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ARTICLE

Language and executive function relationships in the real world: insights from deafness

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Abstract

Executive functions (EFs) in both regulatory and meta-cognitive contexts are important for a wide variety of children's daily activities, including play and learning. Despite the growing literature supporting the relationship between EF and language, few studies have focused on these links during everyday behaviours. Data were collected on 208 children from 6 to 12 years old of whom 89 were deaf children (55% female; *M* = 8;8; *SD* = 1;9) and 119 were typically hearing children (56% female, *M* = 8;9; *SD* = 1;5). Parents completed two inventories: to assess EFs and language proficiency. Parents of deaf children reported greater difficulties with EFs in daily activities than those of hearing children. Correlation analysis between EFs and language showed significant levels only in the deaf group, especially in relation to meta-cognitive EFs. The results are discussed in terms of the role of early parent–child interaction and the relevance of EFs for everyday conversational situations.

Keywords: deafness; every-day functions; executive functions; interaction; language

1. Introduction

The relationship between language and wider cognitive abilities is of great interest in developmental psychology (D'souza et al., 2017; Nip et al., 2011). The origins of this link are in place by the first months of life when listening to language can assist object categorization (Perszyk & Waxman, 2018). From 12 months, infants begin to establish relations between language and abstract representations (Carey, 2009; Perszyk & Waxman, 2018) and in the next few years language begins to organize into three interrelated components: content (semantics and vocabulary); form (phonology, morphology syntax) and language use (pragmatics, Bloom & Lahey, 1978). In addition to these three components, language reference and cohesion are essential when communication requires symbols to refer to information beyond the immediate context or relations between utterances, respectively (Bebko & McKinnon, 1998). The current study focuses on the link between language and the executive function (EF) system. This link not only illuminates how children use their growing cognitive abilities to support their language learning, but also illustrates how the language system itself can be co-opted for cognitive reasoning tasks that require EFs. One scenario, which can shed light on this relationship, is when children experience delays in language development, for example, in the context of deaf children with hearing versus deaf parents. It is possible EF might help compensate for difficulties, or conversely could be affected by poor language.

In the rest of the paper, we briefly describe the EF system and then explain why we are interested in exploring the relationship between EF and language in both typically developing and deaf children who have variable language development. To do this, we split EF into two main types of abilities: meta-cognitive and behavioural regulation – and then empirically ask what the relationship is between these EFs and language.

2. Executive functions

The EF system comprises a set of top-down processes involved in coordinating and manipulating information, as well as controlling thoughts, behaviours and emotions (Zelazo & Carlson, 2012). EFs are required to solve a novel task, or plan a sequence of actions, for example, a child thinking what to put in a bag for a school trip the next day (Diamond, 2012). Different models exist for how the EF components work together (Miller et al., 2012; Usai et al., 2014; Wiebe et al., 2011). Most models (Diamond, 2013; Miyake & Friedman, 2012) include three areas: the resistance to interference (inhibition); the ability to flexibly shift from one area of focus to another (cognitive flexibility) and the ability to hold and manipulate information (working memory). It has been suggested that these three EFs underlie other executive abilities such as planning and cognitive fluency. In the model used in the current research, Gioia et al. (2000) defined eight clinical scales for children, which were inhibition, shifting, emotional control, initiation, working memory, planning, organization of materials and monitoring. Three of these scales form the Behaviour Regulation Index (inhibition, shifting and emotional control), while the Meta-cognition Index includes five subdomains (initiation, working memory, planning organization of materials and monitoring). All these subdomains are interrelated during everyday behaviour such as when a child gets their school bag ready for the next day. EFs in the Gioia et al. (2000) and Zelazo and Müller (2002) model adopts a multifactorial approach that integrates cognitive and emotional processes.

Based on these models, Brock et al. (2009) proposed two sets of interrelated but distinguishable processes: behavioural regulation (hot) components of EF (e.g., inhibition or regulation of emotion) and meta-cognitive (cool) components (e.g., working memory or planning). Experimental tasks such as the Wisconsin Card Sorting Test or Stroop are considered meta-cognition tasks since they lack an emotional component. In contrast, the assessment of behavioural regulation components involves more motivational contexts (e.g., delay of gratification tasks; Zelazo & Carlson, 2012). Using these concepts with a large group of kindergarteners, Brock et al. (2009) found cool EF predicted maths achievement and learning-related classroom behaviours.

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The development of the EF system takes place throughout childhood, with emerging abilities in regulation in the first year and continuing refinements of meta-cognitive control in adolescence and young adulthood (Munakata et al., 2012). Deficits in EF can negatively affect children's participation in many areas of social and academic activities (Rosenberg, 2014). Developmental studies show that while behavioural regulation and meta-cognition components are not clearly dissociable during infancy (Peterson & Welsh, 2014), they develop rapidly during the preschool years when prefrontal regions undergo considerable growth (Carlson & Wang, 2007; Hongwanishkul et al., 2005; Kerr & Zelazo, 2004). Inhibition is one of the most extensively studied EF skills in relation to development. Basic inhibitory control emerges in the first year of life and continues to develop rapidly throughout infancy and preschool years (Diamond, 2002; Gandolfi et al., 2014). This early development enables toddlers to regulate their behaviour in the face of external demands and challenges of conflict, delay and compliance (Kochanska & Aksan, 2006; Kopp, 2002). However, inhibitory skills are characterised by great interpersonal variation and early inhibitory development is very diverse (Wolfe & Bell, 2007). More complex meta-cognitive skills, such as planning, develop beyond infancy throughout childhood and adolescence (Best et al., 2009; Best & Miller, 2010). From middle childhood and adolescence onwards, a distinction between behavioural regulation and meta-cognition components seems more compelling, with studies suggesting different developmental trajectories (Fernández García et al., 2021; Peterson & Welsh, 2014). It may be the case that the EFs used for regulation, are more strongly associated with early social skills and interaction behaviours (Fernández García et al., 2021; Tsermentseli & Poland, 2016). From 6 to 12 years old, children use EFs to acquire and consolidate conceptual or social skills (Brocki & Bohlin, 2010; Eccles, 1999; Fernández García et al., 2021). Meta-cognitive EFs are more significantly related to later complex language comprehension and academic achievement (Hooper et al., 2004; Lensing & Elsner, 2018).

