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Expressive vocabulary predicts non-verbal executive function: a 2-year longitudinal study of deaf and hearing children

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Abstract

Numerous studies suggest an association between language and executive function (EF), but evidence of a developmental relationship remains inconclusive. Data were collected from 75 deaf/hard-of-hearing (DHH) children and 82 hearing age-matched controls. Children were 6-11 years old at first time of testing, and completed a battery of nonverbal EF tasks and a test of expressive vocabulary. These tasks were completed again two years later. Both groups improved their scores on all tasks over this period. DHH children performed significantly less well than hearing peers on some EF tasks and the vocabulary test at both time points. Cross-lagged panel models showed that vocabulary at Time 1 predicted change in EF scores for both DHH and hearing children but not the reverse.

Keywords: Executive function; language; deafness; longitudinal; development

Executive function (EF) represents the higher-order self-regulatory cognitive processes that allow the modulation of attention and control of behaviour to achieve a specific goal (Blair, 2016). The specific components of EF are debated (Anderson, 2002), yet it is commonly measured behaviourally as three key skills: the resistance to interference (inhibition), the ability to flexibly shift from one mental frame of focus to another (cognitive flexibility), and the ability to hold and manipulate information in the mind (working memory; Miyake et al., 2000; Zelazo, 2015). These key skills are argued to underlie other executive abilities such as planning and cognitive fluency (Miyake et al., 2000). EF is a crucial factor in both successful classroom learning (Blair & Razza, 2007) and the development of physical and mental well-being (Kusche & Cook, 1993; Miller, Barnes & Beaver, 2011). As EF is linked to so many positive outcomes for children, there is a clear rationale for identifying factors, such as language, that might facilitate its optimal development (Blair & Diamond, 2008). Although the link between EF and language is well-established (e.g., Fuhs & Day, 2011; Kuhn et al., 2016), the direction of the developmental pathways remains uncertain.

This study examines the developmental relationship between expressive vocabulary and EF in hearing and deaf/hard-of-hearing (DHH) children in the middle childhood years. The comparison of DHH and hearing children allows us to directly test the hypothesis that language, as indexed by vocabulary, is the facilitator of EF development. DHH children represent a population that has typical non-verbal cognition (as measured by standardised tests) but displays an extremely wide variation in vocabulary skills. Variation is also present in typically developing hearing children but to a far narrower degree. Expressive vocabulary is a good proxy for language more generally as it predicts a range of outcomes including other language abilities (Marchman & Fernald, 2008), literacy (Biemiller, 2003), and social and behavioural skills (Dawson & Williams, 2008). Furthermore, given grammatical differences between signed and spoken languages, expressive vocabulary is the fairest assessment of language ability that can be used with DHH children who communicate using sign and/or speech (Botting et al., 2017).

We conducted this study with a group of DHH children because of the added clarity they provide for exploring the relationship between language and EF. There are several reasons why DHH children allow us to uncover the nature of the relationship between language and EF more effectively than focusing solely on typically developing children. We describe these here in the introduction section. If differences in EF are found between DHH and hearing children, and language is found to predict these differences, then this has implications for the wider story of how EF develops via communication and language experiences. We will describe these wider implications in the discussion section.

Traditionally, the relationship between EF and language has been investigated in two ways: first using typically developing children; and more recently involving participants with language disorders. However both these populations have an inherent confound between language and cognition. In the former, language and cognition are expected to develop in parallel making it difficult to tease apart which is the driving factor developmentally. In the latter, although language is a primary difficulty (and therefore appears to afford a dissociation between language and EF), there is increasing evidence that the language impairments of these children are accompanied by co-morbid problems with EF, that are not necessarily caused by language delay but by shared neurological deficits. DHH children, on the other hand have great diversity in their language development linked to several factors including having DHH parents or early cochlear implantation. The vast majority of DHH children have language delay, because of the lack of accessible input in their environment and not because of inherent cognitive differences from the hearing comparison group (unlike other samples of children with atypical development who have been included in previous EF studies). Early access to sign language from DHH parents protects against language delay but good quality sign language input is rarely available to DHH children from birth, because 96% of DHH infants have two hearing parents; therefore, the majority of children who learn a sign language do so late (Mitchell & Karchmer, 2004; Lu, Jones & Morgan, 2016). In terms of acquisition of spoken language DHH children have experienced an absence of sound stimulation up to the point at which they began wearing hearing aids consistently and later had cochlear implants fitted. Generally DHH children experience impoverished early language and communicative stimulation and as a group, their reduced exposure to audition and language leads to weak spoken language development (Houston, et al., 2012; Nicholas & Geers, 2013). Speech perception outcomes are similar for DHH children implanted before 13 months and those implanted between 16 and 23 months, but vocabulary outcomes are substantially worse for children implanted during the latter window. Grammar outcomes in late-implanted children are similarly poor (Harris, 2010). So while DHH children experience delays in comparison to hearing children in language comprehension, grammar, and vocabulary (Chilosi et al., 2013; Geers, Nicholas, & Sedey, 2003) and syntax and verb morphology (Chilosi et al., 2013; Le Normand & Moreno-Torres, 2014) which are similar to children with language disorder, the aetiology of these delays are different. Further, DHH children's development is characterized by slower and more variable language trajectories (Geers, Nicholas, Tobey, & Davidson, 2016; Niparko et al., 2010).

