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Executive function in deaf native signing children

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Abstract

The aim of this study is twofold: to examine if deafness is invariably associated with deficits in executive function (EF) and to investigate the relationship between sign language proficiency and EF in deaf children of deaf parents with early exposure to a sign language. It is also the first study of EF in children acquiring Polish Sign Language. Even though the mothers of the deaf children ($N = 20$) had lower levels of education compared to the mothers of a hearing control group, the children performed similarly to their hearing peers (N =20) on a variety of EF task-based assessments. Only in the Go/No-go task were weaker inhibition skills observed in younger deaf children (6-9 years) compared to hearing peers, and this difference was not seen in older children (10-12 years). Hence, deafness does not necessarily impair EF; however, attentional and inhibition abilities may be acquired via a different route in deaf children. Sign language receptive skills predicted EF in deaf children. In conclusion, we highlight the importance of deaf parenting building the scaffolding for EF in deaf children.

Keywords: executive functioning, sign language, deaf

Executive function in deaf native signing children

Children go through many changes in their ability to manage thinking, emotions and actions. As they grow up, their behaviors become more organized and strategic, thanks to a set of skills called executive function (EF) (Hughes et al., 2004). EF includes the high-level cognitive processes necessary to obtain a chosen goal or to overcome new, unexpected challenges. EF is needed in situations where it is necessary to switch off ‘automatic pilot’, leave the routine and abandon habitual reactions (Diamond, 2013); for example to go to school following an unfamiliar route. These types of actions involve more effortful and conscious processing than automatic responses.

The functional organization of EF is still under debate (Friedman & Miyake, 2017): some scientists present evidence for unified EF organization (Brydges et al., 2012) while others suggest EF diversity (e.g. Godefroy et al., 1999; Gonzalez-Gomez et al., 2021). In this study, we adopted a nonunitary model of EF, focusing on the components – a variety of higher-level functions - that are widely postulated in the literature: 1) interference control, that permits focus on one stimulus and suppression of attention to other stimuli; 2) inhibition: which enables resistance to acting automatically; 3) working memory (WM): the ability to hold information in the mind and process it; and 4) cognitive flexibility, which enables consideration of different perspectives (Diamond, 2013; Miyake et al., 2000). Because of its particular importance to educational success (Bull et al., 2008), the present study also included a more complex EF domain: 5) planning - the ability to formulate, evaluate and select the sequence of responses that should be made to achieve a chosen goal (Owen, 1997).

The ability to control thinking is crucial for learning; the processes involved have a common neuronal basis: the prefrontal cortex and basal ganglia (Collins & Frank, 2013; Manini et al., 2022). EF is important for school readiness, correlating with mathematical and reading abilities in children attending kindergarten (Blair & Razza, 2007). EF explains a significant proportion of variance in academic performance independently of IQ and socioeconomic status (SES) (Alloway & Alloway, 2010). Children also need to use EF to control their own behavior, and adjust their reactions to changed demands in order to participate in social life. Children with poorer EF skills are at risk of social difficulties; for example they exhibit more problems with peers (Holmes et al., 2016) and may struggle with social understanding (Hughes et al., 1998). EF deficits are considered as a factor increasing vulnerability to substance use disorder and aggressive behavior (Giancola & Tarter, 1999).

Taking into account the importance of EF in daily life, researchers and professionals have sought to identify groups of children who are at particular risk of EF deficits, with a growing body of research about EF problems in children with attention-deficit hyperactivity disorder (ADHD, Barkley, 1997) and with autistic spectrum condition (Barkley, 2012). The question of whether deaf children may also be at risk of EF deficits has also been addressed. Hall et al. (2017, 2018) have described two contrasting views which have emerged from recent studies on EF in deaf individuals: the auditory deprivation hypothesis (also called the auditory scaffolding hypothesis by Conway et al. (2009)) that has evolved into the auditory neurocognitive model (Kronenberger & Pisoni, 2020); and the early language deprivation hypothesis (e.g. Hall et al., 2018).

Auditory deprivation hypothesis versus early language deprivation hypothesis

The auditory deprivation hypothesis (Kral et al., 2016) suggests that because the brain works as a system of interacting and dynamic networks organised in response to sensory experience, impoverished or absent auditory stimulation has a negative impact on the functioning of other brain areas. Auditory experience is a key driver of other cognitive functions because sound provides the temporal and sequential patterns for brain processing. The consequences of auditory deprivation are seen as substantial: “loss of hearing has cascading neurological and neurocognitive effects” (p. 614, Kral et al., 2016) on different cognitive functions, *inter alia* EF, sequential processing and sequence learning. According to Kral et al. (2016), EF processes heavily depend on auditory experience and spoken language, two domains impaired and impoverished by hearing loss. In other words, EF is an area of cognitive functioning that may be substantially disrupted in deafness by direct effects (diminished auditory input) and indirect effects (spoken language delay). Even children who benefit from cochlear implants (CIs) are at risk of EF deficits (Kronenberger & Pisoni, 2020). Deafness and associated spoken language problems are not seen as minor factors causing delay in EF development but “these risks appear to be broad based, involving multiple domains of EF at preschool and school ages” (Kronenberger et al., 2014, p. 613). Indeed, research showed that deaf children with CIs have delays in different components of EF: inhibition; WM; problem solving; cognitive flexibility and planning (Beer et al., 2011; Beer et al., 2014; Kronenberger, Colson, Henning, & Pisoni, 2014; Kronenberger et al., 2013; Figueras et al., 2008). EF deficits in deaf children with CIs have been reported in studies using rating scales completed by parents or teachers (e.g. Beer et al., 2014) and also on EF performance based measures (e.g. Kronenberger et al., 2013). However, it is essential to note that the auditory deprivation hypothesis is mainly based on studies of deaf children with CI who use spoken language as their dominant language of communication and who have hearing parents, non-signers (e.g. Beer et al., 2014). Before implantation these children usually did not have full access to language and communication because of their deafness and lack of signing in the environment (Hall et al., 2018).

