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The relationship between reasoning and language ability: comparing children with cochlear implants and children with typical hearing

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ABSTRACT

Purpose: Language has been suggested to play a facilitating role for analogical reasoning tasks, especially for those with high complexity. This study aims to evaluate if differences in analogical reasoning ability between children with cochlear implants (CI) and children with typical hearing (TH) might be explained by differences in language ability.
Methods: The analogical reasoning ability (verbal; non-verbal; complex non-verbal: high relational integration demand) of children with CI (N = 15, mean age = 6;7) was compared to two groups of children with TH: age and language matched (TH-A+L, N = 23, mean age = 6;5), and age matched (TH-A, N = 23, mean age = 6;5).
Results: Children with CI were found to perform comparable to Group TH-A+L on non-verbal reasoning tasks but significantly more poorly on a verbal analogical reasoning task. Children with CI were found to perform significantly more poorly on both the non-verbal analogical reasoning task with high relational integration demand and on the verbal analogical reasoning task compared to Group TH-A. For the non-verbal analogical reasoning task with lower relational integration demand only a tendency for a difference between group CI and Group TH-A was found.
Conclusions: The results suggest that verbal strategies are influencing the performance on the non-verbal analogical reasoning tasks with a higher relational integration demand. The possible reasons for this are discussed. The verbal analogical reasoning task used in the current study partly measured lexical access. Differences between the children with CI and both groups of children with TH might therefore be explained by differences in expressive vocabulary skills.

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Language comprehension; analogical reasoning; DHH; cochlear implant

Introduction

Analogical reasoning is a central part of human cognition [1,2] and is connected to learning, problem-solving, decision making, and language ability [1–3]. Gentner [4] argues that language and analogical reasoning have a reciprocal relationship, with language boosting analogical reasoning ability and with analogical reasoning helping to detect new linguistic meanings. In the current study, we aim to analyze the relationship between analogical reasoning and spoken language ability in children with cochlear implants (CI) and children with typical hearing (TH). The term "receptive and productive language ability" refers to spoken language ability in the current paper.

Analogical reasoning involves the ability to compare two situations or objects and to evaluate what they have in common. For example, fire is to hot, as ice is to ___ (cold). The known situation or object (fire-hot) is referred to as *source*, whereas the new object/situation (ice-cold) is referred to as *target* [1]. Different cognitive processes are needed for analogical reasoning. The core process is *mapping* [1]. Mapping involves detecting how the source and target are related and drawing inferences from the source to the target situation/object [1]. The perceptual (visual) features or the conceptual (usage; what they do) features of the target and source can be similar.

Analogical reasoning has a strong connection to language acquisition as evidenced by its associations with category word learning [5], learning to name parts of objects [6], learning the meaning of adjectives [7] and verbs [8], as well as learning the syntax of a language [9,10] and learning new grammatical constructs [11,12]. It has even been found that training analogical reasoning ability leads to an improvement in language ability [13,14]. Semantic, syntactic, and morphological skills seem to profit [13,14]. Furthermore, it has been argued that one of the reasons for the language delay seen in children with Developmental Language Disorder (DLD) could be their problems with non-verbal reasoning [15–18]. However, another explanation for the

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pattern seen in children with DLD could be that language ability influences reasoning ability. If this was the case, it would be expected that the reasoning ability of other groups with language delays or language difficulties, such as children with CI or patients with aphasia, would be more poorly as well.

Baldo et al. [19] argue that language, by means of inner speech, facilitates performance on complex non-verbal reasoning tasks. In accordance with this, Baldo et al. [19,20] found that aphasic patients perform lower on complex reasoning tasks and that the degree of language impairment is associated with the degree of reasoning impairment. The studies by Baldo et al. [19,20] were carried out with aphasic patients with a brain injury and might thus not be applicable outside this clinical population. However, verbal strategies like articulation rehearsal processes have been found to improve performance on working memory tasks in children from around 6 years of age [21]. It is likely that similar verbal strategies are used by children for complex reasoning tasks. Gentner [4] also argues that language is important for non-verbal reasoning. She reviews evidence suggesting that the knowledge of relational language increases relational (analogical) reasoning ability. Gentner [4] emphasizes that the relationship between relational language and analogical reasoning is reciprocal, with relational language serving as a cognitive tool kit for analogical reasoning and with analogical reasoning helping to develop/detect new linguistic meanings.

The majority of deaf and hard of hearing (DHH) children are born into hearing families [22] and their exposure to language often starts when their first CI is turned on as most hearing parents are not able to use sign-language. The language deprivation early in life might explain why many children with CI have a language delay [23–25]. This is a likely explanation as DHH children who do not experience a time of language deprivation (native signers) have not been found to be delayed in terms of their language ability [26,27]. With children with CI, it is possible to study the influence of a language delay on reasoning ability without assuming that the language delay is caused by cognitive deficits.