There is also a growing literature looking at how early experiences influence EF development (Lewis et al., 2009; Pascual et al., 2019; Robson et al., 2020). For example, early parental interaction with infants at 2 years of age can facilitate the regulation of emotional regulation (Hughes & Ensor, 2009). Individual differences in this type of maternal scaffolding predicted children's growing abilities to hold things in mind or inhibit impulse-driven responses 2 years later. Hughes et al. (2014) point out that these early EF skills affect children's ability to engage in social interactions such as early pretend play and enable infants to benefit from conversational environments. Children's early family context and interaction, which supports self-regulation, have been identified as important factors in explaining variability in EF development (Carlson, 2003; Shonkoff & Phillips, 2000). This is particularly important in instances where early interaction is disrupted, for example, in neonatal deafness (Morgan et al., 2021; Rieffe, 2012; Thompson & Steinbeis, 2020).

2.1. How do EF and language relate during development?

Despite a rich body of research that has examined the relationship between EF skills and language, the nature of this developmental relationship is still unclear (Gandolfi & Viterbori, 2020; Slot & von Suchodoletz, 2018; Tonér & Gerholm, 2021). Some studies propose a model whereby EF is a driver of language

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development in typical (Baddeley, 2003; Gandolfi & Viterbori, 2020; Traverso et al., 2022; Verhagen & Leseman, 2016) and atypical groups (Blom & Boerma, 2020; Pellicano, 2010). Gandolfi and Viterbori (2020) showed that early inhibition control in typically developing 2–3-year olds predicted future language outcomes in receptive grammar. EF skills may also contribute more than general intelligence in the language use scores of preschool children by helping them control their assertiveness and respond in socially appropriate ways (Blain-Brière et al., 2014). EF skills can facilitate language development by enabling children to focus attention, handle multiple sources of information simultaneously, consolidate meaning, monitor mistakes and make decisions in light of information received (Diamond, 2013; Weiland et al., 2014).

Other research argues for a model whereby language is the primary influence of EF development (Kuhn et al., 2016; Miller & Marcovitch, 2015). The role of language as a key mechanism of self-regulation was recognised by Vygotsky (1962, 1987) and Luria (1959, 1961), who argued that from around the age of 2–3 years children develop the capacity to use private or self-directed speech to self-regulate. More recently, Zelazo (2015) has extended this relationship to broader EFs in their iterative reprocessing model, whereby language has a core role both in reflection (the elaborative reprocessing of information) and in the formulation and maintenance of goal-specific rules in working memory. In other words, language, via private speech, in older children acts as a meta-cognitive tool during EF tasks (Müller et al., 2004). In the few existing longitudinal studies looking at this question, early language appears to predict later self-regulation skills and EF in typically developing children (Blom & Boerma, 2020; Kuhn et al., 2016; Petersen et al., 2014) more than the other way around.

Finally, other studies suggest a bidirectional relation (Bohlmann et al., 2015; Romeo et al., 2022; Slot & von Suchodoletz, 2018). Although language and EF are likely to be at least partially bi-directionally related during development, a model that identifies which is the stronger influence would be useful both theoretically and clinically. Notably, none of the studies cited above have considered the distinction between behavioural regulation and meta-cognition EF and language development. Finally, some of the mixed findings in the literature may be due to different researchers using different measures of EF and language ability, making clear conclusions difficult to interpret.

2.2. Measuring EF

Two primary approaches exist to measure EF competence in childhood: experimental tasks and questionnaires or inventories. Historically, the study of EF has been addressed through neuropsychological tests in adults under relatively decontextualized, non-emotional and analytical testing conditions (Peterson & Welsh, 2014). Turning to assessments of children, many previous studies (Elliott, 2003; Funahashi, 2001) use experimental tasks of language and EF rather than assessments of how these abilities work in real life scenarios. Experimental tasks (e.g., Stroop) are less related to real-world scenarios (Guare, 2014) and normally take place in laboratory-based settings or in quiet environments for minimizing distractions. Also, the examiner tests the participant individually in non-dynamic and non-emotional charged contexts. This means children are usually evaluated in a context that is removed from the real world such as the home or classroom settings.

In contrast, inventories such as the Behavioural Rating Inventory of EF (BRIEF: Gioia et al., 2000) measure EF capabilities in real scenarios (e.g., does your child have difficulties waiting in line at school?) and as such may have more ecological validity. The BRIEF also has cut-offs for clinically significant EF difficulties which can identify children at risk and provide information for which behaviours can be targeted to therapists and educators (McCoy, 2019). Despite the BRIEF being designed to complement experimental tasks, they often do not correlate well with each other. This suggests that the two approaches (experimental vs. inventories) may be assessing different aspects of the same construct (Isquith et al., 2013; Toplak et al., 2013). One premise relevant to the present study is that language and EF are both multidimensional constructs. However, to date, research on the language and EF developmental relationship has focused narrowly on children's knowledge of language forms (i.e., words or grammar) rather than how language is used in different communicative situations (Gandolfi & Viterbori, 2020; Newbury et al., 2016; Usai et al., 2020; Verhagen & Leseman, 2016; Yuile & Sabbagh, 2021).

A weakness in EF coincides in many populations with language and communication difficulties (Bishop et al., 2014). A range of factors in early childhood, such as neurobiological disorder or environmental restrictions to language access, can disrupt the development of language and EF skills. This is particularly relevant in the case of congenital deafness.