The importance of deaf children’s language experience has been shown in studies of cognitive functioning of deaf children. For example, in Figueras et al. (2008), deaf children with and without CI, all raised by hearing parents, were reported to have deficits in multiple domains of EF (inhibition, WM, cognitive flexibility and planning). However, when language was entered in the analysis as a covariate, differences between deaf and hearing children disappeared, suggesting that potentially the discrepancy between children might be explained by language delay, not by deafness *per se*. Studies of deaf children with likely language delays have not distinguished whether their EF deficits are caused by deafness or by language deprivation, as mentioned by Hall et al. (2018).

Following the auditory deprivation hypothesis, deaf native signers who do not use CIs and who have limited access to auditory stimulation and to spoken language, should exhibit EF problems. This supposition has been investigated by Hall et al. (2018); their findings revealed that deaf children – native signers of American Sign Language (ASL) without CI - did not differ from their hearing peers in relation to EF on performance based tasks of WM, planning and inhibition. Similar results were reported by Hall et al. (2017) and Goodwin et al. (2022) when EF skills were assessed by a parent report measure - the Behavioral Rating Inventory of Executive Function (BRIEF), a questionnaire with good psychometric parameters on which high scores indicate a child's real-world problematic behaviors related to EF deficits (Gioia et al., 2000). In Hall et al. (2017), deaf children's results on the BRIEF were similar to their hearing peers when the two groups were compared, and there was no evidence of deaf children being outside the normal range. However, deaf children were at greater risk of elevated (although not clinically significant) scores indicating problematic behaviors than hearing peers on two subscales (Inhibition and Working Memory). This result might have been caused by "surprisingly low rates of elevated scores in hearing group" (Hall et al., 2017, p. 13). It is worth highlighting that even though this elevated risk was captured, deaf children had age-appropriate scores in all subscales of the BRIEF. The studies presented above provide evidence against the auditory deficit hypothesis, with deafness not invariably associated with EF deficits. According to Hall et al (2018), it is highly probable that the EF problems observed in some deaf children are caused by lack of early access to language. In line with this suggestion, Goodwin et al. (2022) found that in deaf children the age of language exposure significantly predicted the BRIEF overall composite score as well as the Shift, Working Memory, and Plan/Organize subscales.

Supporters of both the hypotheses discussed above also acknowledge that their view does not exclude the existence of other explanations of the variability in deaf children's EF; for example there might be a link to family environment or aetiology of deafness (Hall, 2020; Kronenberger & Pisoni, 2020). Taking into account the complexity of cognitive functioning, the auditory deprivation hypothesis has evolved into an auditory neurocognitive model (Kronenberger & Pisoni, 2020) that sees EF impairments in deaf children as caused by a system of interacting biological (auditory deprivation with its negative influence on brain structures and functioning), psychological (e.g. language skills, fluid intelligence and intervention) and sociocultural (e.g. mother-child interaction, peer relations, education environment) factors. Both hypotheses: the early language deprivation hypothesis and the auditory neurocognitive model agree that EF development in deaf children is a complex process with a set of interrelated biopsychosocial factors and with language playing an important role (Hall, 2020; Kronenberger & Pisoni, 2020).

However, the main conflict between these two points of view remains: according to the auditory neurocognitive model, the lack of auditory stimulation directly hinders EF development in deaf children; whereas the early language deprivation hypothesis proposes that deafness itself is not a directly influencing factor in deaf children's EF. In order to make visible the difference between the two hypotheses, we call them: "the auditory deprivation hypothesis" and "the language deprivation hypothesis".

Present study

In the present study we investigated the EF skills of deaf children who had deaf parents and who were native signers of Polish Sign Language (PJM, *polski język migowy*). As discussed above, much of the earlier research on EF in deaf children has not distinguished between lack of experience with sound and lack of early access to language. For this reason, the present study used a highly selective sample of deaf children with similar communication backgrounds: all with early access to sign language and a strong signing environment (deaf parents, other signing family members and attendance at a school for deaf children).

A set of specially designed performance-based assessments using non-verbal material was used to measure EF. Sign language assessment focused on receptive grammatical knowledge.

Firstly, we investigated the two conflicting hypotheses about EF in deaf children: the auditory deprivation hypothesis and the language deprivation hypothesis. To test them, deaf children's EF abilities were compared to those of age-matched hearing peers, with the aim of answering the following question: Do deaf children with early sign language input from deaf parents exhibit deficits in EF in comparison to age-matched hearing children?

According to the auditory scaffolding hypothesis, lack of early auditory experience causes high-level cognitive deficits; hence, all other factors from the auditory neurocognitive model being similar, deaf children should perform more poorly than hearing peers on EF assessments. Conversely, if early auditory deprivation in itself does not lead to difficulties in EF in children with early sign language exposure (language deprivation hypothesis), then deaf native signing children should obtain similar scores in EF tasks to hearing children.

Furthermore, we aimed to analyse more precisely the relationship between language and EF in deaf children who did not experience delayed access to language. Hence, the second question was formulated as follows: Does sign language proficiency (measured in terms of receptive language skills) predict EF level in deaf native signing children?

As language skills (whether signed or spoken) have been found to be important for EF performance in both deaf and hearing children (Botting et al., 2017; Merchán et al., 2022) we hypothesized that one of the predictors of EF skills in deaf native signing children would be their sign language proficiency.

Method

Participants

Children were recruited via schools: deaf children attended schools for deaf students and hearing children were in mainstream schools. All children met the following inclusion criteria: 1) normal or above normal non-verbal intelligence measured by Raven's Progressive Matrices. The raw scores in Raven's Progressive Matrices were translated into sten scores with a mean of 5.5 and a standard deviation of 2. The cut-off was 1 SD, which in sten scores was translated into a score under 3.5 (Jaworowska & Szustrowa, 2000). In both groups the scores ranged from 5 to 10 sten. Groups did not differ in non-verbal intelligence (the assumption of normality was violated and the non-parametric *Mann-Whitney test* was used: $U = 150$, $z = -1.392$, $p = .164$, $r = -.22$); 2) none of the children had additional disabilities, learning difficulties, language delay or language impairments as reported by parents/teachers; 3) additionally, researchers were able to check the psychological diagnoses of all the deaf children to confirm parents'/teachers' statements. This information was not available in the case of the hearing children.