Few studies have evaluated the reasoning ability of DHH children [28–33]. Davidson et al. [32] found that children with CI have domain-specific problems with verbal cognitive skills but perform comparably to peers with TH on a non-verbal reasoning task. This is in accordance with results of Edwards et al. [29], who found that DHH children using either CI or hearing aids (HA) perform significantly more poorly on verbal reasoning but not on a non-verbal reasoning task. However, the difference between the children with TH and the DHH children was also close to significant for the non-verbal reasoning task, with a large effect size ($d = 0.6$) observed. Edwards et al. [29] tested a very heterogeneous group of DHH children, which could have led to the statistical non-significance of such a large effect. In addition, Cejas et al. [31] found that children with CI perform within one standard deviation of their age-norm in terms of their non-verbal reasoning skills, but significantly more poorly than an age-matched comparison group with TH.

Complex analogical reasoning is supported by language according to Baldo et al. [19,20] and Gentner [4]. In accordance with this, Cejas et al. [31] found language ability to be the most important predictor for perceptual reasoning ability for both children with CI and children with TH. Complex analogical reasoning involves relational integration, which is the ability to integrate two or more mental representations into one complex reasoning structure [34,35]. If simple pattern matching can be used or only one relation needs to be taken into consideration (no relational integration needed, see Figure 1), language may not play an important role in non-verbal reasoning. It might be the case that the children in the studies by Cejas et al. [31] and Edwards et al. [29] had to solve more complex reasoning tasks than the children in the study by Davidson et al. [32]. Both Davidson et al. [32] and Cejas et al. [31] used the Matrix Reasoning task from the Wechsler Non-Verbal Scale of Ability (WNV) battery [36]. This task aims to measure perceptual reasoning [36]. The matrix reasoning task starts with easier trials that can be solved *via* pattern matching, the trials then increase in complexity and relational integration needs to be used for the later trials (see Figure 1). However, as the task is ended after a child gives four wrong answers to five consecutive tasks, younger children do not reach the complex trials. Depending on their age, it is likely that the children mostly solve those trials for which pattern matching ability is needed. This might explain the differences between the results of Cejas et al. [31] and Davidson

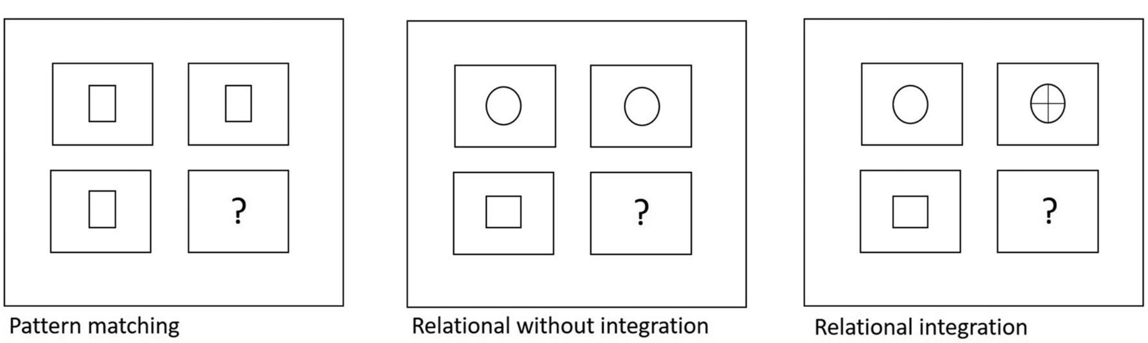

Figure 1. Examples of an analogical reasoning task. The left picture shows an example which can be solved by simple pattern matching. The picture in a middle shows a one-relational problem. For this problem relational integration is not needed. The right picture shows a two-relational problem. The horizontal and the vertical dimension have to be integrated. This means relational integration is needed to solve the task.

et al. [32] as the children in the study by Cejas et al. [31] were older.

The current study aims to investigate if children with CI and children with TH differ in terms of their verbal and non-verbal analogical reasoning skills. In addition, the aim is to evaluate if differences are due to differences in language ability. A further aim of the study is to analyze if non-verbal analogical reasoning tasks with higher relational integration demands are more dependent on language ability. In the present study, a group of children with CI was compared to two groups of children with TH, one matched for age and one matched for age and receptive language skills. A spoken language measure was used as all children with CI participating in this study used oral language as their main communication mode. All children were tested on three analogical reasoning tasks: The Matrix test from the Wechsler Non-verbal Scale of Ability (WNV) test battery [36], Animalogica [37], and the Spoken Analogies subtest of the Swedish ITPA-3 battery [35]. By comparing children with CI to both a group matched for age and a group matched for age and receptive language skills it is possible to evaluate if language ability is a deciding factor for analogical reasoning ability. As both groups of children with TH are matched for age, the influence of differences in life experience on the results can be reduced. In addition, by using two non-verbal analogical reasoning tasks, differing in complexity, it is possible to evaluate if language ability might be of greater importance for more complex analogical reasoning tasks including relational integration.

Hypotheses

H1: Based on previous literature it is hypothesized that children with CI perform comparably to age-matched children with TH on a non-verbal analogical reasoning task (low relational integration demand).

H2: It is hypothesized that language facilitates complex analogical reasoning. It is therefore predicted that children with CI show a comparable performance on a non-verbal analogical reasoning task with high relational integration demands (HRI) as peers with TH matched for age and receptive language skills (H2a). Both the children with CI and the children with TH matched for age and receptive language skills are expected to perform more poorly on a complex analogical reasoning task than the children with TH matched for age (H2b).