Both of these factors (i.e., reduced auditory experience leading to limited accessible input in their environment and low quality sign language input) lead to delays in vocabulary development. We hypothesise that this vocabulary delay will not only impact on DHH children's language development but will also have a negative influence on the development of their early EF skills. EF difficulties have been repeatedly reported in DHH children (e.g. Figueras, Edwards & Langdon, 2008; Hintermair, 2013; Kronenberger, Colson, Henning & Pisoni, 2014). Rather than looking at how a language processing disorder (such as in developmental language disorder) impacts on EF skills, as some previous authors have done (Gooch, Thompson, Nash, Snowling & Hulme, 2016; Henry, Messer & Nash, 2012), the inclusion of a cognitively typical DHH group allows us to hypothesize more about the effects of early barriers to communication and sensory difficulties on EF development. There are two main reasons why delayed language development might negatively affect EF development: (1) Early difficulties in self-other coordination via interaction and communication, and (2) Reduced abilities to use self-regulating talk online during the EF tasks themselves. We leave a more detailed consideration of these two reasons to the discussion section.

Several theories hypothesise a developmental link between language skills and EF. First, better language skills may enhance EF; for example, the Cognitive Complexity and Control theory (CCC) maintains that rules derived from learning language enable children to better plan and monitor their behaviour via the ability to use vocabulary labels to create internal representations (Zelazo & Frye, 1998). Conversely, EF may support the acquisition and development of language, including vocabulary, 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, Barata & Yoshikawa, 2014). These theoretical viewpoints are not mutually exclusive as there may be a reciprocal relation in the development of EF and language (Bohlmann, Maier & Palacios, 2015).

The findings of previous longitudinal studies in early childhood are mixed: some studies showed that early language predicts later EF performance (Kuhn et al., 2016), some found the reverse relationship (Weiland et al., 2014), and others suggest that the relationship between EF and language may be bidirectional (Bohlmann et al., 2015; Fuhs, Nesbitt, Farran, & Dong, 2014).

Previous research on the relationship between EF and language has focused on the early childhood period (i.e., age 2-5; Fuhs et al., 2014; Bohlmann et al., 2015; Weiland et al., 2014), but there is evidence that all components of EF continue to develop after age 5, and even into adolescence (Best, Miller & Jones, 2009; Miller & Best, 2010). In addition, while vocabulary growth is rapid in the early years, it continues to develop steadily throughout childhood, going through a continuous process of restructuring of lexical representations (Verhoeven, van Leeuwe, & Vermeer, 2011).

There is also mounting evidence that EF difficulties are often concomitant with delayed or disordered language development (e.g. dyslexia, specific language impairment: Gooch, et al., 2016; Henry, et al., 2012). Research with atypically developing children can shed light on the relationship between these two sets of abilities that may not be obvious in typically developing children. While most of these studies examine children at just one point in time, an exception is the study by Gooch et al. (2016) which assessed children aged 4-7 years, including those at risk of dyslexia, over 4 time-points. Strong concurrent associations between EF and language (vocabulary and grammar) were found, but there was no longitudinal relationship. Gooch et al. (2016) postulated that the co-morbidity of cognitive and language difficulties might confound attempts to determine the relationship between the two constructs (Bishop, Nation & Patterson, 2014). We argue that DHH children provide a clearer case for investigating the developmental relationship between language and EF because although most experience a delay in language acquisition, they do not typically present with the comorbid cognitive deficits that occur in other language-impaired groups.

In the most extensive study of EF in DHH children to date, Botting et al. (2017) reported that in a large group of DHH (n=108) and hearing children aged 6–11 years, vocabulary mediated EF skills in both groups, but the reverse pattern was not statistically significant. Botting et al. (2017) acknowledged that DHH children's EF might only be impacted at the time of testing (i.e., the relationship is concurrent), and vocabulary might not predict later EF development. The current study is a follow-up to Botting et al.'s (2017) study, this time focusing on the two-year longitudinal relationship between expressive vocabulary and EF in DHH and hearing children. Even relatively short-term longitudinal studies have an advantage over cross-sectional studies because they allow a prediction of whether *change* in one score over time (e.g., growth in EF scores) is the function of another (e.g., vocabulary growth). Autoregressive effects can be controlled to determine whether vocabulary still predicts EF once pre-existing levels of vocabulary are controlled, and vice versa.