Each child in the deaf group was individually matched with a hearing child on gender (in each group: ♂=4 ,♀=16) and age (within 12 months); as a consequence, there was no significant difference in age between groups ($t(38) = .007$, $p = .995$, *Cohen's d* $< .001$). Demographic information about the participants is presented in Table 1.

<Insert Table 1>

Deaf children were compared with hearing monolingual peers, even if deaf children used PJM and written Polish (mainly at school). Hearing bilingual children with two spoken languages were not included in the study. This decision was made in order to avoid possible bilingual EF advantage in hearing children as spoken bilingualism might have enhanced EF skills (Anderson et al., 2018, but Duñabeitia et al., 2014), whereas it is unclear about the presence of EF advantages for deaf sign-print bilinguals (Dye & Hauser, 2014).

Deaf children. Twenty deaf native signing children, aged between 6;1 and 12;11 (years; months) (*M* = 9;11, *SD* = 1;11) took part in the study. All deaf children had at least one deaf parent, with most (*N* = 18) having two deaf parents. One of the hearing parents was a native signer with deaf parents. All parents used PJM to communicate with their deaf children, and all children had acquired PJM as their first language. None of the children had a CI. According to parents' and teachers' reports, all children used hearing aids, as required in schools for deaf children in Poland. All children were prelingually severely (*N* = 7; hearing loss between 75-90 dB in better ear) or profoundly deaf (*N* = 13; hearing loss greater than 90 dB in the better ear), with deafness attributed either to genetic etiology (*N* = 18), an accident (*N* = 1) or of unknown etiology (*N* = 1). All children attended schools for deaf children that used manual communication approaches: Total Communication with either sign supported Polish, Polish and PJM (*N* = 4); or bilingual/bicultural education with PJM and Polish (*N* = 16). Eighteen children attended boarding schools for deaf children. Before beginning schooling, 13 deaf children had attended nursery schools for deaf children, six had attended inclusive nursery settings that had both deaf and hearing children, and one child did not attend nursery school.

All deaf children were immersed in a sign language environment outside school. Nine had contact with deaf grandparents, and 7 communicated with them in PJM. Five children lived in multigenerational homes together with their deaf grandparents. Twelve had deaf and/or hard of hearing siblings; five had no siblings. Five children had additional deaf members of their extended family (uncles, aunts, cousins etc.). The majority of parents had used PJM from childhood. Only two parents (one hearing and one deaf) had used spoken language in childhood as their dominant mode of communication.

All deaf children used written Polish at school. Adapted version of the Reading Test by Grzywak-Kaczyńska was used to measure hearing and deaf children reading skills –

comprehension of written short sentences. ANCOVA was computed with hearing status (deaf, hearing) as between-participant factor and age as a covariate. Deaf children obtained lower scores than their hearing peers (F(1.37) = 56,427, p < .001, $\eta 2$ = .604), and the age was a significant covariate (F(1.37) = 20,611, p < .001, $\eta 2$ = .358) (Kotowicz, 2020).

Seven mothers and four fathers of deaf children were not in paid employment. Twelve mothers and fifteen fathers were unskilled or skilled manual workers (e.g. seamstress, paint sprayer, upholsterer, carpenter, locksmith). All deaf parents and one hearing parent had completed secondary school education; one hearing parent had completed higher education (5 years of university) and this parent had the highest professional occupation of the sample (working as a teacher).

Hearing children. Twenty hearing monolingual Polish-speaking children aged 6;6 to 12;7 (years; months) (*M* = 9;11, *SD* = 1;11) took part in the study. All hearing children attended monolingual mainstream schools and had never attended a bilingual school or nursery.

Three mothers were not in paid work; all fathers were employed. The most frequent occupation for mothers was teacher (*N* = 8) and for fathers, IT specialist (*N* = 4). The majority of mothers (*N* = 15) and fathers (*N* = 16) had university degrees. Five mothers and four fathers had completed secondary school education.

Maternal education level as a proxy of socio-economic status was higher in the hearing children when compared to the deaf children ($\chi^2(1) = 20.417$, p < .001). Although attempts were made to recruit hearing parents with similar SES to the deaf parents, families with comparable SES were unwilling to take part, so the deaf and hearing groups differed in parental educational level and employment level. This difference might be important for the results of present study, as multiple studies have shown a positive relationship between SES and children’s EF (Lawson et al., 2018).

Procedure

Prior to commencing data collection, as well as obtaining written parental consent, spoken/signed/written consent was obtained from: 1) the children, 2) their teachers, and 3) school principals. Permission was obtained from the Regional Department of the Polish Ministry of Education to conduct the research.

Participants were tested individually in a quiet setting in their school. Children were tested over five sessions, each lasting approximately 15-30 minutes. The first session consisted solely of non-verbal intelligence measurement (Raven's Progressive Matrices), as a non-verbal intelligence level at or above the average range was one of the inclusion criteria for participating in the study. None of the children, hearing or deaf, were excluded from the study because of low non-verbal intelligence scores.

The other four sessions were designed to test EF on five performance-based measures and to assess language abilities. After completing all five sessions, children received a small thank-you gift (pencils, pens, erasers) and a certificate.

In the deaf group, tasks were administered by two hearing signers of PJM (one was a psychologist and special educator for deaf children and the second was a PhD student in the Section for Sign Linguistics at the University of Warsaw, who was also a teacher of deaf children and PJM interpreter). Hearing children were tested by two Polish native speakers who were students of psychology at Jagiellonian University in Cracow, Poland.

Materials

EF measures

All EF measures were carefully designed as tasks: the presented material did not contain linguistic information (spoken, signed or written) and responses did not require any use of language. All EF tasks were preceded by video-recorded instructions in the children's preferred dominant language, presented by either a deaf signer (for deaf children) or a native speaker of Polish (for hearing children). Forward and backward translations were undertaken as part of piloting in order to ensure equivalent versions of the instructions. The comprehensibility of the instructions was confirmed in a pilot study with deaf (*N* = 12) and hearing children (*N* = 40). After the pilot study, some modifications were implemented (e.g. longer training in the Go/No-go task), so the pilot data were not included in the analysis.