H3: No difference is predicted when comparing the verbal analogical reasoning ability of children with CI and children with TH matched for age and receptive language skills (H3a).

As language ability is of importance for verbal reasoning it is predicted that children with CI and children with TH matched for age and receptive language skills perform more poorly on a verbal reasoning task compared to age-matched children with TH (H3b).

Methods

Participants

Sixty-five children participated in the study. Sixteen of them were DHH and had one or two CIs (see Table 1). The children received stickers for their participation. A consent form was signed by both caregivers. The study was approved by the local Research Ethics Review Committee in Linköping, Sweden [dnr 2015/308-31]. Two of the children were removed from the analysis because of missing data. One child was removed from the analysis because the testing was disturbed several times. In addition, one child with CI was removed from the group analysis. This child had unexpectedly high scores on all outcome measures (verbal and non-verbal reasoning), scoring higher than all other children with CI (>3SD above the mean) and all children with TH (age-matched: >3SD above the mean for non-verbal reasoning and >1 SD above the mean for verbal reasoning; age + receptive grammar matched: >3 SD above the mean for non-verbal reasoning and >2 SD above the mean for verbal reasoning). We assume, therefore, that this is an especially gifted child and a highly interesting case to look at. However, we assume that this child is not representative for the average child (neither with CI nor with TH). The final sample size was 61 children (15 with CI).

Fifteen (nine girls) of the participants were DHH and were fitted with cochlear implants (CI). They were recruited from a special school as well as *via* a hearing clinic. For one of the children, the cause of the hearing loss was Usher syndrome, which also leads to visual impairment. However, no difficulties with vision were reported by the test leader. To our knowledge, none of the other children had an additional disability apart from their hearing loss. All parents reported that the children used language as their main communication mode. Information concerning the age, age at detection of deafness, and implantation as well as language use are reported in Table 1. All children with a cochlear implant were assigned to *Group CI*.

The forty-six (22 girls) children with TH were recruited from schools in Linköping, Sweden, and attended pre-school

Table 1. Descriptive data of Group CI, Group TH-A + L, and Group TH-A.

Group	Age	Detection of deafness	Age at implantation	Language use
CI (*N* = 15)	Mean: 6;7 (0;11) Range: [5;6–8;2]	Mean: 0;7 (1;2) Range: [0–3;8]	Mean: 2;0 (1;8) Range: [0;5–5;6]	Spoken Swedish: 6 Spoken Swedish + Sign-supported Swedish: 7 Bilingual (Spoken Swedish + Swedish Sign): 2
TH-A + L (*N* = 23)	Mean: 6;5 (0;4) Range: [6;1–7;1]			Spoken Swedish: 23
TH-A (*N* = 23)	Mean: 6;5 (0;4) Range: [5;8–7;3]			Spoken Swedish: 23

Note: TH-A + L: children with TH matched for age and receptive language skills; TH-A: children with TH matched for age.
The data were collected by means of a questionnaire filled in by the caregivers. Spoken language was reported to be the main communication mode of all children with CI.

class. To our knowledge, none of them had any disability. Thirty-eight of the children took part in an intervention study and the results reported here are their pre-test results. The remaining eight children were tested later to increase sample size. Performance on the Swedish version of the Test for Reception of Grammar version 2 [38,39] was used as a separation criterion for the children with TH. The age-equivalent [38] of the children was calculated. Those performing one year or more below their expected age-equivalent were assigned to *Group TH-A + L* (typically hearing; age and receptive grammar matched) ($N = 23$), children performing in accordance or above their expected age-equivalent were assigned to *Group TH-A* (typically hearing; age-matched) ($N = 23$). The mean age and age range of the groups are presented in Table 1.

Group TH-A + L, Group TH-A, and Group CI were matched in terms of their age, $\chi^2 = 0.203$, $p = .903$, $\epsilon^2 = 0.003$. Furthermore, Group TH-A + L and Group CI were matched in terms of their receptive language skills, $t(20.978) = -0.197$, $p = .845$, $d = .072$.

The data from the Matrix test [36], the Test for Reception of Grammar version 2 [38,39], and from the Spoken Analogies sub-test of the Swedish ITPA-3 battery [40] have been reported previously in a study about pragmatic language ability (Author) and a study about expressive language (Author). The differences in sample size are due to missing data.

Material

To evaluate the receptive language skills of the children, the Swedish version of TROG-2 – Test for Reception of Grammar version 2 [38,39], was used. In this test, the child saw four pictures and listened to a recorded sentence. The sentences were spoken by a native female speaker. The child was then instructed to point to the image corresponding to the sentence. In total, the test consisted of 20 blocks each including four sentences. A block was rated as being incorrect if the child gave the wrong answer to one or more of the four sentences. The child received one point for every correct block. This was in accordance to the scoring described in the manual [38]. In order to explain the task, two practice trials were used. After five wrong blocks in a row, the test was terminated. Alternatively, if the child did not give an answer in two consecutive blocks, the test was also terminated.

Non-verbal analogical reasoning

Two tests were used to assess non-verbal analogical reasoning: The Matrix test from the WNV test battery [36], which is a standard test with a multiple-choice answer format and Animalogica [37] which has an open answering format and a high relational integration (HRI), demand from the first trial.