We had two key questions:

- How do DHH children's EF skills and vocabulary develop over a two-year period in comparison to their hearing peers? We expected that both groups would improve in both their EF and expressive vocabulary skills. As DHH children have previously been reported to have poorer EF than their hearing peers, we did not expect them to catch up with the hearing children on EF over the two-year period.

- The primary goal of the study was to clarify the longitudinal relationship between vocabulary and EF in middle childhood. We therefore expected that a measure of vocabulary at Time 1 would predict growth in EF skills in both groups over a two-year period, whereas EF at Time 1 would not predict growth in expressive vocabulary. A comparison of typically and atypically developing language groups where cognitive differences are minimal will allow us to narrow in on the contribution of vocabulary skills to EF development.

Method

Participants

The participants were 157 children living in the UK or Ireland, with either English or British Sign Language (BSL) as their primary language. None of the children had any known co-occurring developmental disorders such as autism, attention deficit/hyperactivity disorder or cerebral palsy. They had been previously recruited as part of a bigger sample (Botting et al., 2017): 67% of the original sample (69% DHH; 66% hearing) was available to take part in the present study. There were no statistical differences in terms of age, gender, nonverbal cognitive ability, vocabulary ability or overall EF scores at T1 between the original and the present study's sample. There were also no differences on these variables when comparing those who took part at T2 and those who did not (*p*s all >.05), with the exception of age. This gives us confidence that the missing data mechanisms is missing completely at random, which allows us to analysis the sample at both time-points without risk of bias (Sterne et al., 2009).

We retained a younger subset of children at the follow up testing phase (mean age at T1=8.7; SD=1.6) than those who were not tested at T2 (mean age at T1=9.4; SD=1.5; *t* (234) = -3.65, *p* =.001), and this was largely due to the older children transitioning to secondary/high school between testing points, making them more difficult to recruit at T2.

Table 1 shows participant characteristics of DHH and hearing groups including age at first and second testing, gender, nonverbal intellectual ability and parental education and employment. There were no significant differences between the groups in age or nonverbal cognitive ability at either T1 or T2, and there were also no significant differences in gender or socio-economic status (as measured by the employment status of the parent completing the form: employed/unemployed; and parental education: whether the participating parent had further education beyond compulsory schooling). Ethnicity was broadly comparable, with both groups having a majority of white British children and a minority from other ethnic backgrounds. In the DHH sample, 56 children (i.e., 75%) were white British, 11 were Asian, 2 mixed race and 6 from "any other" background. In the hearing sample, 74 children (i.e., 90%) were white British, 4 were Asian and 4 were mixed race. Both groups were recruited from schools with similar demographics, which included a range of primary schools in rural and urban settings.

Table 2 summarises deafness-related characteristics of the DHH sample.

[Table 1 here]

[Table 2 here]

Tasks and procedures

The DHH and hearing children completed the same battery of tests at T1 and T2. This comprised six EF tasks selected for their low verbal demands and to tap into the three key components of EF: working memory, cognitive flexibility and inhibition. We also assessed two further EF skills underpinned by the three main ones, namely planning and cognitive fluency. The battery also included an expressive vocabulary test and a test of nonverbal cognitive ability.

Executive function

Odd One Out Span (Henry, 2001) is a measure of **executive-loaded visuo-spatial working memory**. The child must identify which shape is the odd-one-out and remember its location. When a trial is complete, the location of the odd shapes is recalled by pointing to the correct box in a sequence of empty grids. There are four trials within a block, beginning with one item to recall. Each block of trials increases in the number of shape locations to recall with a maximum of six. The test is terminated when two errors are made within the same block. A score is calculated by totalling the number of correctly recalled shape locations (maximum 36).

The *Backwards Spatial Span task* (Wechsler Nonverbal Scale of Ability; Wechsler & Naglieri, 2006) is also a test of **executive-loaded visuo-spatial working memory**. The experimenter taps a sequence of blocks and the child is instructed to tap this sequence in reverse. Each trial increases the number sequence to a maximum span of nine. The test is terminated after two errors at the same span length, and scored by tallying the number of correct sequences.

The *Design Fluency* (NEPSY, Korkman, Kirk & Kemp, 1998) task contains a series of dot arrays. Children are required to generate as many different designs as possible in one minute by joining two or more dots with a straight line. The assessment measures **visuo-spatial cognitive fluency** and is scored by adding the total number of original designs.

Children's Color Trails Test 1 and 2 (CCTT) (Llorente, Williams, Satz & D'Elia, 2003) is a test of **cognitive flexibility or switching**. For test 1, the children are timed drawing a line connecting the numbered circles from 1 to 15. In Test 2, two sets of numbered circles are printed: one set of circles filled with pink, and the other, yellow. Children are required to join the numbers in ascending order, alternating between colours. In this study, an interference score was calculated, showing the ‘additional time’ taken in Test 2.

