explained by differences in executive functioning of the compared groups. The results for the hearing age matched groups in the current study indicate that the time of access to the tested language plays an important role for the differences in network topology. In addition, the correlation analysis shows that length of access to the tested language is associated with verbal fluency performance. However, further studies are needed to evaluate how executive functions and length of access to the tested language in combination influence the network topology of children with CI and children with TH.

The results for the hearing age matched groups indicate that children with CI perform as would be expected by their hearing age (i.e. their time of exposure to intelligible spoken language) on an oral semantic verbal fluency task. No difference in terms of total score, number

of switches, or average cluster size was found. Further, the differences in terms of the network measures were reduced in magnitude and the bootstrapped analysis showed that the differences were not consistently significant for all proportions of nodes. This indicates that there was no true difference between the networks (Kennett et al., 2013). Therefore, the size and topology of the taxonomic category animal seems to be comparable for children with CI and children with TH with the same time of exposure to the tested language (here: spoken Swedish). The significant correlation between hearing age and verbal fluency further supports this claim.

This study had several limitations. The most important one is that hearing age can only be seen as a rough estimate of the time the children had access to intelligible spoken language. Many children with CI do not use their CIs for large proportions of the day (Wiseman & Warner-Czyz, 2018) and less of the spoken language input that children with CI receive might be accessible to them in comparison to their peers with TH due to differences in auditory perception (Ashori, 2020). A study by Busch et al. (2017) shows that children with CI in primary school are exposed to on average 5.17 hours of speech input per day. However, of these hours, 3.42h are speech in noise. Compared to typical hearing, hearing with a CI reduces the auditory quality of spoken language input and speech in noise is less accessible for children with CI than for children with TH (Ren et al., 2018). This needs to be addressed and more comprehensive measures for the duration the children had accessible language input are needed. Further, as in most research on children with CI, the included sample was heterogeneous. One child had a hearing aid in one ear and a CI in the other ear, three of the children had a unilateral CI, while the rest of the children had bilateral implants. It is possible that having either one or two implants changes how accessible spoken language input is and this in turn influences the oral semantic network development. Further, the children differed in terms of age at implantation, schooling, and language modality (using only oral language: $n = 18$; using oral language + sign support: $n = 8$,

using both sign language and oral language: $n = 3$). All these factors likely influence the language environment of the child. As a study by Hall and De Anda (2021) shows, the language access profiles of children with CI can differ tremendously. However, as only one verbal fluency task was used in the current study it was not possible to compute individual networks in order to correlate them with other variables such as the language access profile. Future studies are needed investigate the influence of individual differences in the language environment on the development of the semantic network of children with CI. As Wulff et al. (2021) have pointed out, research is needed to link how an individual's linguistic and social environment is shaping mental representation and thereby performance on cognitive (and language) tasks. Also, more studies are needed to investigate the development of multimodal semantic networks of children with CI using more than one language modality. A further important limitation of the current study is that the data used was from two different projects and for some variables such as vocabulary, grammar skills, and non-verbal cognitive ability different measures have been used or data has not been collected for the typical hearing group. Therefore, it was not possible to investigate if the compared groups differ in terms of their general language abilities. To get more insight into the effects of the semantic network structure and verbal fluency ability on other language skills it would be important to include comprehensive language measures in future studies. The current study as well as the study by Kenett et al. (2013) both used animal category to estimate the semantic networks of children with CI. It would be important to replicate the analysis using different semantic categories to see if the results can be generalized.

To conclude, the current study shows that children with CI use comparable strategies when performing a semantic verbal fluency task as children with TH. In addition, their size and

533 topology of the taxonomic category animal is similar to children with TH with the same hearing
534 age. Hearing age has also been found to be positively associated with the number of animals
535 named during the semantic verbal fluency task. Therefore the results in sum indicate, that the
536 length of language exposure needs to be taken into consideration when comparing the
537 performance on a verbal fluency task as well as when comparing the network structure. Future
538 studies are needed to explore how differences in the language access profile or cognitive
539 functions influence the development of the semantic network of children with CI.