Non-verbal analogical reasoning

The Matrix test from the WNV test battery [36] consists of a demonstration trial, three practice trials, and 41 test trials. The first six trials were bypassed [36]. For each trial, the child saw geometric patterns as well as a question mark presented in a matrix. The size of the matrix varied between 2×2, 2×3, and 3×3. Five response alternatives were presented. The child was asked which of the five alternatives fits best with the other stimuli. The test was terminated as soon as the child had given a wrong answer to four out of five consecutive trials. The child received one point for every correct answer. The test begins with trials which can be solved by pattern matching and continuously gets more complex, with later task including relational integration (pattern matching – one-relational problem – two (and more)-relational problems: relational integration). Relation integration first had to be used in the ninth trial.

Non-verbal analogical reasoning (HRI)

Animalogica was created by Stevenson et al. [37] who tested children in the same age range as the participants in the current study. The original task is in Dutch and the task is also available in English. For this study, the spoken instructions were translated from English to Swedish by a native Swedish speaker. They were recorded and spoken by a native, female speaker. Animalogica is a computer-based test. An example task from the program is displayed in Figure 2. The children saw a 2×2 grid with one empty cell. In the other three cells, animals (one or two) of different colors (blue, yellow, red) and size (big and small), either facing left or right, were displayed. The position of the animals within the cells varied as well. They were either displayed in the top, middle, or bottom of the cell. In addition to the 2×2 grid, animals the children could use to construct their answers were displayed on the screen. They were displayed in the right and left upper corner. There were always two kinds of animals that the children could choose from to construct their answers (e.g. elephants and dogs). Both animals were presented in two sizes (big and small) and three different colors (blue, yellow, red; see Figure 2). The children were able to drag and drop the animals into the empty cell. They could choose the number of animals, their color, their size, their placement in the cell (bottom, middle, top), and their viewing direction. The children got the instruction to "solve the puzzle" by filling the empty cell in a way that matched the three other cells. The test started with two practice trials in which the task was explained, and the child got feedback. If the child answered incorrectly his/her answer was automatically replaced by the correct one. There was no feedback indicating why this answer was correct. After the practice trials, 24 test trials followed. The child received one point for every correct answer. If the child was not able to use the computer mouse properly, s/he could instruct the test leader to drag and drop the animal. For the children to solve the tasks within Animalogica they had to integrate two or more mental representations into one complex reasoning structure from the first trial. For example in the trial shown in Figure 2 the