The *Tower of London (ToL)* is a simplified version of the Tower of Hanoi task (Shallice, 1982) that measures **executive planning.** Coloured disks need to be moved from their initial formation, one by one, to match a target configuration. The ToL task was presented using Psychology Experiment Building Language (PEBL) version 0.14 (Müller & Piper, 2014) via a laptop. The first trial was used as an example, and the children continued to complete the seven trials that followed. To score the task, the number of additional moves over the minimum number of possible moves was calculated.

A computerised version of the *Simon task* was administered as a measure of **cognitive inhibitory control**. On each trial either a sun or an apple appears on the screen either left or right of centre. The children are instructed to respond by pressing a key with a sun sticker on the left hand side of the keyboard when they see a sun appear, or a pressing a key with an apple sticker on the right hand side when they see an apple appear. Each stimulus appears for 750ms. The order of trials was randomised for each child and no feedback was given. There were a total of 32 trials, half congruent (picture on the same side as the response) and half incongruent (picture on the opposite side of the response). The increased time to respond to incongruent items is known as the Simon effect (Simon, 1990): an ‘interference score’ was therefore created for the analysis by subtracting congruent from incongruent scores.

Language

Single word vocabulary production was tested using the *Expressive One Word Picture Vocabulary Test* (EOWPVT; Brownell, 2000) following the standardised administration guidelines. Children are required to name single pictures (mostly simple nouns e.g., goat; but also verbs e.g., writing, and category labels e.g., lights). Three alternative pictures were used to make it more suitable for children in the UK (e.g. badger replaced raccoon). In the current study children completed the entire standard version (all the items on the test) which allowed us to create a standardised score. However, Kyle, Campbell and MacSweeney (2016) previously ascertained appropriate BSL responses i.e., items that were determined to be signed and not gestured responses. To ensure that the EOWPVT could be used to assess the vocabulary of both hearing and DHH children who use either spoken or signed language, 15 test items that are not lexicalised in BSL (e.g. cactus) were removed at the point of scoring. An adjusted EOWPVT score was calculated for analysis that excluded these items.

Control task

The *Matrix Reasoning* subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) was administered as a control measure for **nonverbal cognitive ability**. This subtest is a test of nonverbal logical reasoning that correlates highly with performance IQ. Children are required to select the missing section of a pattern from five choices. The test is terminated after 4 errors occur in any sequence of 5 test items.

Procedure and ethical considerations

The study received ethical approval from the UCL Research Ethics Committee. Informed consent was obtained from all the participating families prior to testing, and children gave verbal consent, with the option to opt out at any time during the testing session.

Testing took place in a quiet room in the child’s school or home. Each session was video recorded and lasted between 60 and 75 minutes. Children could opt to take short breaks when necessary. Researchers were all very experienced in communicating with DHH children and used the child’s preferred form of communication (BSL, SSE or spoken English) to present all task instructions.

Design and statistical analysis

To test whether DHH children’s EF and vocabulary improved over time (T1 to T2) in comparison to a group of hearing children, we carried out a series of repeated measure ANOVAs.

To determine whether there was a longitudinal relationship between EF and vocabulary across the two time points, we ran a series of cross-lagged panel models to test this association, and to see whether hearing status moderated the effect of vocabulary ability on later EF ability (and vice versa). We tested the longitudinal autoregressive associations between each EF task across time, in addition to the cross-lagged paths between vocabulary at T1 and EF at T2, and also the reverse paths (EF T1 to vocabulary T2). We did not include age as a covariate because cross-lagged panel models evaluate T2 variables after having accounted for the auto-regression effect measuring change within variables across time (e.g., vocabulary T1 and vocabulary T2).

All cross-lagged panel models were implemented in Mplus Version 7.2 (Muthén & Muthén, 1998-2014) using maximum likelihood means and variance adjusted, to account the non-normal distribution of many of the EF tasks. Observed variables were used instead of creating a latent variable of inhibition, cognitive flexibility and working memory due to insufficient number of measurements of each domain of EF. Evaluation of the correlations (found in the supplementary materials) supports the conclusion that there is not an underlying “EF” latent variable, as correlations were only moderate across all tasks, with the highest correlation within the working memory tasks. . We used raw scores rather than standardized scores for both expressive vocabulary and EF, as recommended for the analysis of longitudinal data, to enable the measurement of growth over time (Willett, Singer & Martin, 1998). We did not engage in any model *building* as such, since our theoretical model was the classic cross lag panel model. As we had a specific theoretical framework we were aiming to test, it was not possible to evaluate alternative specifications of the model with other outcome or predictor variables, as is advisable in model building.