2.3. EFs and deafness

Deafness provides a unique lens for understanding the relationship between EF and language because in this case, language difficulties are usually caused by sensory rather than cognitive impairments. Research involving deaf children with hearing parents has documented EF difficulties both in the case of experimental tasks (Botting et al., 2017; Jones et al., 2020; Kronenberger et al., 2014b) and inventories (Beer et al., 2014; Hintermair, 2013; Kronenberger et al., 2014a). There are some inconsistencies reported across these studies potentially because of different methods of assessing EF and language or because studies conflated both behavioural regulation and meta-cognition EF tasks. For example, Figueroa et al. (2022) found no significant differences between a deaf group with cochlear implant and a hearing control group on experimental EF tasks, while other authors found difficulties with meta-cognition and behavioural regulation skills (Kronenberger et al., 2020). A small number of studies comparing deaf children with deaf parents (native signers) finds comparable performance on EF measures with hearing peers, strengthening the proposed link between early communication and language experience and typical development of EFs (Goodwin et al., 2022; Hall et al., 2017, 2018; Marshall et al., 2015).

Those studies using the BRIEF (Beer et al., 2011, 2014; Hintermair, 2013; Kronenberger et al., 2014a; Kronenberger et al., 2020) suggest EF problems at different developmental stages and with different aspects of EF in the questionnaires. Beer et al. (2014) and more recently Blank and Holt (2022) document that hearing parents of deaf toddlers reported greater difficulty in meta-cognitive skills such as working memory than parents of a matched hearing group. Parents of deaf children did not report greater difficulty in behavioural regulation skills at this age. At school age, Hintermair (2013) assessed 214 deaf children from general schools and schools for the Deaf and found that both meta-cognition and behavioural regulation skills were both significantly lower in deaf children, especially if they were enrolled in schools for the Deaf. This is consistent with Hall et al. (2018), which showed that even with cochlear implant, deaf children have greater EF difficulties than hearing children. Beer et al. (2011) conducted a study on 45 deaf children with cochlear implants. Results revealed poor behavioural regulation when compared with age norms. Thus, some studies report better behaviour regulation early on while consistent difficulties with meta-cognitive aspects, which would be consistent with a developmental explanation, while other studies report extended difficulties in both domains.

Furthermore, within the subscales of EF there are inconsistent findings with the BRIEF. Recently, McCreery and Walker (2022) examined 177 deaf and 86 hearing children on working memory, shifting and inhibition. Deaf children only exhibited difficulties in working memory. Highlighting the heterogeneity of the deaf child population across these studies, deaf parents of deaf signers reported similar EF levels to parents of hearing children (Goodwin et al., 2022; Hall et al., 2017, 2018). This finding emphasises the importance of early successful language development and interaction (Morgan et al., 2020). See Table S1 in the Supplementary Material for an overview of studies on behavioural regulation and meta-cognition studies in deaf populations.

In the literature concerning the developmental relationship between language and EF in deaf samples, the results have also been mixed. Several studies show EF growth is linked to deaf children's knowledge of vocabulary and grammar that is language influences EF rather than in the other direction (Botting et al., 2017; Figueras et al., 2008; Goodwin et al., 2022; Hall et al., 2018; Jones et al., 2020; Remine et al., 2008). Most of these studies used experimental methods to test EF. It is not clear if the influence of language over EF would be the same if measures of real EF scenarios and language were used. By comparing performance on sub-domains of the measure, we may be able to evaluate in a more nuanced way how language and EF relate to each other. The wider literature on hearing children points to a developmental progression between early and later EF abilities. Early to appear is basic behaviour regulation involving inhibition in the first year of life, which improves throughout infancy and the preschool years (Gandolfi et al., 2014). More complex meta-cognitive skills, such as planning, develop in later childhood and adolescence (Best et al., 2009; Best & Miller, 2010). In the current research on deaf children, we extend the question of how language and EF relate by examining the particular types of EF that have different developmental trajectories and language abilities with more real-world validity. The Language Proficiency Profile-2 (LPP-2: Bebko et al., 2003) measures real-world uses of language as well as forms (i.e., knowledge of vocabulary and grammar). Furthermore, the LPP-2 was originally developed and has been used with studies of deaf children's language (e.g., Sidera et al., 2020). In the current research, it is suggested that some of the ambiguity in the previous literature in how language and EF relate in deafness comes from the failure to decompose EF into behaviour regulation and metacognition. It is possible that these have different relationships with language, and this question is addressed in the current study.

In summary, it is unclear how EF and language work together in development. It is also necessary in regard to this question, to look at different components of EF, such as behaviour regulation and meta-cognition in order to ask if these are differentially affected by delayed language skills. EF development has been compared in deaf and hearing samples with neuro-psychological tasks, but less is known about how different meta-cognition and behavioural regulation components function in real-

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world scenarios (Ching et al., 2021; Guardino & Antia, 2012). The questions that guided the present study were therefore:

1. Do deaf and hearing children differ on EF behaviours as reported by the BRIEF? Based on the wider literature reviewed previously, our hypothesis is that deaf children will perform significantly poorer than hearing children.
2. Are there differences between deaf and hearing children within sub-parts of the BRIEF related to meta-cognition versus behavioural regulation? We predict meta-cognition will be more delayed than behaviour regulation EFs. This prediction is based on the wider literature, which finds that behavioural regulation emerges earlier than meta-cognition in development.
3. Does language correlate with the BRIEF? We predict, based on consideration of the literature outlined previously, that a correlation exists, but we do not predict which direction of influence will be primary. In order to explore the contribution of EF and language to development, we ask further questions connected to the specific roles of meta-cognition versus behavioural regulation and different aspects of language.

3. Methodology

3.1. Participants

A total of 208 children from the United Kingdom and Ireland took part in this study of which 89 were deaf children and 119 were typical hearing children. All children were recruited through schools. In this study, the term 'deaf' means mild to profound hearing loss (range 26–91 dB). All included children fell into these categories.

Children with professionally diagnosed additional disabilities were not included in the current study. As the two groups differed significantly in non-verbal intelligence, deaf children with a score below the 10th percentile on non-verbal intelligence were also excluded. The deaf sample averaged 8 years and 9 months of age (*SD* = 1;9; range = 6;9–11;10; expressed as "years;months") when parents completed the forms (see Table 1 and Table 2 for descriptive statistics). Analysed by ethnicity, 78% of deaf children were White British followed by 10% Asian, 5% Black and 7% from other backgrounds or where ethnicity was not reported. This is representative of the UK population. Concerning the socioeconomic background of the families, parents of deaf children worked mainly in skilled (36%) or semi-skilled jobs (36%), while a smaller percentage of them were unskilled workers (28%).