All EF tasks were presented as computer-based tasks in Inquisit 4 Millisecond software (https://www.millisecond.com/), modified to be suitable for the present study (e. g. all written information was deleted).

Simon task. In the Simon task (Bialystok et al., 2004) children were instructed to react to butterflies appearing on the screen: a blue butterfly required children to press the left shift key and a red butterfly required them to press the right shift key. In order not to overload WM in the interference control task, the shift keys were covered with blue and red stickers. Children were shown 28 trials equally split between two conditions: in the congruent condition, the butterfly appeared on the same side of the screen as the response key; in the incongruent condition, the butterfly was presented on the side of the screen opposite to the response key. Each trial started with a fixation cross (800ms) followed by a blank interval (250ms). Then a blue or a red butterfly appeared on the screen and remained until the child responded, or for up to 1000ms if there was no response to the stimulus. Each trial ended with a 500ms blank interval. Accuracy and RT in incongruent and congruent conditions was measured. Only RT for correct answers was included in the analysis. The difference (in accuracy and RT) between the congruent and incongruent conditions is called the Simon effect and, in the present study, it was taken as a measure of interference control (Simon, 1990). When interpreting children's scores on the Simon task, it is worth keeping in mind that a smaller Simon effect indicates better interference control skills.

Go/No-go task. In the Go/No-go task (Fillmore et al., 2006) children were required to react differently depending on the stimulus shown on the screen. They were required to tap the spacebar bar whenever a boat appeared on the screen, and to not respond when a fountain appeared. The task contained 90 trials: 63 Go trials with pictures of boats (70%) and 27 No-go trials with pictures of fountains (30%). Before a target appeared on the screen, a fixation cross appeared for 200ms. The target (a boat or a fountain) was displayed for 200ms, followed by a blank screen for 1200ms. We calculated the number of false alarms (%) (when participants falsely tap the spacebar in the No-go trials), as an indicator of inhibition (Meule, 2017). A high number of false alarms is seen as an index of low inhibition skills.

Corsi block. In the Corsi block task (Corsi, 1972; Kessels et al., 2010) an array of nine spatially separated blocks was displayed on the computer screen. Blocks were lit up in sequence and the child's task was to repeat this sequence in reverse order. The task started with a sequence of two blocks and increased to nine blocks. Each sequence length was presented twice (sequence length trials: 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9). If the child accurately repeated at least one of two sequences of the same length then they continued the task. Last sequence length (longest sequence recalled correctly) was measured as an indicator of the WM span.

Wisconsin card sorting task (WCST). The WCST task measures cognitive flexibility (switching between categories). Children were shown a computerized version of the WCST (Grant & Berg, 1948). Participants received two decks of cards, each of them containing 64 cards in random order. Cards varied in color (red, yellow, green and blue), shapes (circle, triangle, star, and cross) and number (1, 2, 3, and 4). Children were presented with a card at the top of the screen to be sorted into one of four sets in accordance with a rule that children were required to discover by themselves (sorting on the basis of the color, shape or number). After each trial feedback was given (smiley or sad face). The categorization rule (color, shape or number) changed after 10 consecutive correct responses. A sequence with 10 correct responses was called a block. The number of blocks was scored.

Tower of London (ToL). In the ToL task (Shallice, 1982) children were instructed to rearrange a set of colored balls on three sticks mounted on a board so that they matched the arrangement presented on a second board. They were required to follow three rules: (1) there was a limit to the number of moves they could perform to obtain the goal; (2) they were allowed to move only one ball at a time, (3) and they could only move the uppermost ball on a stick (they were not allowed to move a ball that was below another ball). Children had to complete 13 tasks of gradually increasing complexity (with the following limits of movement: 2,2,2,3,3,4,4,4,4,5,5,5,5). The number of correctly resolved items was scored.

Polish Sign Language measure.

Polish Sign Language Receptive Skills Test. The PJM RST (Kotowicz et al., 2021) is the first reliable and valid assessment tool that measures the development of PJM in deaf children. Created as an essential prerequisite for the present study, the Receptive Skills Test was adapted into PJM from the British Sign Language (BSL) Receptive Skills Test (RST) (Herman et al., 1999). The BSL-RST is an assessment tool with established psychometric properties (Herman & Roy, 2006). Based on the first steps of the adaptation process (Kotowicz et al., 2021), the PJM RST has acceptable psychometric properties although it is not yet standardized: validity was measured as the statistically significant difference between scores obtained by deaf children of deaf parents and deaf children of hearing parents ($t(46) = 5.81$, $p < .001$, Cohen's $d = 0.158$); reliability (internal consistency) was calculated by the Kuder-Richardson formula (KR-20 = .737); and sensitivity to age was confirmed by a significant Pearson correlation between PJM scores and age in deaf children of deaf parents ($r = .63$, $p < .01$).

The PJM RST was designed to evaluate knowledge of five morphosyntactic areas: (1) negation, (2) number and distribution, (3) spatial verb morphology, (4) size and shape specifiers, and (5) handling classifiers. The PJM RST is a computer-based test comprising: a pre-test check of the vocabulary used in the main test (27 signs elicited from pictures) and a video-based RST (50 items: 3 practice items and 47 test sentences). All instructions and test items are signed in PJM in the computerized version of the PJM RST. In the vocabulary check, the tester verifies that the child is familiar with the signs used in the PJM RST by requiring the child to provide PJM signs for pictures presented on the computer screen. In the main part of the RST, each item consists of a short sentence signed in PJM. The child is asked to select the picture which best matches the signed utterance from a choice of three or four pictures comprising the target and distractors.

Results

Children were divided into younger (6-9 years) and older (10-12 years) groups similarly to previous research on attentional processes in deaf children (Dye & Hauser, 2014; Quittner et al., 1994). Between-group differences in EF were examined using analysis of variance (ANOVA) with hearing status (deaf, hearing) and age (younger, older) as between-participant factors. Bonferroni correction was applied for multiple comparisons. We decided to enter normally and non-normally distributed data without transformation, because it has been suggested that the ANOVA can be robust to violations to the assumption of normality when the sample sizes are equal (Field, 2013).