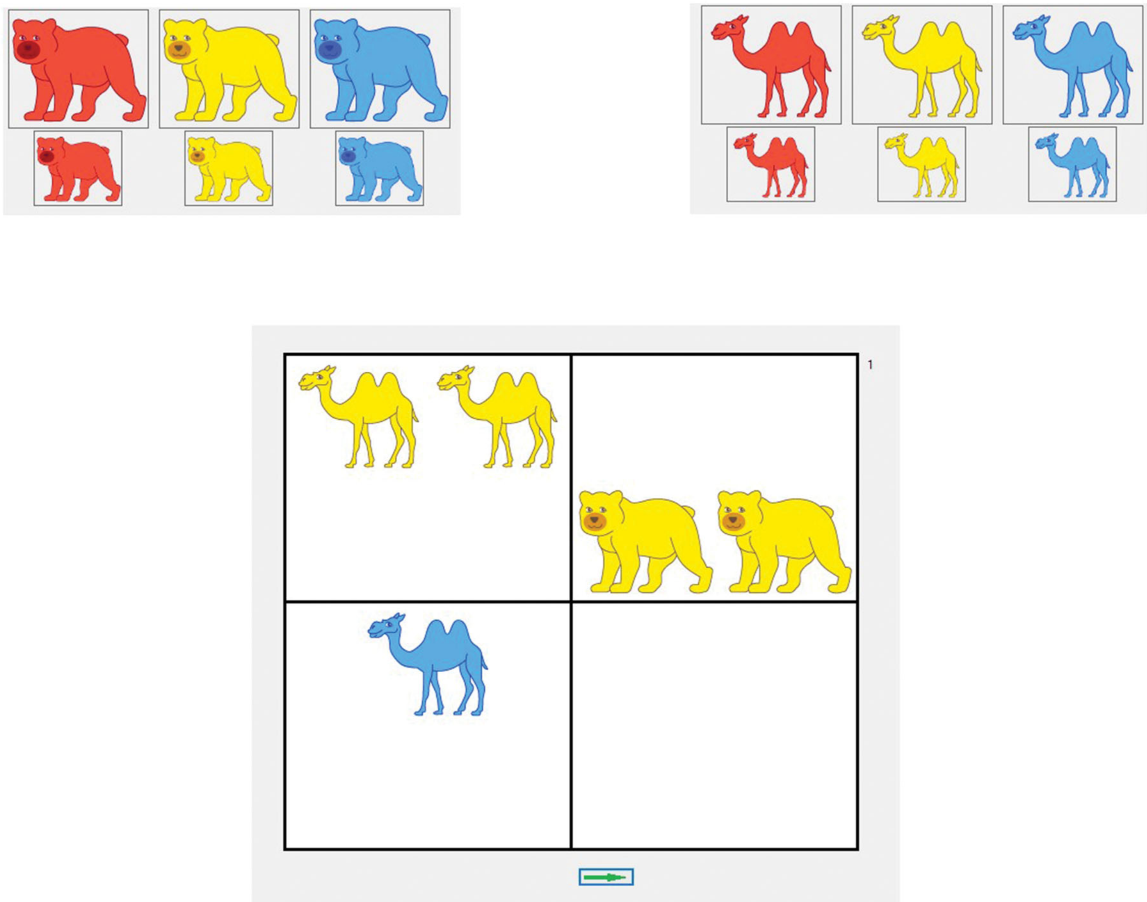

Figure 2. An example task from Animalogica a task developed by Stevenson et al. [37]. The children were asked to solve the puzzle by adding of Group CI, Group TH-A + L and Group TH-A.

children had to integrate the two-relational structure (number of animals and color) of the vertical dimension with the one-relational structure of the horizontal dimension. Therefore, this test puts a high relational integration demand on the children.

Verbal analogical reasoning

In order to test verbal analogical reasoning skills, the Spoken Analogies sub-test of the Swedish ITPA-3 battery [40] was used. This test consisted of two practice trials and 25 test trials. The test was terminated after three consecutive incorrect answers. The child listened to sentences of the following kind: "Ice is cold, fire is … ", and was asked to fill in the missing word. For every correct word, the child got one point.

Procedure

The children were tested face-to-face, individually in a quiet room either at school or at home. The order of the tests was randomized. The testing was recorded using a Dictaphone. If available in the school, a microphone and/or an amplifier was used during the testing to enhance the speech signal. If this was not possible, the child listened to the oral test material *via* the computer loudspeakers. The practice trials were used to adjust the sound level in accordance to the need of the child.

Statistical analysis

We used R [41] with the package coin [42] for all our analyses. To sort and edit the data for data analysis, the packages dplyr [43], tidyr [44], and purr [45] were used. The graphs were made using the package ggplot2 [46].

The data were checked for normality using histograms and for homogeneity of variance using Levene's test.

To analyze the group differences for the WNV Matrix task, a one-way ANOVA was calculated. Eta-squared (η^2) was used as a measure of effect size. Tukey's test adjusted for mildly unbalanced designs [see TukeyHSD documentation, 42] was used as a *post hoc* test, and Cohen's *d* was calculated as a measure of effect size for the pairwise comparisons. For the other two reasoning measures (Animalogica and verbal reasoning), Kruskal–Wallis was used as the data were non-normally distributed. Epsilon squared (ϵ^2) was used as a measure of effect size. A pairwise Wilcoxon test with p values adjusted using the Benjamin

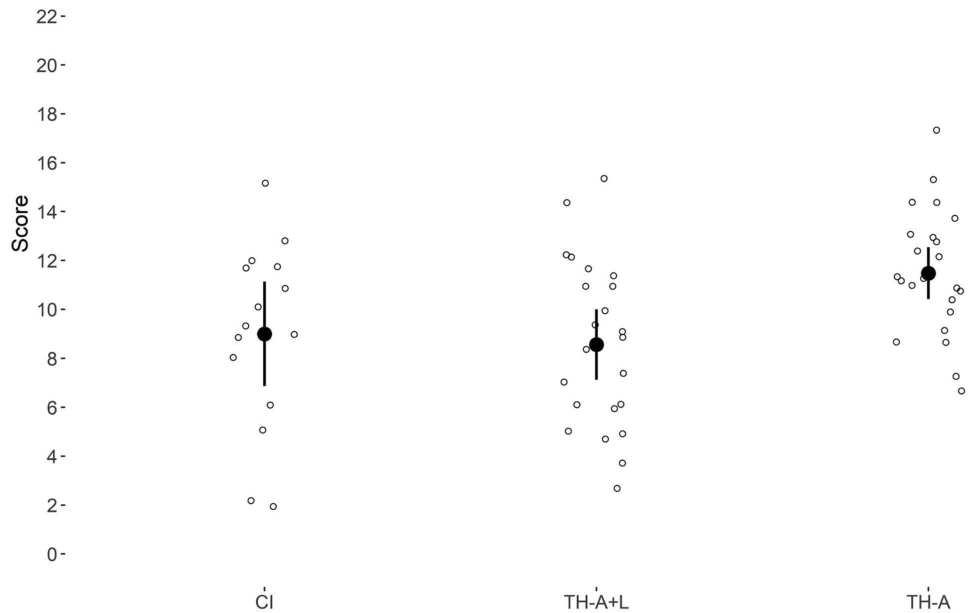

Figure 3. Non-verbal analogical reasoning: performance of Group CI, Group TH-A + L, and Group TH-A.