Hearing children averaged 8 years and 9 months of age (*SD* = 1;5; range = 6;0–11;11). In the hearing sample, children were White British (88%), 3% Asian, 3% Black and 5% from other backgrounds or backgrounds that were not reported. This

Table 1. Descriptive characteristics of the sample

Group	Age (years; months)	Gender (male/female)	WAIS	Parents with low-skilled jobs	Parents with further studies
Deaf group	8; 8 (1; 9)	49/40	52.3 (8.4)	28%	75%
Hearing group	8; 9 (1; 5)	67/52	53.7 (10.3)	28%	81%
p	.46	.86	.31	.86	.67

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Table 2. Audiological and linguistic characteristics of deaf group

Descriptive characteristics	Deaf group (N = 89)
Age of onset of deafness	
Prelingual (at birth)	76
Prelingual (before 2 years)	6
Perilingual (before 5 years)	7
Postlingual (after 5 years)	0
Degree of hearing loss	
Mild/moderate	10
Severe	25
Profound	54
Cochlear implants	32
Unilateral	30
Bilateral	9
No cochlear implant	57
Age of cochlear implantation	
≤2	9
>2 ≤ 4	18
>4	5
N/a	57
Hearing aids	
Yes	53
No	27
Sometimes/not any more	9
Children preferred language of communication	
British Sign Language (BSL)	14
Sign Supported English	5
Both BSL and Sign Supported English	7
Both BSL and Spoken English	23
Spoken English	40
Deaf parents	15

is representative of the U.K. population. Parents of hearing children worked in skilled jobs (43%) followed by semi-skilled (29%) and unskilled jobs (28%). To control for socioeconomic background, hearing children were enrolled at the same schools as deaf participants. Participants attended several different schools in urban (58%) and rural (42%) settings. In order to obtain a representative sample, deaf children studied in mainstream educational settings with specialist classrooms/units (37%) or without such resources (37%) and 25% were enrolled in deaf only specialist schools.

The deaf group was divided in two groups according to their language characteristics: deaf children who used British Sign Language or Sign Supported English (BSL/SSE; n = 49, M_{age} = 8;10, SD = 1;9) and deaf children who used spoken English (n = 40, M_{age} = 8;6, SD = 1;8). The BSL/SSE group consisted of 49 children of which 19% were native signers. Most of the BSL/SSE children had profound hearing loss (69%) and only a small proportion had severe (17%) or mild/moderate hearing loss (14%). Regarding deaf children who used spoken English, 42% of them had severe hearing loss followed by 38% with profound hearing loss and 20% with mild/moderate hearing loss (see Table S2 in the Supplementary Material).

We then compared the specific group of deaf children with deaf parents. The results showed a significant effect of early language exposure in language and EF scores. We thus report this comparison in Section 4.

3.2. Measures

3.2.1. Executive functions

The BRIEF questionnaire (Gioia et al., 2000) was filled out by parents. The BRIEF is designed for school-aged children, and has been widely used with children with language difficulties such as deaf children (Hall et al., 2018; Hintermair, 2013; Kronenberger et al., 2014a). Through this checklist, parents indicate how often (never, sometimes or often) a child displays various behaviours over the past 6 months. The BRIEF contains 86 items divided into eight clinical scales. Five scales (Initiate, Plan/Organize, Working memory, Organization of materials and Monitor) form the Meta-cognition Index. Three scales (Inhibit, Shift and Emotional control) comprise the Behavioural Regulation Index. Both the Behaviour Regulation Index (raw scores range 28–84) and the Meta-cognition Index (raw scores range 44–132) form the Global Executive Composite (raw scores range 72–216). Internal consistency of the BRIEF is excellent for the Meta-cognition Index (Cronbach's alpha of. 96 for clinical populations and. 94 for typical populations), the Behavioural Regulation Index (Cronbach's alpha of. 96 for clinical populations and typical populations) and the Global Executive Composite (Cronbach's alpha of. 98 for clinical populations and. 97 for typical populations). Forms were scored according to the instructions in the manual and raw scores were converted into *T*-scores which higher values indicate poor child functioning. A *T*-score of 50 represents the mean of the *T*-score distribution, while a *T*-score of 65 represents the point 1.5 standard deviation above the mean. *T*-scores at or above 65 are considered as having potential clinical significance (Gioia et al., 2000). *T*-scores range between 30 and 101.

3.2.2. Language

The LPP-2 was filled out by parents. It is a rating scale developed to assess language and communication skills across all communication modes (such as sign language, gestures and/or oral language). Thus, the LPP-2 was designed specifically for use with deaf children with consideration of the complexity and heterogeneity of their expressive communication styles (Bebko et al., 2003). Despite this, the LPP-2 can also be used in hearing children demonstrating good construct and acceptable concurrent validity with other language measures. The LPP-2 is based on Bloom and Lahey's (1978) model of language development and thus assesses five domains of children's expressive language and communication skills: content, form, use, cohesion and reference. The LPP-2 contains 56 items, and each item was scored as follows: two points are given if the child is either past that skill level or currently has the skill, one point when the skill is currently emerging and zero point if either the child does not acquire the skill or the parent does not know the level of mastery the child has achieved. Up to 18 points can be obtained for form, 24 for content, 22 for reference, 22 for cohesion and 26 for use (total maximum score is 112 points). Both the BRIEF and LPP questionnaires were completed 1 week after parental consent was given to join the study, at the same time as the experimenter collected the non-verbal IQ data.

3.2.3. Non-verbal intelligence

The matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) was administered as a control measure for nonverbal cognitive ability. The child is presented with a pattern with a missing section and

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must select the correct response from five choices. After 4/5 successive incorrect answers, the test is terminated. This subtest yields a *T*-score with a mean of 50 and a standard deviation of 10 (*T*-scores range 20–80). The matrix reasoning has been shown to demonstrate good internal consistency (Cronbach's alpha reliability of. 87).