The full path analysis model was ‘just-identified’ with no degrees of freedom (which is common in path analyses and particularly cross-lagged models; “Analyzing Data: Path Analysis”, 2016) and thus was a perfect model fit. This model allowed all paths to be estimated and included two autoregressive paths and two cross-lagged paths. Covariances between T1 and T2 vocabulary and EF were also included. As model fit could not be established with no degrees of freedom (df), we evaluated overall fit when the non-significant covariance between T2 vocabulary and EF task was set to zero. This allowed fit statistics to be calculated with one df. These model fit statistics can be viewed in Table S1. In one case (ToL task), the covariance at T2 was significant in the full model (p=.045), so the non-significant path of ToL at T1 predicting vocabulary at T2 was set to zero. In all cases, the chi-square was not significant (ps > .52). In total, the models with one df (and additional models tested with more dfs) provide excellent model fit. The constrained models were directly compared to the just identified models (using log likelihood comparison and *difftest* procedures to comparing nested models) and in all instances were not found to be a better fit. Therefore, the unconstrained just identified models were used as the baseline model.

To test for moderation of DHH versus hearing group on the cross-lagged effects, we added an additional path to the model. This path was an interaction term between the cross-lag predictor (vocabulary or EF task), and a 0/1 dummy variable for group membership. This path tested whether there was significantly different strength or direction in the cross-lag relationship between the hearing and DHH group. When conducting cross-lagged panel models in Mplus, it is not possible to get an estimate of effect size on each path in the model. However, we do provide standardised coefficients, to allow for easily comparable β values between and within each model.

Nonverbal cognitive ability was not included as a covariate in any of the analyses. Given the overlap between components of general intelligence and EF (particularly working memory), covarying for cognitive ability is not appropriate when examining group differences on EF (Dennis et al., 2009). Furthermore, neither IQ (nor speed of processing) are suitable covariates as they do not meet the criteria of random assignment to the IV (deaf vs hearing). There were non-trivial differences in the correlation of the WASI test to both the vocabulary and several of the EF tests across the differing levels of the IV (deaf/hearing). The lack of any differential association was another condition specified by Dennis et al. (2009) which causes problems including covariates. Furthermore, no significant differences were seen in nonverbal cognitive ability between the groups at either time point (see Table 1 for details).

Although we acknowledge the main panel analysis presented has not separated out the deaf and hearing groups, we also test for group differences here, and thus the justification for not using WASI as a covariate in the group differences holds additionally for this analysis.

Results

Development over time

i) Executive function

Table 3 reports the means and standard deviations of raw scores for DHH and hearing children's performance on the EF tasks and expressive vocabulary at both T1 and T2. The proportion of missing data at T1 (< 10%) is also shown, and there was no data missing at T2. A series of repeated measures ANOVAs[1] revealed significant main effects of Group for the CCTT (switching), the Odd One Out (working memory) and the Backwards Spatial Span tasks (working memory), meaning that the hearing group performed significantly better than the DHH group on these EF tasks (Table 3). There were significant main effects of Time for all EF tasks, indicating improved performance between the two testing time points for groups overall. None of the Group x Time interactions for performance on EF tasks were significant, indicating that the amount of improvement of DHH and hearing children did not differ significantly.

ii) Expressive vocabulary

There was a main effect of Group for raw adjusted EOWPVT scores, indicating that the hearing children had significantly better expressive vocabulary than the DHH children. There was a main effect of Time, but no Group x Time interaction, showing that DHH and hearing group children both significantly improved their EOWPVT scores between T1 and T2, and neither group made a greater level of improvement than each other.

[Table 3 Here]

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[1] Number of months between testing at Time 1 and Time 2 was investigated as a potential confounding variable, but it did not result as a significant predictor of any of the EF tasks, or vocabulary, so it was not added as a covariate.

Correlations between EF and vocabulary

For the whole sample, all correlations among EF tasks were significant and were moderate in magnitude or lower (*r*s ranging from .17 to .58). This was with the exception of the Simon task, which did not correlate with design fluency at T1, or with any other EF tasks at T2; and there was no significant correlation between design fluency and CCTT at T2 (see Table S2 available online). Correlations within EF variables were stable from T1 to T2 (*r*s .20 to .63). All of the EF tasks correlated with expressive vocabulary at both time points (*r*s .19 to .57), with the exception of Simon T1, which did not correlate with T2 vocabulary. Vocabulary correlated highly over time (*r* =.83).

The separate group correlations showed a similar pattern of results (see Table S3), although the Simon task did not correlate with any other EF task or expressive vocabulary at T1 or T2, except with CCTT at T1 for the DHH children and T2 for the hearing children. In addition, the correlation between the ToL task and the Backwards Spatial Span Task at T1 and the CCTT at T2 were non-significant for the hearing children. For the DHH children, the ToL did not significantly correlate with the CCTT at T1 or T2, and ToL and vocabulary did not significantly correlate at T2.