The maternal educational level was not entered as a covariate in the analysis, because ANCOVA can be biased when groups differ on the covariate. ANCOVA is not a statistical method to control for differences between group (Field, 2013). Moreover, the maternal educational level had very little variation in each group: almost all deaf children had mothers with secondary education (N =19) and the majority of the mothers of the hearing children had university degrees (N = 15).

The relation between EF composite score (‘general EF’) and PJM RST in deaf children was investigated using simple regression. Before running the regression analysis, the homogeneity of variance was checked, with the residuals at each level of the predictors having similar variances. We did not implement multiple regression with age as a predictor because in the small sample size group of deaf children there was not enough variation in language skills at any particular age to see an additional effect of language on EF.

The online supplement to this study provides additional information about data and figures as well as additional statistical analyses. Group means and standard deviations in scores of all EF tests and PJM RST scores for the deaf and hearing children are reported in Table 2.

<Insert Table 2>

EF

Simon task. The Simon effect (accuracy and RT) was analysed using a 2 x 2 x 2 repeated measure 2-way ANOVA, with congruency (congruent, incongruent) as a within-participant factor, and with hearing status (deaf, hearing) and age (younger, older) as between-participant factors.

Simon task: accuracy. The main effect of congruency was significant ($F(1,36) = 27.988$, $p < .\ 0.001$, partial $\eta 2 = .437$), indicating that all children (deaf and hearing) were more accurate in the congruent condition than in the incongruent condition. The overall main effect of hearing status was significant ($F\ (1,36) = 5.830$, $p = .021$, partial $\eta 2 = .139$), meaning that hearing children had better overall accuracy (for both conditions) than the deaf children. The main effect of age was significant ($F(1,36) = 4.873$, $p = .034$, partial $\eta 2 = .119$); in other words, older children had better overall accuracy than younger children. The 2-way interaction between hearing status and age was not statistically significant ($F(1,36) = 1.199$, $p = .281$, partial $\eta 2 = .032$). The 2-way interaction between congruency and hearing status ($F(1,36) = .471$, $p = .497$, partial $\eta 2 = .013$) showed that deaf and hearing children did not differ on the Simon effect, the indicator of interference control skills. The 2-way interaction between congruency and age was not significant ($F(1,36) = 2.321$, $p = .136$, partial

$\eta 2$ = .061), nor was the three-way interaction between congruency, hearing status and age (F(1,36) = .055, p = .816, partial $\eta 2$ = .002).

Simon task: RT. The main effect of congruency was significant (F(1,36) = 35.469, p < .001, partial $\eta 2$ = .496). In other words, all children were faster in the congruent condition when compared to the incongruent condition. There was an overall main effect of hearing status (F (1,36) = 5.108, p = .030, partial $\eta 2$ = .124), showing that hearing children had faster overall RT (in both conditions) than the deaf children. There was no significant main effect of age (F (1,36) = 3.498, p = .070, partial $\eta 2$ = .089). The interaction between hearing status and age was not significant (F (1,36) = .135, p = .716, partial $\eta 2$ = .004). The 2-way interaction between congruency and hearing status was not significant (F(1,36)= 2.150, p = .151, partial $\eta 2$= .056) showing that the groups did not differ significantly on the Simon effect. The 2-way interaction between congruency and age was also not significant (F (1,36) = .917, p = .345, partial $\eta 2$ = .025), nor was the three-way interaction between congruency, hearing status and age (F (1,36) = .001, p = .973, partial $\eta 2$ < .001).

Go/No-go. We used a 2-way ANOVA with hearing status (deaf, hearing) and age (younger, older) as between-participant factors. The analysis revealed significance for the main effect of hearing status (F (1,34) = 10.967, p = .002, partial $\eta 2$ = .244): deaf children obtained significantly higher scores on false alarms than their hearing peers (see Figure 2 in the online supplement). The main effect of age was also significant (F (1,34) = 6.338, p = .017, partial $\eta 2$ = .157) as was the 2-way interaction between hearing status and age (F (1,34) = 7.321, p = .011, partial $\eta 2$ = .177).

In order to analyse the 2-way interaction between hearing status and age, separate t-tests with Bonferroni correction were conducted for younger and older subgroups. Younger deaf children had more false alarms than younger hearing peers (t(15)= 4.474, p < .001, *Cohen's d*

= 2.174). However, there was no difference in scores between older deaf and hearing subgroups (t(19)= .424, p= .677, *Cohen's d* = .185).

Corsi block. A 2-way ANOVA was computed, with hearing status (deaf, hearing) and age (younger, older) as between-participant factors. There was no significant main effect of hearing status (F(1,32) = .276, p = .603, $\eta 2$ = .009), age (F(1,32) = 3.165, p = .085, $\eta 2$ = .090) or the 2-way interactions between hearing status and age (F(1,32) = .249, p = .621, $\eta 2$ = .008).

Wisconsin card sorting task. We ran a 2-way ANOVA with hearing status (deaf, hearing) and age (younger, older) as between-participant factors. There was no significant main effect of hearing status (F(1,36) = .620, p = .436, $\eta 2$ = .017), age (F(1,36) = .099, p = .755, $\eta 2$ = .003) or the 2-way interaction between hearing status and age (F(1,36) = .620, p = .436, $\eta 2$ = .017).

Tower of London. A 2-way ANOVA was computed with hearing status (deaf, hearing) and age (younger, older) as between-participants factors. There was no significant main effect of hearing status (F(1,36) = .873, p = .356, $\eta 2$ = .024), age (F(1,36) = .133, p = .718, $\eta 2$ = .004) or the 2-way interaction between hearing status and age (F(1,36) = 2.264, p = .141, $\eta 2$ = .059).

Sign Language comprehension as a predictor of EF in native signing children

In order to execute the regression analysis, the scores from the tasks measuring different components of EF were transformed into z-scores (Simon task: Simon effect in accuracy computed as congruent condition minus incongruent condition; Go/No-go task: false alarms; Corsi block: last sequence length; WCST: number of blocks; and ToL: number of correctly resolved items). For the Simon effect and false alarms in the Go/No-go task, we calculated z-scores x (-1) (reversing the scores) in order that higher scores indicated better performance. Then all z-scores were added and a new variable 'general EF' was constructed. Three children had obtained 0 scores in the Corsi block task, so the missing data were replaced by a mean score (for the z-score the mean value is 0).