3.3. Procedure

The study was approved by the UCL Research Ethics Committee. Informed written consent was obtained from all parents. Children gave verbal consent at the time of testing and were informed that they could opt out at any time. Researchers recommended that parents complete LPP-2 and BRIEF forms in a quiet setting within a week of receiving them. The completion of the forms took 15 min each. Once forms were completed and returned by one of the parents, children were evaluated with the WASI in a quiet room at school or at the child's home.

3.4. Analysis

Statistical analyses were conducted using IBM SPSS 26.0. First, descriptive statistics were computed and then group differences were analysed using Welch's *t* tests as the deaf and the hearing group had unequal variances (data are available at https://osf.io/srauf/?view_only=f41142d74a844c0ba35b1920cbc5c8a0). The relative risks of clinically significant scores of deaf participants relative to hearing controls and the expected rates according to a normal distribution are reported. For the latter, a hypothetical sample of the same size as the deaf groups and subgroups was created. The clinically significant scores expected according to the normal distribution were calculated by multiplying the sample size of each group by 6.7% and the resulting values were rounded to the nearest integer.

Pearson's correlations were employed, and the effect sizes were set at. 10 (small effect),. 30 (medium effect) and. 50 (large effect). The statistical significance was set at $p < .05$. In addition, we applied the Benjamini–Hochberg procedure with a false discovery rate of 0.05 to reduce the familywise error rate. Multicollinearity was not present as tolerance values ranged between. 50 and. 98, and all variance inflation factors ranged between 1.00 and 2.00.

3.4.1. Subdivision of the deaf group by language use

There was a possibility that the group of DHH children were too heterogeneous in respect of language and EF skills to be treated as one group. Therefore, an analysis was carried out by comparing subgroups of deaf children. The group of deaf children was divided according to their linguistic characteristics: deaf children who used BSL/SSE and deaf children who used spoken English. Means, standard deviations and statistical differences are shown in Table S2 in the Supplementary Material.

The analysis of subgroups of deaf children showed that there were no significant differences in the global BRIEF score. Regarding the rates of elevated scores, both subgroups of deaf children were at significantly greater risk relative to the hearing group and the normal distribution (BSL/SSE children: RR vs. hearing group = 4.34; 95% CI = 1.95, 9.67 and RR vs. normal distribution = 4.67; 95% CI = 1.43, 15.20; spoken English children: RR vs. hearing group = 5.58; 95% CI = 2.56, 12.17 and RR vs. normal distribution = 3.94; 95% CI = 1.18, 13.11). Furthermore, the analysis of sub-parts of BRIEF revealed no differences in behavioural regulation or meta-cognition scores. Relative risk ratios of behavioural regulation index indicated again that both subgroups of deaf children were at significantly greater risk of having elevated scores (BSL/SSE children: RR vs. hearing group = 2.67; 95% CI = 1.36, 5.25 and RR vs. normal distribution = 4.67; 95% CI = 1.43, 15.20; spoken English children: RR vs. hearing group = 2.98; 95% CI = 1.51, 5.87 and RR vs. normal distribution = 4.66; 95% CI = 1.43, 15.15). All subgroups of deaf children were also at significantly greater risk of meta-cognition difficulties in comparison to the hearing group and the normal distribution (BSL/SSE children: RR vs. hearing group = 4.65; 95% CI = 2.11, 10.24 and RR versus normal distribution = 5.00; 95% CI = 1.55, 16.16; spoken English children: RR vs. hearing group = 4.09; 95% CI = 1.77, 9.45 and RR vs. normal distribution = 3.94; 95% CI = 1.18, 13.11). We subdivided the deaf group into a small number of deaf children with deaf parents and compared their language and EF scores with the hearing peers and deaf children with hearing parents. The risk ratio of deaf signers indicate that they are as likely as hearing participants to have *T*-scores at or above 65 in meta-cognition (RR vs. hearing group = 1.06; 95% CI = 0.14, 7.88 and RR vs. normal distribution = 1.00; 95% CI = 0.07, 14.45). Risk ratios in behavioural regulation and global BRIEF scores cannot be calculated because no children scored within the clinically significant range on these scales. However, those participants with late language exposure were at significantly greater risk of global EF difficulties in comparison with the hearing group and the normal distribution (RR vs. hearing group = 5.03; 95% CI = 2.39, 10.55 and RR vs. normal distribution = 8.04; 95% CI = 3.22, 20.08), as well as, behavioural regulation (RR vs. hearing group = 3.22; 95% CI = 1.77, 5.86 and RR vs. normal distribution = 1.00; 95% CI = 0.07, 14.45) and meta-cognition difficulties (RR vs. hearing group = 5.23; 95% CI = 2.50, 10.93 and RR vs. normal distribution = 8.36; 95% CI = 3.36, 20.82).

3.4.2. Subdivision the deaf group by age band

Another possibility was that age played a role in results and the sample could be divided into age groups. Additional analysis was conducted in order to study the effect of age on language and EF skills. Deaf and hearing groups were divided into three subgroups: from 6 to 7 years (young deaf group: $n = 33$, $M_{age} = 6;10$, $SD = 0;7$; young hearing group: $n = 38$, $M_{age} = 7;2$, $SD = 0;2$), from 8 to 9 years (middle-aged deaf children: $n = 33$, $M_{age} = 8;11$, $SD = 0;9$; middle-aged hearing children: $n = 59$, $M_{age} = 9;0$, $SD = 0;8$) and from 10 to 11 years (deaf pre-adolescents: $n = 23$, $M_{age} = 10;11$, $SD = 0;7$; hearing pre-adolescents: $n = 25$; $M_{age} = 10;10$, $SD = 0;7$). The analysis revealed a non-significant effect of age on language summaries, for deaf and hearing subgroups (see Table S3 in the Supplementary Material). Thus, in the following sets of analyses we do not sub-divide by age groups.