Cross-Lagged relationship between EF and vocabulary

Cross-lagged models were implemented for all EF tasks with DHH and hearing groups combined to gain sufficient power (*see moderation analysis later*). For all models, the autoregressive effects were significant, such that EF at T1 was strongly related to EF at T2, and vocabulary at T1 was strongly related to vocabulary at T2. The cross-lagged model results are presented in Table 4. Vocabulary at T1 was related to EF ability at T2 for five of the six tasks

(CCTT, Design Fluency, Simon task, Backwards Spatial Span and Odd One Out). Importantly, EF at T1 was not related to vocabulary at T2 for any of the models showing predictive value over time in only one direction (earlier language to later EF, but not earlier EF to later language). For the concurrent relationships at T1 and T2, all T1 vocabulary and EF tasks were significantly correlated. At T2, only the ToL EF task was correlated with T2 vocabulary, with the remaining EF tasks having a non-significant correlation with vocabulary at T2. As an example, Figure 1 displays the cross-lagged model for the Design Fluency test (the cross-lagged models for the remaining EF tasks can be found in Figure S1).

Moderation of Group on Cross-lagged Effects

Due to the relatively small sample size, we combined the DHH and hearing groups above but then evaluated the potential differences in the two groups using an interaction term in predicting T2 outcomes. The interaction variable was created by multiplying a dummy variable for Group with the cross-lagged predictors (EF for predicting vocabulary at T2 and vocabulary for predicting EF at T2). There was no moderation of Group on the effect of vocabulary at T1 predicting EF at T2 (all *p*s > .07). For four of the EF tasks (CCTT, Design Fluency, Odd One Out, Backwards Spatial Span), there was a significant group moderation effect on how EF at T1 predicted vocabulary at T2. For these four tasks, the DHH and hearing groups were run within the same overall cross-lagged model in order to evaluate the direction of the moderation effects. This indicated that EF at T1 had a stronger relationship with vocabulary at T2 for the hearing group than for the DHH group. This path was significant in the hearing group only for the Backwards Spatial Span task.

[Insert Table 4 here]

[Insert Figure 1 Here]

Discussion

The primary goal of this study was to determine whether there was a longitudinal relationship between vocabulary and EF in the middle school years in DHH and hearing children. Both sets of children significantly improved on all EF and vocabulary tasks over the two-year period. The DHH children had a large language developmental delay. At time 1 there were 25 standard score points between these two groups on their vocabulary scores. Although the DHH children did not catch up with their age and nonverbal ability-matched hearing peers, the gap did not widen. While language and EF improve DHH children still performed more poorly than hearing peers on some EF tasks, in particular on two working memory tasks (Odd One Out and Backwards Spatial Span) and on the switching task (Colour Trails). This is still the case even though the tasks have low verbal demands. This finding extends the study by Botting et al. (2017), who also found lower scores for DHH children and who postulated that the correlations between EF and vocabulary tasks might imply a role of vocabulary in EF development. However, in that study, while vocabulary mediated EF differences, it remained unclear whether this was a concurrent task effect or a developmental predictor.

For both groups in the present study there was a strong concurrent relationship between vocabulary and EF at T1, but vocabulary at Time 1 also predicted *change* in EF scores over the two-year period, even when controlling for pre-existing EF ability. The reverse pattern was not evident. This pattern was across all EF tasks apart from the Tower of London (planning).

The DHH population allows us to explore a situation where language delay is the outcome of experience (i.e., auditory deprivation, and, in most case, resultant language deprivation) rather than an intrinsic neuro-cognitive disorder; and to investigate potential moderation effects across different groups. Interestingly, there were few moderation effects across groups but where they appeared, the hearing group showed a more bi-directional relationship over time between EF and vocabulary. We found a moderation effect of Group for EF at T1 predicting expressive vocabulary at T2, showing that the relationship in the opposite direction was stronger for hearing than for DHH children. However, only Backwards Spatial Span (working memory) at T1 significantly predicted change in expressive vocabulary.

The results of our study have several implications. The reason for including a group of DHH children was to further our understanding of how language might be linked to EF. We go further than just signalling a link between language and EF; instead, our cross-lagged models reveal that vocabulary predicts changes in EF over time and not in the other direction. The longitudinal data reveal a developmental pathway suggesting EF skills do not develop optimally when earlier vocabulary skills are weak. The DHH group has significantly poorer vocabulary skills compared with their peers (25 standard score points below) and we argue this has had a negative impact on their EF skills. As we mentioned in the introduction, we think there are two reasons for this relationship: one is developmental and the other concerns how children use language while carrying out the EF tasks. We expand on these two explanations next.