Previous studies have shown that level of language proficiency influences EF levels in deaf children (Botting et al., 2017; Merchán et al., 2022) rather than *vice versa.* For this reason, in our analysis language proficiency was entered into the model as a predictor of general EF level.

Simple regression analysis indicated that sign language proficiency (PJM RST) was a significant predictor of EF in deaf children (R^2 = 0.260, $R^2_{adj.}$ = 0.219, F (1, 18) = 6.317, p = .022) and accounted for 26% of the variance in EF in the group of deaf children (see Table 3); however, age was not entered into this model.

<Insert Table 3>

Discussion

The aim of this study was to investigate EF skills in deaf children who were immersed in sign language from birth by their deaf parents. Deaf children of deaf parents were chosen for this research because they are less likely than deaf children of hearing parents to face consequences of deafness such as language deprivation (Baker et al., 2008). Firstly, deaf children's EF skills were compared with those of hearing peers in order to address whether deafness *per se* causes high-level functioning deficits (auditory deprivation hypothesis) or whether language experience rather than deafness itself affects high-level cognitive functioning (language deprivation hypothesis). Secondly, the relationship between EF and sign language proficiency was investigated in the deaf group, as sign and spoken language proficiency has been found to mediate group differences in EF between deaf and hearing children (Botting et al., 2017).

In the present study, deaf native signing children performed similarly to their hearing peers on four performance-based measures designed to assess EF functioning: the Simon task, the Corsi block, the WCST and the ToL. These findings are consistent with previous research on EF skills in deaf children who are native signers of a different sign language (ASL) (Hall et al., 2017; 2018; Marshall et al., 2015).

It is worth highlighting that the samples were not matched on SES as measured by maternal educational attainment: deaf children had lower SES than the hearing comparison group. Taking into account that SES is significantly associated with EF (Last et al., 2018), deaf children would have been expected to obtain lower scores in EF tasks. The null findings of the present study are thus contrary to general expectations, and are of particular importance when compared to sample characteristics in previous studies: in Hall et al (2017, p. 17) “nearly 80% of the Deaf parents were college graduates”, which may not be representative of Deaf parents in other populations. Hence, the present study provides additional evidence of good EF performance by deaf children of deaf parents where there is a lower maternal educational level.

Inhibition skills measured by the Go/No-go task depended on child age: while older deaf children scored similarly to older hearing children, younger deaf children had weaker inhibition skills than their hearing peers. Six to nine year old deaf children were still learning how to deal with attention tasks and suppress reactions, as has also been found in previous studies (Dye & Hauser, 2014). Taking into account that deaf children had a lower level of maternal education, it is hard to disentangle the two factors of deafness and SES when analysing their difficulties with the Go/No-go task. Moreover, in the present study, Simon scores were also puzzling: deaf children had lower overall scores on the Simon task, but they did not differ on the Simon effect - the indicator of interference control. To explain this inconsistency in relation to previous findings on interference control, inhibition and attention in deaf children (Hall et al., 2018), careful analysis of the design of the tasks used in the present study is helpful.

In the present study, the Go/No-go task was more demanding than in a previous study of deaf children with deaf parents (Hall et al. 2018) because of a shorter stimulus presentation window (present study - 200ms versus Hall et al. (2018) - 500ms). It is likely that the greater demands of this task caused by the shorter stimulus presentation window revealed inhibition problems that were not observed in the easier inhibition task used by Hall et al. (2018).

One factor which is likely to be important in capturing differences and similarities between deaf and hearing children, is the visual design of attention tasks (Dye et al., 2009); the presence of distractors in the visual field is one example. In a previous study, Dye & Hauser (2014) specifically asked participants to ignore distractors presented in the peripheral visual field; they discovered that younger deaf children (age 6-8 years) showed greater distraction than hearing same-age peers, while this difference was not observed in older children. Dye and Hauser's results are in accord with other studies (e.g. Bavelier et al., 2006) showing enhanced peripheral attention in deaf signers. In the Simon task in the present study, although there was no distractor at the periphery of vision, the location of the stimulus was a key factor. In the incongruent condition, participants were asked to respond to the visual stimulus (color) and to ignore the position of the stimulus. In contrast, in the congruent condition, spatial information helped to achieve success. Deaf children had lower overall scores in both conditions than hearing peers. One possible explanation is that the location of the stimulus may be a more salient cue for deaf children than for their hearing peers. For this reason, in the incongruent condition, inhibition of the irrelevant information relating to location of the stimulus was likely to be more difficult for younger deaf children. Moreover, after the effort of suppressing strong spatial information in the incongruent condition, using spatial information in the congruent condition may also have been challenging. Support for this interpretation comes from the finding that spatial cues are more salient in attentional tasks for young deaf children than for their hearing peers (Daza & Phillips-Silver, 2013). It is also possible that sign language experience may influence attention and inhibition by deaf children (Dye et al., 2016).

Results from the Go/No-go task and the Simon task suggest that deaf children may acquire attentional skills and inhibition ability along a different time course or via a different route than their hearing peers. In the Go/No-go task, the older deaf group had no problems with attention and inhibition; this might mean that deaf children need more time to acquire these skills or that studies need to take greater account of visual factors associated with experimental design. In addition, further investigation using longitudinal studies would be required, as cross-sectional research does not permit conclusions about developmental trajectories.

In the present study, we also investigated the relation between sign language knowledge and EF. Our results showed that sign language knowledge predicted EF skills in a highly selective sample of deaf native signing children. The present scores are in alignment with a large scale study of deaf and hearing children (Botting et al. 2015) showing that language proficiency (whether signed or spoken) played a crucial role for EF development. However, the present analysis of the relationship between sign language proficiency and EF was restrained by the small sample and fact that measurement of the variation in sign language proficiency at each age point was limited. For this reason, we did not use multiple regression analysis with age as predictor and we suggest that simple regression analysis best fits the present data. In future studies, there should be a larger sample of deaf native signing children at each age point. We also recommend using additional tools to measure sign language lexical and grammatical receptive and productive skills.