3.4.3. Missing data

The original sample included 208 children; however, some missing data were detected. Low levels of missing data occurred primarily on the language variables. The missing rates for the language dimensions ranged from 2.8 to 4.3% in the overall sample, (5.6–7.8% in the case of deaf sample and 0.8–2.5% in the case of hearing sample), while the missing data for the BRIEF variables were only 0.5% (1.1% in the deaf sample and no missing data in the hearing sample).

4. Results

4.1. Preliminary analysis

Descriptive statistics and group differences in language are depicted in Table 3 and show that hearing children outperformed deaf children on LPP scores. Group differences were found in each language domain, and they favoured the hearing children.

Research question 1a: Do deaf and hearing children differ on EF behaviours as reported by the BRIEF?

According to BRIEF global scores, deaf children showed significantly lower EF capabilities. Following previous studies, we analysed clinically significant scores in the deaf group compared to the hearing group, that is, scores at or above 65. Table 4 reports the percentage of children in each group that fell within the clinically significant range on each BRIEF index and the relative risk ratios for the deaf group. When the confidence intervals are above one, risk ratios are considered significant. Deaf children were 4.77 times more likely than those with typical hearing to be at clinical risk for EF capabilities. When the relative risk was calculated according to the normal distribution, the relative risk for EF was also greater in the deaf group.

We also analysed the effect of early language experience by comparing deaf native signers and the hearing group with those deaf participants whose language (signed or spoken) was not acquired early (see Table S4 in the Supplementary Material). The results showed a significant effect of early language exposure in language and EF scores. Post hoc comparisons revealed that both the hearing group and the native signers group obtained similar language scores, while the deaf participants with late language exposure exhibited more language difficulties than both hearing ($p < .001$) and deaf signers group ($p = .005$).

Table 3. Means and standard deviations of BRIEF and LPP-2 by group and Welch's *t*-tests between both groups

		Deaf	Hearing	Welch's *t*-test	
Scales	Subscale/index	*M (SD)*	*M (SD)*	*t (df)*	*p*
BR	Inhibit	54.9 (12.3)	49.4 (9.8)	3.42 (162.2)	.001
BR	Shift	56.4 (12.2)	48.4 (9.9)	5.06 (164.3)	<.001
BR	Emotion control	55.8 (12.9)	49.4 (11.1)	3.70 (170.8)	<.001
MI	Initiate	53.5 (11.1)	48.5 (9.2)	3.36 (162.6)	.001
MI	Working memory	55.0 (10.9)	48.8 (9.1)	4.36 (166.0)	<.001
MI	Plan/organize	55.0 (11.2)	49.0 (10.3)	3.95 (178.5)	<.001
MI	Organization of materials	50.8 (11.6)	50.6 (10.1)	0.85 (172.3)	.932
MI	Monitor	54.2 (12.4)	47.9 (10.3)	3.88 (166.9)	<.001
Summary	BRI	56.4 (12.8)	49.0 (10.9)	4.37 (169.3)	<.001
Summary	MI	56.4 (13.3)	49.4 (10.1)	4.31 (154.9)	<.001
Summary	GEC	54.9 (12.3)	49.2 (10.9)	4.30 (177.6)	<.001
LPP	Form	16.3 (2.4)	17.9 (0.5)	−5.64 (89.5)	<.001
LPP	Content	20.9 (3.5)	23.6 (1.3)	−5.78 (103.6)	<.001
LPP	Reference	18.2 (3.7)	21.3 (1.4)	−6.75 (102.3)	<.001
LPP	Cohesion	16.1 (5.3)	20.8 (2.7)	−6.32 (115.48)	<.001
LPP	Use	21.5 (4.3)	24.8 (2.2)	−5.94 (121.8)	<.001
Summary	Total LPP-2	93.0 (16.9)	108.4 (6.2)	−7.21 (101.4)	<.001

Note: BRIEF and LPP-2 variables are expressed in *T*-scores and raw scores, respectively. Higher *T*-scores on BRIEF reflect increased incidence of problematic behaviour, while higher scores on LPP-2 reflect better language skills. Abbreviations: BRI, Behavioural Regulation Index; GEC, Global Executive Composite; LPP, Language Proficiency Profile; MI, Meta-cognition Index.

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Table 4. Relative risk for each scale and subscale of the BRIEF

Scales	Subscale/index	Percent clinically significant scores (number)		Relative risk [95% confidence level]	Relative risk [95% confidence level]
		Deaf	Hearing	Deaf vs. hearing	Deaf vs. normal distribution
BR	Inhibit	23% (20)	8% (9)	3.01 [1.44–6.28]	3.33 [1.41–7.90]
BR	Shift	28% (23)	8% (10)	3.11 [1.56–6.20]	3.83 [1.64–8.96]
BR	Emotion control	25% (22)	11% (13)	2.29 [1.22–4.29]	3.67 [1.56–8.60]
MI	Initiate	22% (19)	5% (6)	4.28 [1.78–10.28]	3.17 [1.33–7.55]
MI	Working memory	23% (20)	8% (9)	3.01 [1.44–6.28]	3.33 [1.41–7.90]
MI	Plan/organize	19% (17)	8% (10)	2.59 [1.25–5.37]	2.83 [1.17–6.85]
MI	Organization of materials	19% (17)	13% (16)	1.53 [0.83–2.80]	2.83 [1.17–6.85]
MI	Monitor	23% (20)	6% (7)	3.86 [1.71–8.73]	3.33 [1.41–7.90]
Summary	BRI	30% (26)	11% (13)	3.05 [1.67–5.56]	4.33 [1.88–10.01]
Summary	MI	31% (27)	7% (8)	5.15 [2.46–10.74]	4.50 [1.95–10.36]
Summary	GEC	28% (25)	7% (8)	4.77 [2.27–10.02]	4.17 [1.80–9.66]

Note: BRI, Behavioural Regulation Index; GEC, Global Executive Composite; LPP, Language Proficient Profile; MI, Meta-cognition Index.

Research question 1b: Are there differences between deaf and hearing children within sub-parts of the BRIEF related to meta-cognition versus behavioural regulation?