Early parent-child interaction and the development of self-regulation is crucial not only for the development of good language skills (Akhtar, Dunham & Dunham, 1991; Cartmill, et al., 2013), but also for the development of EF skills - especially emotional and cognitive regulation (Lowe, et al. 2012; Hughes, White & Ensor, 2014). In the typical scenario, infants will have full access to the rich interactions offered by caregivers’ scaffolding of communication (Hughes, et al., 2014), and they will be surrounded by adults who use language to regulate and foster self-regulation in the same children. In contrast, communication between hearing parents and a DHH infant is much less effective (Wedell-Monnig & Lumley, 1980; Harris, 2010). For example, mothers of CI-implanted children use less complex utterances (Moeller & Tomblin, 2015) and reduce the communicative demand (e.g., less use of open-ended questions - DesJardin & Eisenberg, 2007). Fagan et al. (2014) found that mothers of children with CI also use more directives (e.g., “say” ‘cat’, “sit here”) and prohibitions (e.g., “no”, “don’t open it”) than mothers of age-matched hearing children. Thus, as a group DHH children experience a reduced and less demanding communication interaction with primary caregivers (Levine, et al, 2016). While this experience undoubtedly contributes to a language development delay, we propose that it also impacts on the development of early EF abilities as it offers far fewer opportunities for self-planning, inhibition and control of interactions by DHH children.

Delay in vocabulary development because of impoverished opportunities for early interaction has a secondary effect, which surfaces later on in development, hence the older age range represented in this study. Cognitive Complexity and Control (CCC) theory (Zelazo & Frye, 1998 and Doebel & Zelazo, 2016) maintains that good vocabulary enables children to automatically process information via integrated language representations thus freeing up cognitive load to engage in meta-cognitive strategies. During several higher-level cognitive tasks such as those requiring EF, it is evident that children and adults use these meta-cognitive strategies i.e. self-talk, to assist them, even in in situations where the task is non-verbal in nature (Duncan &

Cheyne, 2001; Fernyhough, & Fradley, 2005). The age range of our sample allows for direct comparison of EF performance with other studies of atypical children of the same age but with neurologically-based language difficulties (e.g., Henry et al, 2012; Im-Bolter et al, 2006). For example, children with Developmental Language Disorders have delayed and reduced self-regulatory speech (Abdul Aziz, Fletcher & Bayliss, 2017). As EF involves the control of behaviours via accessing these previous language-mediated experiences, DHH children who have poorer integration of language representations are also likely to be at a disadvantage. DHH children will experience more cognitive load in EF tasks and might not engage in good meta-cognitive strategies.

Thus, on both counts children with delayed language development resulting from their deafness will experience difficulties in both the establishment of early EF skills where self-regulating speech is linked to early experiences of interaction with an adult which the child first models and internalises (Fernyhough, & Fradley, 2005). This can be seen in the later implementation of those EF skills when language resources are needed to boost EFs through self-talk. Indeed, these two elements may be more or less present depending on the particular EF task. For example, the working memory, inhibition and fluency measures might be more associated with early developmental disruptions. However, the planning task (Tower of London) may be more reliant on concurrent implementation of self-talk and less on developmental experience of good interpersonal interaction (e.g., Lidstone et al, 2011). The DHH sample allowed us to evaluate both these types of associations (early interaction-communication and concurrent vocabulary skills) on EF development because the DHH group represent a population with impoverished early communicative experience, as well as having weaker spoken language skills. The current results show that it is not just that children with delays in vocabulary development are limited verbally at the point of testing but that language predicts growth in EF.

Lastly, our results relate to typical development more widely. Hearing children have a variety of early interactive experiences and the better-language-leads-to-better-EF proposal has found mixed results in these typically developing children (e.g. no influence: Connor et al, 2016; positive relationship: Kuhn, et al, 2016). However, early variations in communication might be might be particularly relevant for children with atypical development. The quality of parent-child interaction is perhaps more important for language and EF development in DHH children. The developmental delays caused by early language deprivation could be compounded by the negative effects of a communication-poor environment (see Levine et al., 2016). The inclusion of the DHH group allows us to evaluate the developmental impact of these early experiences when they are curtailed because of barriers to communication in deafness. Thus, our study provides support for a language –EF link and highlights the importance of early stimulation and language development for the robust development of EF.

We observed different language relationships across different EF measures. Although we selected non-verbal and assessment-fair measures this does not mean we eliminated the role of language to do the task. This may explain the group differences between DHH and hearing children on some, but not, all of the EF assessments. The tasks measuring working memory and switching may have higher language demands through verbal strategizing (Fernyhough & Fradley, 2005). Indeed, these tasks showed the strongest concurrent relationship with vocabulary at T1. The lack of group difference on the inhibition task may be because response inhibition shows rapid development in the preschool years and less change later in development, whereas working memory and shifting show more gradual improvement (Best & Miller, 2010).