It is important to put the present study's findings in the perspective of the two main hypotheses about EF development in deaf children: the auditory deprivation hypothesis and the language deprivation hypothesis, although the findings do not unambiguously support either of the two hypotheses. The auditory deprivation hypothesis and its current version (the auditory neurocognitive model) suggests that deafness *per se* degrades EF skills in deaf children. The present research, contrary to this hypothesis, showed that deaf children obtained similar scores to their hearing peers on EF tests: the Simon task, the Corsi block task, the WCST and the ToL, even though deaf children had lower SES measured by mother's educational level. Our data, rather, are in accordance with Hall et al.'s (2017) early language deprivation hypothesis: in the present study, deaf children who had acquired sign language as a first language did not demonstrate deficiencies in EF measured by the four above-mentioned tasks, while problems in cognitive flexibility and planning have been reported in studies with deaf children with CI who were at elevated risk of language delay (Beer et al., 2011; Figueras et al., 2008)).

However the present findings are not unambiguously in agreement with the language deprivation hypothesis, because, contrary to Hall et al. (2017), in the present study younger deaf children did not score similarly to their hearing peers on the Go/No-go task. We postulate that different paths of attentional and inhibition development should not be seen as an EF deficit caused by the lack of auditory input, as assumed in the auditory deprivation hypothesis.

Socio-emotional approach on EF development in deaf children

Our findings and the current debate on EF (Hall, 2020; Kronenberger & Pisoni, 2020; Morgan & Dye, 2020) have encouraged us to re-examine the language deprivation hypothesis and Hall et al.'s (2018) conclusions, as there are other possible explanations of Hall et al. (2017, 2018) and of the findings of the present study. The third, recently formulated view on the topic: "the intersubjectivity hypothesis" - suggests that intersubjectivity is crucial for EF skills in deaf children; in other words, the early communicative experience of engagement in shared and reciprocal exchanges is a key factor for EF skills in deaf children (Morgan & Dye, 2020). Signing children of deaf parents have been reported to follow a typical trajectory of intersubjectivity (e.g. Roos et al., 2016), whereas communication between deaf children and their hearing parents is deficient in sharing involvement in reciprocal exchange (Nowakowski et al., 2009). For example, hearing mothers use more directive talk and prohibitions with their deaf children when compared to hearing parents with hearing children (Fagan et al., 2014). Morgan and Dye (2020) have suggested that the reduced and impoverished early interactions between deaf child and hearing parent result in language delay and less frequent training of self-control, and in consequence deaf children struggle with EF. Intersubjectivity might be one factor in EF development by deaf children. However, research on hearing children provides a more complex picture of the relationship between socio-emotional and EF development, rather than on a single mechanism of intersubjectivity.

Within the social relational framework of EF (Lewis & Carpendale, 2009), interpersonal activities contribute to developmental change and individual differences in EF. Previous studies on hearing children have provided evidence that parenting plays an important role in children's EF development. Different aspects of parenting behavior have been described in the literature (e.g. Fay-Stammbach, Hawes, & Meredith, 2014) as supporting or hindering the emergence of EF in children. Among these, development of EF in children is correlated with emotional and verbal responsiveness of parents (Blair et al., 2014), flexibility in parental guidance (Hughes & Devine, 2019) and verbal and nonverbal parental efforts to promote children's goal-directed activities (Lowe et al., 2013). Some parenting characteristics such as parenting stress (de Cock et al., 2017), and expression of negative feelings, intrusiveness, parental harsh behaviors and control are negatively associated with EF in children (Blair et al., 2011).

A small number of studies have explored whether parenting behaviors are also significant for EF in deaf children (Andrew Blank & Holt, 2022; Blank & Frush Holt, 2022;

Blank, Frush Holt, Pisoni, & Kronenberger, 2020; Holt et al., 2019). Future research should be sensitive to dimensions of parenting that have been found to be important in hearing children's EF development which may be challenging for hearing parents of deaf children: for example parental sensitivity and responsiveness have been shown to predict developmental gains in EF in hearing children (Blair et al., 2014), while hearing parents of deaf children have been described as less sensitive than hearing parents of hearing children (Meadow-Orlans, 1997; Meadow-Orlans & Steinberg, 1993) and less likely to respond to a single and isolated acts of communication than the hearing parents of hearing children (Roberts & Hampton, 2018). Jamsek et al. (2021) showed that parental sensitivity was associated with inhibitory control in deaf children using spoken language. This kind of study remains to be done with other aspects of parenting behaviours in hearing and deaf parents that may influence development of EF in deaf children.

We suggest that a number of features of deaf parenting may build the scaffolding for EF development in deaf children. Deaf parents not only provide early access to fully accessible sign language, but also fully accessible language input to their deaf children and this rich language environment is important for deaf children's development (Hall, 2020b). Deaf parents also adjust to the visual needs of the deaf child in developing joint attention (Chasin & Harris, 2008; Harris, 2001; Lieberman et al., 2013); prepare their child to coordinate complex visual information – a skill critical in educational settings (Singleton & Morgan, 2014); have positive attitudes to deafness and accept their child's deafness with ease (Hauser et al., 2010); and build an environment where implicit learning and access to information is assured for visually oriented children (Hauser et al., 2010). Additionally, deaf parents serve as role models who can guide children in the socialization process and development of their identity (Singleton & Morgan, 2014) and enable their children to enter into deaf culture and the deaf community. This community cultural wealth is considered to be a protective factor, building deaf children's resilience and supporting academic success (Listman et al., 2011). All of these and other possible factors support the cognitive development of deaf children; as a result, deaf children born to deaf parents have cognitive skills that are similar to their hearing peers and superior to those of deaf children of hearing parents in such areas as analogical reasoning (Bandurski & Gałkowski, 2004), non-verbal intelligence (Sisco & Anderson, 1980), and theory of mind (Courtin, 2000; Schick, de Villiers, de Villiers, & Hoffmeister, 2007).