Deaf children displayed more difficulties than hearing children in both behavioural regulation and meta-cognition sub-parts. However, in one area of meta-cognition: the organization of materials, there was no difference between groups (see Table 4).

Clinical risk on EF items was very low in the hearing sample. The relative risk for EF was greater in the deaf group (relative risk of 3.05 for behavioural regulation EF and 5.15 for meta-cognition EF). The deaf group obtained the highest risk ratios in the meta-cognition subscales of 'monitor' and 'initiate' when compared with the hearing group. However, when the scores of the deaf group are compared with the normal distribution, the highest risk ratios were found in the behavioural regulation subscales.

When deaf native signers and the other deaf children were compared (see Table S4 in the Supplementary Material), the deaf participants with late language exposure obtained poorer scores in behavioural regulation and global BRIEF than hearing (behavioural regulation: $p < .001$; global BRIEF: $p < .001$) and deaf signers group (behavioural regulation: $p = .001$; global BRIEF: $p = .006$). In the case of meta-cognition, the hearing group and the deaf native signers group obtained a similar performance. Deaf children with late language exposure had higher scores for EF problems than the hearing group ($p < .001$).

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Research question 2a: Does global language score on the LPP correlate with global EF scores on the BRIEF?

Pearson's correlations were performed in each group (see Table S5 in the Supplementary Material for r values). Given the exploratory nature of the correlation analyses, Table S5 in the Supplementary Material indicates both uncorrected statistically significant correlations and ones that were robust to the Benjamini–Hochberg procedure. The deaf group showed significant correlations between global BRIEF scores and total LPP-2 scores, while no significant correlations were found in the hearing group. When the Benjamini–Hochberg procedure was applied, no significant correlations were found between global BRIEF and total LPP-2 scores.

Research question 2b: Are there associations between language and sub-parts of the BRIEF?

The correlations between total LPP-2 scores and behavioural regulation and meta-cognition showed a different pattern between groups. Meta-cognition was linked to language in deaf children, while no correlations were found between sub-parts of the BRIEF and language for hearing children (see Table S5 in the Supplementary Material). This correlation in the deaf group remained significant after the Benjamini–Hochberg adjustment.

Research question 2c: Are there associations between language domains and the BRIEF?

In the deaf group, the results showed that the LPP-2 variable 'language use' was closely linked to meta-cognition, even after Benjamini–Hochberg adjustment (see Table S5 in the Supplementary Material). Turning to the hearing group, we only observed significant correlations between the global BRIEF scores and LPP-2 for language reference ($r = -.22$; $p = .018$). Language reference was also significantly related with the behavioural regulation EF index ($r = -.25$; $p = .007$). These significant correlations in the hearing group also remained significant after Benjamini–Hochberg adjustment.

5. Discussion

This study investigated the relationship between EF and language skills in a large sample of deaf and hearing children from 6 to 12 years old. The results revealed that when examining EF and language with parent-report tools, we find different relationships between the various EF subdomains for deaf than we find for hearing children of the same age. In the deaf native signers, we find protected EF and language development. Hearing parents of deaf children reported greater difficulties with EF in daily activities than parents of hearing children. Moreover, correlation analyses showed significant associations between EF and language only for the deaf group. In the case of the hearing group, this only occurred between EF and one specific LPP subscale: the control of reference. We had a small group of deaf children with deaf parents who typically would have better language and EF abilities (Goodwin et al., 2022; Hall et al., 2017, 2018; Marshall et al., 2015) and this was borne out in our results. We discuss these findings in more detail in particular how this is relevant to the ongoing debates about the relationship between EF and language in deaf children in the following sections.

The first set of research questions concerned a comparison of EF abilities as measured by the BRIEF. As a group (all deaf children together), the deaf children

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show more than four times as many clinical concerns for EF development than hearing children of the same age. In a novel step, we separated out the BRIEF items into behavioural regulation and meta-cognitive abilities (Brock et al., 2009). There is some suggestion that typically developing children develop inhibition or regulation of emotion before the meta-cognitive components of working memory or planning (Best & Miller, 2010; Kochanska & Aksan, 2006). There is mixed information on this topic in previous studies of deaf children, as we reviewed in Table S1 in the Supplementary Material. When we separated out different domains of EF from the BRIEF data, we observed heightened concerns for the deaf group with hearing parents on meta-cognition. Meta-cognition EF items in the BRIEF involve behaviours that demand concentration to plan a sequence of actions during problem-solving (e.g., a child planning what to put in a bag for a school trip tomorrow; Diamond, 2012). These meta-cognition skills typically develop later in childhood and are required for the academic development of children (Fernández García et al., 2021) for example to solve abstract problems with minimal affective or motivational content. There are many implications of this heightened difficulty with meta-cognition for the continued academic gap (especially in literacy and numeracy) seen between deaf and hearing children; Marschark & Knoors, 2020).

Turning to the relationship between EF and language. The LPP-2 language scores were correlated with global EF level but only in the deaf group. Both behaviour-regulation and meta-cognitive sub-components of EF were correlated with language in the deaf children. While some research observes a link between language and EF in young (pre-school) hearing children (Blain-Brière et al., 2014; Gandolfi & Viterbori, 2020), our study suggests the link between language and EF continues to exist in much older deaf children. Studies of the development of meta-cognition propose an extended period of growth (Luria, 1959, 1961; Vygotsky, 1962, 1987). Recently, Zelazo (2015) has proposed that language, via private speech, in older children acts as a meta-cognitive tool during EF tasks (Müller et al., 2004). In a few studies of this question in hearing children with language delays, meta-cognition was also affected by difficulties with implementing private speech (Lidstone et al., 2011; Vissers et al., 2020).