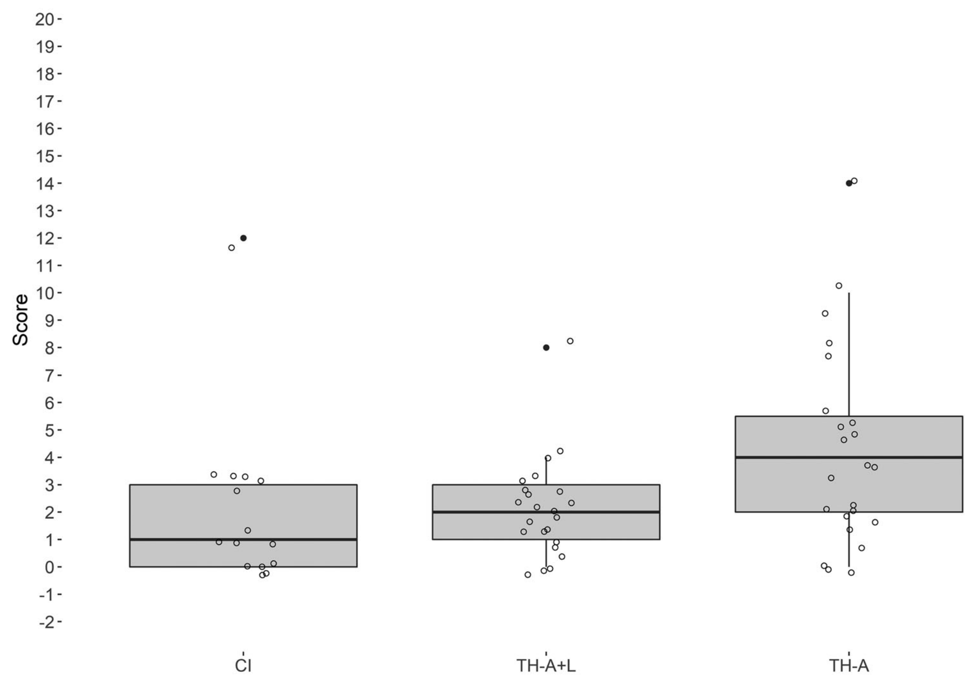

Figure 4. Non-verbal analogical reasoning (high relation integration demand): performance of Group CI, Group TH-A + L, and Group TH-A.

Hochberg method was used as a *post hoc* test. As a measure of effect size, *r* was calculated for the pairwise comparisons.

Results

Non-verbal analogical reasoning

A significant difference was found between the three groups in terms of their non-verbal analogical reasoning ability, $F(2, 58) = 5.44$, $MSE = 10.66$, $p = .007$, $\hat{\eta}^2_G = 0.158$ (see Figure 3). Tukey's test revealed that the difference was attributed to Group TH-A, performing significantly higher than Group TH-A + L, $p = .008$, $d = 0.99$. There was no significant difference between group CI and TH-A, $p = .057$, $d = 0.80$. There was no significant difference between Group CI and TH-A + L, $p = .910$, $d = 0.12$.

Non-verbal analogical reasoning (HRI)

For non-verbal analogical reasoning (HRI) ability, a significant difference between the groups was found, $\chi^2 = 7.14$, $p = .028$, $\epsilon^2 = 0.119$ (see Figure 4). Group TH-A performed significantly better compared to Group TH-A + L, $W = 166.5$, $p = .045$, $r = 0.321$, and Group CI, $W = 98$, $p = .045$, $r = 0.365$. In addition, no difference was found between Group TH-A + L and Group CI, $W = 146.5$, $p = .435$, $r = 0.129$.

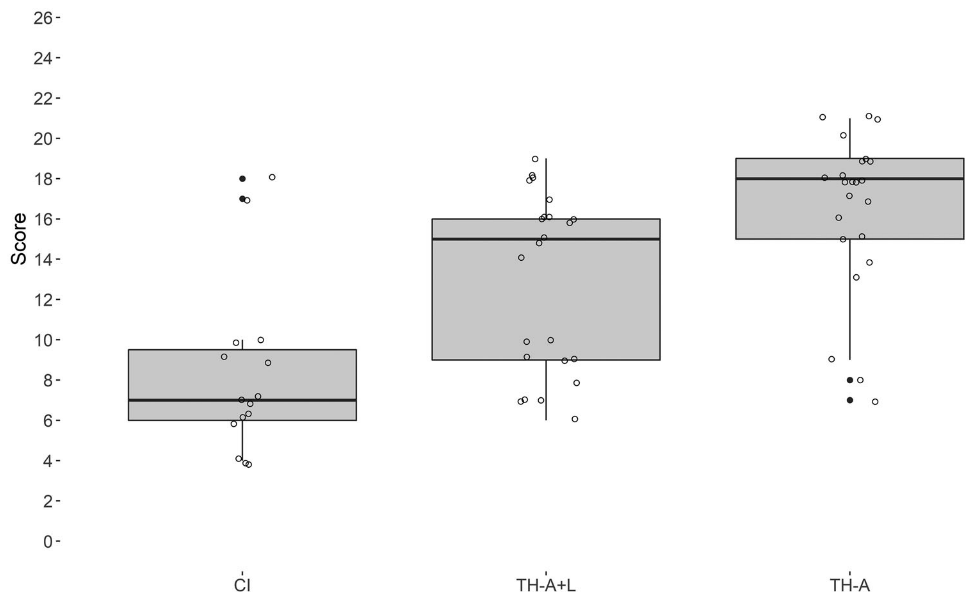

Figure 5. Verbal analogies (ITPA): performance of Group CI, Group TH-A + L, and Group TH-A.