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Acknowledgment

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[Removed for blinded review]

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691 **Table X**

692 Individual Data

PP	Gender	Group	Matching	CA	HA	Age at Implantation	Number of Implants	Language modalities	schooling
1	m	CI	CA matched + HA matched	7;15	5;11,5	1;2	2	oral	Mainstream (with assistant)
2	f	CI	CA matched	7;0	3; 11	3;1	2	oral	Mainstream (hearing class)
3	f	CI	CA matched + HA matched	6;9	6;2	0;7	2	oral	Mainstream
4	f	CI	CA matched + HA matched	6;11	6;3	0;8	2	oral	Mainstream (with assistant)
5	f	CI	CA matched	6;1	4;7	1;6	2	oral	Mainstream
6	m	CI	CA matched	6;2,5	5;2.5	2;0	1	oral	Mainstream (with assistant)
7	m	CI	CA matched + HA matched	6;11,5	6;1.5	0;10	2	oral	Mainstream (with resource)
8	f	CI	CA matched + HA matched	7;0	6;0	1;0	2	oral (sign as support)	Special
9	NA	CI	CA matched	6;4	5;3	1;1	1 + hearing aid	oral (bilingual - two oral languages) + sign as support	Special
10	f	CI	CA matched + HA matched	6;6	5;6	1;0	2	oral (seldom: sign support)	Special

11	f	CI	CA matched + HA matched	6;6	5;10	0;8	2	bilingual: oral + sign language	Special (with focus on bimodal language)
12		CI	CA matched	6;3	3;3	3;0	1	bilingual oral + sign (uses both modi at the same time)	Mainstream (before pre- school using oral and sign language)
13	m	CI	CA matched	5;8	5;1	0;7	2	oral	Mainstream
14	m	CI	CA matched	5;9	5;1	0;8	2	oral	Mainstream
15	f	CI	CA matched + HA matched	7;0	6;0	1;0	2	oral (sign as support) (not signing self but learning)	Mainstream (with assistant)
16	f	CI	CA matched	5;8	5;1	0;7	2	oral + sign as support	Mainstream (before pre- school using sign language)
17	f	CI	CA matched	5;6	5;1	0;5	2	oral	Mainstream
18	f	CI	CA matched + HA matched	7;0	6;3	0;9	2	oral + sign as support	Mainstream
19	f	CI	HA matched	10;11, 5	7;1	3;11	2	oral + sign language in school	Mainstream (sign language class)
20	m	CI	HA matched	9;7	6;1	3;6	2	oral	Mainstream (hearing class)
21	m	CI	HA matched	9;6,5	7;4,5	2;2	2	oral	Mainstream
22	m	CI	HA matched	8;3	7;1	1;2	2	oral	Mainstream

23	f	CI	HA matched	8;2,5	7;1,5	1;1	1	oral	Mainstream
24	m	CI	HA matched	7;9,5	6;4,5	1;7	2	oral	Mainstream
25	f	CI	HA matched	7;10	7;2	0;8	2	oral	Mainstream
26	f	CI	HA matched	7;15	6;1,5	1;0	2	oral	Mainstream (hearing class)
27	f	CI	HA matched	7;7	6;5	1;2	2	oral	Mainstream
28	f	CI	HA matched	8;1	6;1	2;0	2	oral + sign as support (10% sign)	Special
29	m	CI	HA matched	7;9	5;11	2;0	2	oral + sign as support (10% sign)	Special
30	m	TH	CA	6;8,5				oral	mainstream
31	f	TH	CA + HA	7;1				oral	mainstream
32	m	TH	CA	6;10				oral	mainstream
33	f	TH	CA	6;10,5				oral	mainstream
34	m	TH	CA + HA	6;1				oral	mainstream
35	f	TH	CA + HA	6;2,5				oral	mainstream
36	m	TH	CA + HA	6;11,5				oral	mainstream
37	m	TH	CA + HA	7;0				oral	mainstream
38	f	TH	CA	6;4				oral	mainstream
39	m	TH	CA	6;5,5				oral	mainstream
40	f	TH	CA	6;5,5				oral	mainstream
41	m	TH	CA + HA	5;10				oral	mainstream
42	f	TH	CA + HA	6;1				oral	mainstream
43	m	TH	CA	6;11				oral	mainstream
44	m	TH	CA + HA	6;0				oral	mainstream
45	m	TH	CA + HA	5;7				oral	mainstream
46	f	TH	CA + HA	6;11				oral	mainstream
47	m	TH	CA + HA	6;3				oral	mainstream
48	m	TH	HA	6;4				oral	mainstream
49	f	TH	HA	6;2,5				oral	mainstream
50	f	TH	HA	6;2				oral	mainstream
51	m	TH	HA	6;2				oral	mainstream
52	f	TH	HA	6;4				oral	mainstream
53	m	TH	HA	7;4				oral	mainstream
54	m	TH	HA	6;5				oral	mainstream
55	m	TH	HA	7;0,5				oral	mainstream

56	f	TH	HA	6;5		oral	mainstream
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Note: Age in format year;month

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