The proposal here is that deaf children with delayed language are also more prone to low scores on measures of both behaviour regulation and more so meta-cognition. This is because of how these EFs are related to early social-communication in development (Gandolfi et al., 2014; Kuhn et al., 2016; Miller & Marcovitch, 2015; Morgan et al., 2020). At 2 years of age, children begin to use private speech to self-regulate through intensive social and emotional interactions with parents, so language becomes a key mechanism of self-regulation (Luria, 1959, 1961; Vygotsky, 1962, 1987). We now return to the discussion of family environment and how this influences the growth of EF (Hughes & Ensor, 2009; Peterson & Welsh, 2014; Wolfe & Bell, 2007). In the early years parent–child, as well as, peer interactions provide opportunities to observe and extract models of appropriate behaviours and participate in conversational exchanges (Jung & Short, 2002). Furthermore, parents modulate children's behaviour and help them to regulate their emotions (Alamos et al., 2022). The behavioural regulation aspects of EF are thus functioning before typically developing hearing children reach 6 years old and in deaf children with deaf parents. The deaf children with deaf parents had early and accessible communicative experiences and thus develop both behaviour regulation and meta-cognitive abilities appropriately. In contrast, the vast majority of deaf infants grow up in hearing

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families who typically use spoken language that the child finds difficult to follow. Thus, they miss out on many of these daily conversations involving emotional and behaviour regulation (Rieffe, 2012). In terms of the establishment of behavioural regulation, early social interactions may act as a type of 'experience-expectant' input for later EFs and language development (Thompson & Steinbeis, 2020).

Turning to the meta-cognitive aspects of the BRIEF, language, via private speech in older hearing children acts as a meta-cognitive tool during EF tasks (Müller et al., 2004). If deaf children are still in the process of establishing self-regulation this may delay the connection of private speech during meta-cognitive tasks (Zelazo, 2015). On our LPP-2 measure, this is seen most clearly in the *use* items.

We were interested in specific language abilities and whether these were related to EF in different ways. We found that language *use* and language *form* were associated with meta-cognition EF skills in deaf children and the control of reference (e.g., the planning of narrative language) in hearing children, respectively. In terms of language use, those deaf children with better meta-cognition EF were reported on the LPP-2 measure to engage and maintain a conversation for longer and in more diverse contexts. Language *use* is linked to EF through the need to hold in mind and update linguistic and contextual information and to think ahead to what will be communicated next (Matthews et al., 2018). Therefore, using more advanced language relies on strong EFs especially enabling children to focus attention, handle multiple sources of information simultaneously and analyse meaning in complex language (Diamond, 2013; Weiland et al., 2014).

The second part of the explanation for an EF influence over language in deaf children may relate to how we measured EF and language in the current study compared to previous experimental methods. Using measures of the real-life implementation of EF and language use, we have uncovered a different characterisation of the EF-language relationship than previously reported in the literature (Botting et al., 2017; Figueras et al., 2008; Jones et al., 2020). In addition, the LPP is a broader assessment of language and reflects communication and social interaction related to daily conversations and pragmatics. Thus, EF ability is more salient in real-world scenarios involving deaf children having to follow and use language appropriately. There have been similar reports of this direction of association in deaf children based on questionnaire measures (Hintermair, 2013).

5.1. Limitations

An obvious limitation of this study is that all the analyses reported were based on cross-sectional data. The current study assessed EF and language skills with parent-reports. Despite the ecological validity stemming from parent-reports, these measurements are more susceptible to bias than experimental EF tasks (Robson et al., 2020). For example, parents who know their children have language difficulties might be more prone to rate their child as having poorer regulation or vice versa. Furthermore, the LPP-2 has particular strengths and weaknesses which should be considered. It is ecologically valid, feasibly completed by non-specialists (e.g., hearing parents), and can be uniformly applied across all languages and modalities. However, its psychometric properties are not well-established and it also lacks age-based norms. Our study did not find an effect of age on language scores. However, this does not imply age is not important for language development. Taking a broader view than just vocabulary, the relationship between language and age is complex. The LPP has a high pragmatic load, which may contribute to a lower-than-expected scores in the deaf sample. In addition, at a certain age, the LPP may not be sensitive to change and thus reaching the ceiling effect with the hearing sample. Also, while, the LPP-2 has good construct validity and marginally acceptable concurrent validity with other language tests, no information about reliability is available. Nonetheless, the EF and LPP-2 have been shown to be an appropriately sensitive tool for clinical and research studies in children (Bebko et al., 2003; Hintermair, 2013). Lastly, while we argue early social-interaction explains the EF-language relationship, future research needs to directly measure early communicative experiences in deaf children and follow longitudinally the impacts of early EF variability on future language components.

5.2. Conclusions and implications

The current study is important since, given the heterogeneity and representativeness of the sample, it reinforces the previous literature and highlights the difficulties deaf children have in areas of regulation and meta-cognition in real-life situations. The finding of EF delays in deaf children is in line with previous studies based on parent-report questionnaires (e.g., Hintermair, 2013; Kronenberger et al., 2014a) and experimental tasks (Botting et al., 2017; Kronenberger et al., 2014b). Deaf children are more than four times more likely to have a clinical concern for EF development for both behavioural regulation and the majority of meta-cognitive aspects of EF. Meta-cognition EF components and language are more closely related for deaf children. Our results have implications for clinical practice. First, in order to see strengths and weaknesses better, it is necessary to evaluate EF and language in multidimensional ways (Fernández García et al., 2021; Shokrkon & Nicoladis, 2022). All children depend on good meta-cognition EF and language to enter into essential learning activities in a school environment and to facilitate coordinated play (Yogman et al., 2018). Thus, difficulties in EF have been related to a wide range of effects in both the home and school environment (Ching et al., 2021; Snyder et al., 2004). The real-world assessment of EF and language carried out in the present study may assist clinical and educational specialists when guiding parents in intervention programs in which the context is considered. These interventions could foster better promotion of language and EF in learning situations. Given the strong relationships between language and EF in both deaf and typically developing children, early difficulties in EF may serve as a warning sign for later difficulties in the language domain. Early assessment of these neuropsychological aspects is essential to detect and prevent difficulties in both skills, as well as to define linguistic profiles in deaf children.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/langcog.2024.10.

Data availability statement. The data that support the findings of this study are openly available through the Open Science Framework at https://osf.io/srauf/?view_only=f41142d74a844c0ba35b1920cbc5c8a0.

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Competing interest. The authors declare none.

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