Limitations

Factors possibly bearing on the research findings reported here must be taken into account. In the present study, deaf native signing children used two languages on a daily basis: PJM as their first language and written Polish at school (Kuder, 2021; Tomaszewski & Sak, 2014; Rutkowski & Mostowski, 2020). These deaf children can therefore be considered as bilingual (more specifically, sign-print bilingual (Piñar et al., 2011). However, their bilingualism was not investigated in detail in this study. Future studies might include variables such as age of acquisition, or current level of exposure to spoken/written Polish to investigate more deeply any bilingual effect on EF in deaf native signers which might be comparable to that found in children bilingual in two spoken languages (e.g. Barac, Moreno, & Bialystok, 2016) as suggested by Dye & Hauser (2014).

Research with native signers faces a recurring problem: a limited number of potential participants, as deaf children of deaf parents are a small percentage (5-10%) of the deaf child population (Mitchell & Karchmer, 2004). However, some EF studies of deaf children with hearing parents, which have used similar sample sizes to the present study (e.g. Figueras et al., 2008) have been able to capture differences between those deaf children and hearing children, suggesting that results can be achieved even with small samples.

Research which includes only deaf children of deaf parents does not reflect the complexity and heterogeneity of deaf children's cognitive functioning (Hall et al., 2018). For this reason, in future studies of EF, deaf children with hearing parents should be included, in particular, deaf children who use sign language as a preferred mode of communication and who have hearing parents. This would enable further exploration of the language deprivation hypothesis and will help us to reach conclusions about whether exposure to sign language is a protective factor in EF development for deaf children who grow up in hearing families – the vast majority of deaf children.

Conclusion

The present study was the first to investigate EF and Polish Sign Language (PJM) in deaf children with early exposure to fluent models of sign language. Even though the deaf mothers of these children had lower educational attainments than the hearing mothers of the hearing control group, the children did not struggle with deficits in EF measured by: the Simon task, the Corsi block, the WCST and the ToL. In the Go/No-go task younger deaf children had weaker inhibition skills than their hearing peers, although older deaf children did not differ from hearing peers. The findings suggest that deaf and hearing children may have different patterns of attention and inhibition skills, which might be connected with experience of deafness and sign language. Sign language proficiency predicted the general EF level in deaf native signing children.

Our findings are not clearly in line with either the language deprivation hypothesis or the auditory deprivation hypothesis. However, it is important to highlight that the debate on EF functioning in deaf children is not limited to two opposing views. Another possible explanation has been proposed in which poor EF in some deaf children is seen as caused by differences in social environments; from this perspective, interactions with parents are a potentially important factor for deaf children's EF. Moreover, it is probable that the language deprivation hypothesis and social interaction framework are not mutually exclusive and that both the factors of language environment and parenting quality should be combined into a more complex view of EF development in deaf children. In accordance with the social interaction framework, our findings suggest that deaf parenting ensures an appropriate environment and provides a supportive context for EF development in deaf children. Deaf parenting, including *inter alia* early sign language access, is a protective factor against EF difficulties in deaf children. Future studies need to investigate precisely how deaf and hearing parents support their deaf children's EF development.

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Table 1 Demographic information about sample.

Demographic variable	Deaf	Hearing
Number of participants	20	20
Age (years; months)		
Mean	*M* = 9;11	*M* = 9;11
SD	*SD* = 1;11	*SD* = 1;11
range	6;1-12;11	6;6-12;7
Gender	♂=4 ,♀=16	♂=4 ,♀=16
Ethnicity		
white	20	*20*
Hearing status		
severe hearing loss	7	n/a
profound hearing loss	13	n/a
prelingual deafness	20	n/a
Hearing loss etiology		
genetic	18	n/a
accident	1	n/a
unknown	1	n/a
Child language experience		
L1 PJM	20	0
L1 spoken Polish	0	20
Parental hearing status		
both deaf	18	0
one deaf and one hearing	2	0
both hearing	0	20
Parent-child communication		
both parents PJM	20	0
both parents spoken Polish	0	20

Note. SD = standard deviation; ♂ = male ; ♀ = female; PJM = Polish Sign Language.

Table 2 Descriptive statistics of EF variables by groups and by age.

task	measure	deaf			hearing		
		all mean (SD)	younger mean (SD)	older mean (SD)	all mean (SD)	younger mean (SD)	older mean (SD)
Simon task							
	incongruence accuracy (%)	70 (18.91)	60.32 (16.02)	77.92 (17.92)	81.07 (15.42)	76.98 (11.72)	84.42 (17.73)
	congruence accuracy (%)	82.50 (12.79)	76.98 (13.26)	87.01 (10.98)	90.71 (13.93)	89.68 (11.36)	91.56 (16.23)
	incongruence RT	635.48 (88.33)	661.77 (93.33)	613.97 (82.01)	592.74 (85.46)	608.99 (94.00)	579.45 (79.85)
	congruence RT	589.75 (84.50)	626.90 (80.94)	559.35 (77.88)	517.86 (94.97)	544.23 (112.88)	496.28 (76.19)
Go/No-go							
	false alarms (%)	27.96 (15.03)	37.86 (12.53)	19.87 (11.98)	17.49 (8.01)	17.13 (3.93)	17.78 (10.45)
Corsi block							
	last sequence length	4.24 (1.75)	3.88 (1.89)	4.56 (1.67)	4.53 (1.50)	3.89 (1.27)	5.10 (1.50)
Wisconsin card sorting task							
	number of blocks	3.85 (1.66)	4.00 (1.66)	3.73 (1.74)	4.35 (1.90)	4.00 (1.94)	4.64 (1.91)
Tower of London							
	number of correctly resolved items	6.10 (2.00)	5.44 (2.01)	6.64 (1.91)	6.60 (2.04)	7.00 (.87)	6.27 (2.65)

Table 3 Simple regression analysis: Polish sign language skills (PJM RST scores) as predictor of EF in deaf native signers.

	b	*SE b*	*β*	*t*-statistics	*p*
constant	-16.313	6.513		-2.505	.022
PJM RST	.470	.187	.510	2.513	.022

Note. N = 20; PJM RST = Polish Sign Language Receptive Skills Test.