Verbal analogical reasoning

For the verbal analogical reasoning task, a significant difference between the three groups was found, $\chi^2 = 21.455$, $p < .001$, $\epsilon^2 = 0.358$ (see Figure 5). *Post hoc* analyses revealed a significant better performance of Group TH-A compared to Group CI, $W = 34.5$, $p < .001$, $r = 0.672$, and Group TH-A + L, $W = 136$, $p = .005$, $r = 0.42$. Additionally, the children in Group TH-A + L performed significantly better compared to the children in Group CI, $W = 79.5$, $p = .005$, $r = 0.453$.

Discussion

The aim of the current study was to get more insight into the analogical reasoning ability of children with CI and to evaluate the role of language ability for analogical reasoning. We hypothesized that language facilitates complex analogical reasoning (high relational integration demand) and is of importance for verbal analogical reasoning ability. The result found in the current study indicates that differences between children with CI and children with TH in non-verbal analogical reasoning can be explained by differences in language ability. Language ability seems to be especially important for analogical reasoning tasks with higher relational integration demands. In addition, children with CI seem to have a delay in verbal analogical reasoning ability that is not explained by their receptive grammar skills. The reasons and implications of this have to be analyzed in further studies.

One major reason for the spoken language delay of children with CI is likely to be a lack of speech input within the sensitive period of spoken language acquisition. Thus, a poorer performance by this group on a non-verbal analogical reasoning task could be an indication for the facilitating role of language for non-verbal analogical reasoning. Children with CI performed significantly more poorly on a non-verbal reasoning task with high relational integration demand compared to age-matched children with TH, but not compared to children with TH matched for age and receptive language skills. The children with CI only showed a tendency toward a poorer performance for a non-verbal analogical reasoning task with lower relational integration demands (starting with pattern matching and one-relational tasks) compared to age-matched children with TH. No difference was found between children with CI and children with TH matched for age and receptive language skills. This indicates that language ability is of importance for non-verbal analogical reasoning when the complexity of the tasks is increased, meaning if relational integration is needed. This is in accordance with previous research [19,20]. The influence of language ability on analogical reasoning performance might be due to the importance of inner speech for tasks that involve relational integration. Working memory, the ability to keep and manipulate information in mind, is of importance for relational integration [47]. As inner speech has been found to improve the performance on working memory tasks [48], it is likely that inner speech will also improve the performance on complex analogical reasoning tasks. An alternative explanation for the results of the current study could be that poorer language development leads to delays in analogical reasoning ability. Children with a delay in analogical reasoning ability would be expected to perform more poorly on more complex tasks. This was the case for both groups with lower receptive grammar skills in the current study. A negative influence of poorer overall language ability [49], as well as of productive vocabulary [50,51] has been found in other studies. The results from the studies of Botting et al. [50] and Jones et al. [51] suggest that weaker productive vocabulary skills have a negative influence on non-verbal executive function development. The results from the current study suggest that receptive grammar might influence non-verbal analogical reasoning.

The results from the current study could also be influenced by differences in working memory ability between the participating groups or differences in the abstractness and answer format of the two non-verbal analogical reasoning tasks.

A factor that was not controlled for in the current study is working memory. It could be the case that the three groups tested in the current study did not only differ in terms of receptive language ability, but also in terms of working memory capacity. This would likely influence the results. A higher relational integration demand increases the demand on working memory [47]. In addition, the non-verbal analogical reasoning task with higher relational integration demand had an open answer format. The non-verbal analogical reasoning task with lower relational integration demand had a multiple-choice answering format. An open answer format might be more working memory demanding. This is, however, speculative and research is needed to evaluate the influence of the answer format. Some of the differences found in the current study might be explained by the differences in working memory load for the non-verbal analogical reasoning tasks used. In further studies, it would be important to control for cognitive abilities which might influence the non-verbal reasoning performance of the tested groups.

The non-verbal analogical reasoning tasks used in the current study did not only differ in terms of relational integration demand but also in terms of abstractness. Animals are used as stimuli in the Animalogica task. These animals are moved to specific positions in a cell, they can change their color and their viewing direction. All these operations can be verbalized. The stimuli in the Matrix reasoning task are abstract patterns. Therefore, verbalization of the stimuli is less likely. Davidson et al. [32] found that children with CI perform more poorly on a non-verbal reasoning task compared to children with TH if the task can be verbally mediated. The children with TH in the study by Davidson et al. [32] had higher receptive vocabulary ability compared to the children with CI. This might have influenced their ability to use verbal labeling and thereby improved their performance on the reasoning task. This is in accordance with von Koss Torkildsen et al. [52] who argue that non-verbal cognitive tasks which encourage verbal strategies might overestimate non-verbal cognitive differences between children with CI and children with TH. The differences might then be explained by differences in the use of verbal strategies and not by differences in non-verbal cognitive ability. This is in accordance with the results of the current study. Children with CI and children with TH matched for age and receptive grammar skills have been found to perform comparably on non-verbal reasoning tasks. These two groups might have comparable ability to use verbal strategies. On the other hand, children with TH with higher receptive language skills might be better able to use verbal strategies. This could explain why differences between children with CI and children with TH matched for age are significant for the non-verbal analogical reasoning task which likely profits from the use of verbal strategies.

Children with TH and lower receptive grammar ability performed significantly more poorly on both non-verbal analogical reasoning tasks compared to children with TH and higher receptive grammar ability. Therefore, the children with TH and lower receptive grammar ability in this study seem to have general problems with non-verbal analogical reasoning. This might be due to reduced pattern matching ability. Pattern matching has been suggested to be important for language acquisition [53]. A reason for this might be that pattern matching is essential for statistical learning. It has been argued that statistical learning explains how children learn language from input [54]. To acquire the grammar of a language, children must find rules and regularities (patterns) in the language input they receive. If their ability to do so is reduced this will likely negatively influence their language ability. This is in accordance with findings by Misyak and Christiansen [55] who found that statistical learning is an important predictor for receptive language ability even after controlling for other factors such as verbal working memory and vocabulary. In addition, a study by Kidd and Arciuli [56] shows that individual differences in statistical learning are a predictor for the receptive grammar ability of 6- to 8-year-old children. Therefore, differences in pattern matching ability resulting in differences in statistical learning ability might explain the receptive grammar differences between the two groups of children with TH in the current study. Further studies are needed to evaluate if pattern matching ability is influencing language ability, while relational integration ability is boosted by a higher language competence.

The results from the verbal analogical reasoning task are in accordance with previous research [29] showing that children with CI perform significantly more poorly than children with TH. Edwards et al. [29] suggest that the poorer verbal reasoning ability of DHH children can be explained by their inability to understand complex language. This would, however, suggest that they should perform at the same level as children with TH and comparable receptive language skills. This was not found to be the case in the current study. The children with CI performed more poorly on the verbal reasoning task compared to children with TH and comparable receptive language skills and non-verbal reasoning ability (contrary to H3a). The reasons for this are not clear. However, it might be that the children with CI and the children with TH matched for age and receptive language skills did not differ in language comprehension ability, but instead other language skills important for verbal analogical reasoning. The verbal reasoning task used in the current study is an expressive task. The child had to fill in a missing word. Therefore, the performance depends on lexical access, and children with lower expressive vocabulary will perform more poorly. In another study with the same sample of children with CI, we found them to perform significantly more poorly on an expressive vocabulary task compared to children with TH matched for working memory and non-verbal analogical reasoning ability (Authors). This is in accordance with previous studies suggesting that children with CI have a smaller vocabulary compared to age-matched children with TH [25]. In addition, children with CI have been found to perform more poorly on verbal fluency tasks [57] and this has been suggested to be caused by differences in lexical access ability [58]. Kenett et al. [58] found that the semantic network of children with CI is less developed compared to age-matched children with TH. This might be the case as language acquisition often starts later in children with CI. Unger et al. [59] found evidence that links between words in the semantic network are influenced by co-occurrence. However, links between words based on co-occurrence can only be established after having received a sufficient amount of language input. Therefore, the semantic organization of children with CI might be comparable to younger children with TH. A less organized semantic network likely makes a verbal analogical reasoning task more demanding as corresponding concepts (such as: cat – kitten) are not activated automatically. Differences in terms of vocabulary and lexical organization between the children with CI and the children with TH included in the current study are possible explanations for the differences in terms of verbal analogical reasoning.

Limitations of the study

The sample size in the current study was small. The results should therefore be interpreted with caution. In addition, no data concerning the socio-economic status or the parents' education level was available and it is therefore unclear if these variables influenced the results. Further studies controlling for these possible confounders are needed. In addition, measures that can differentiate between pattern-finding and relational integration ability should be used in future studies. This would make it possible to untangle the relationship between pattern-finding, relational integration, and language ability. The scoring of the receptive language test might have led to an underestimation of the variance in terms of receptive grammar skills in the tested sample. TROG-2 is divided into blocks of four sentences. The children receive one point for a block if they were able to understand all four sentences in the block correctly according to the manual [38]. This means that children with a higher performance on item level might get the same standard score as children with a lower performance on item level. However, each block is testing the understanding of a specific grammatical construct. Children who have mastered the respective grammatical construct should have no problems to understand all four sentences in the block. Only the receptive language skills of the children were measured in this study. Therefore, the influence of sign-language competence on the analogical reasoning ability could not be evaluated. Research is needed to evaluate if sign-language facilitates analogical reasoning ability in the same way as spoken language.

Conclusion

The results from this study are in line with research by Gentner [5] who argues for a reciprocal relationship between language and analogical reasoning ability. Language seems to play a facilitating role for non-verbal analogical reasoning tasks with a higher relational integration demand. However, more studies are needed to evaluate the influence of language competence on non-verbal analogical reasoning ability. It might be the case that the reciprocal relationship between analogical reasoning and language ability is explained by two different abilities involved in non-verbal analogical reasoning: pattern matching which might be of importance for language acquisition and relational integration ability which might be enhanced by higher language competence.

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Michaela Socher has a Ph.D. in Disability Research and this study was part of her Ph.D. project. The purpose of her research is to examine cognitive and linguistic development in children with CI and children with TH. She is especially interested in the relationship between analogical reasoning and language ability.

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