In addition, the present study was not designed to directly investigate whether the relationship between language and EF changes qualitatively with age, and our sample is not sufficiently stratified by age group to address this question here. Neither would covarying age provide a solution, since this would simply control for age, rather than illuminating the nature of the EF-language relationship at different points in development. Nevertheless, we acknowledge that the nature of EF is fluid over time (Lee, Bull & Ho, 2013) and that our results need to be interpreted with this in mind. Furthermore, EF was measured with six separate and distinct tasks. The correlations between the tasks did not support the use of an Executive Function latent factor. As such, the recommended practice of using a measurement model within cross-lagged panel analysis to account for measurement error was not implemented. The results should be considered in light of this limitation. Additionally, the majority of correlations between the EF tasks at T1 and T2 ranged from .46-.63, showing a moderate relationship across time, although the Simon Inhibition Task was only .20. The results of the Simon Task should be considered in light of this low correlation across time, as it may be that with so little stability across time there was little variability able to predict changes in vocabulary between the two timepoints. However, the higher stability across time with the other EF tasks, along with the consistent pattern of results across all tasks, give confidence in the overall results and conclusions of this research. Indeed, a lower autocorrelation may allow for more variability to be accounted for within any cross-lagged paths, but that is not the pattern found in this paper consistently across all EF tasks.

Bishop et al. (2014) set out an argument that suggests EF might affect language, language might affect EF, or a third factor, i.e., a shared genetic risk, might affect development of brain systems for both language and EF. However, a model in which EF is influenced by language in a unitary way is likely to be over simplistic. As illustrated by our data, it may well be that certain subfunctions of EF that have stronger or weaker relationships to differing parts of language and these relationships may change during development.

In this study only one aspect of language was measured, namely expressive vocabulary, meaning that findings only extrapolate to vocabulary acquisition. It is plausible that other language skills (e.g., syntax, narrative ability) have important associations with EF, and including such measures in future research may reveal further bidirectional relationships at different time points in development.

It is also important to note that not all DHH children have poor EF. A recent study with a group of *native* deaf signers (i.e. born to deaf parents, and therefore benefitting from language exposure from birth) found no difference in parental ratings on a questionnaire measuring different domains of EF (Hall, Eigsti, Bortfeld & Lillo-Martin, 2017). A similar lack of group differences was found by comparing the native signers from our study sample to hearing children on non-verbal tasks of working memory (Marshall et al., 2015). Both these studies would support our conclusions that good early child-parent interaction and later use of optimal self-talk via age appropriate vocabulary will protect DHH children from EF delays. Our sample of DHH children is, however, underpowered for finer-grained within-group analyses.

Finally, cross-lagged panel designs reveal predictive variables, but causation cannot be inferred from them. Nevertheless, this study’s finding that vocabulary predicts EF development is an important one, and potentially has vital implications for early language training. While early intervention has been shown to improve weaknesses in language skills (e.g. Fricke et al., 2013), it remains unknown whether this would also benefit EF development. Future training studies and multi-wave longitudinal studies across childhood would be beneficial for understanding the changing and complex relationship between EF and language.

Conclusion

Beyond the preschool years, growth in vocabulary and EF skills continues to be susceptible to environmental differences that mediate development. In the case of deafness, poorer language learning experience caused by reduced quality of parent-child interaction and accessible language input may have a detrimental impact on EF development. Better understanding of the language mechanisms that enable and support how children operationalise their EF is required to guide future interventions.

Supporting information

Additional supporting information may be found in the online version of this article:

Table S1. Model fit statistics.

Table S2. Correlation coefficients among EF tasks and expressive vocabulary at Time 1 and Time 2 (whole sample)

Table S3. Correlation coefficients among EF tasks and expressive vocabulary at Time 1 and Time 2 (DHH and hearing)

Figure S1. Cross-lagged models for executive function subtests

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Table 1

Participant characteristics of deaf and hearing children

	Deaf (N = 75)	Hearing (N = 82)		
	Mean score (*SD*)		*t*	*p*
Age (years; months) T1	8; 5 (1; 8)	8; 8 (1; 5)	-.87	.38
Age (years; months) T2	10; 2 (1; 8)	10; 5 (1; 5)	-.90	.37
WASI [1] matrix T-score T1 [2]	51.44 (10.57)	54.3 (10.1)	-1.74	.09
WASI matrix T-score T2	53.72 (8.45)	54.5 (7.87)	-.60	.55
EOWPVT[3] Standard score T1	86.83 (20.23)	111.6 (13.83)	8.78	.000
	Percentage		χ^2	*p*
Gender (% boys)	53%	54%	.02	.89
Parent with Further Education	82%	81%	.06	.81
Parent in employment	85%	83%	.12	.73

[1] WASI: Wechsler Abbreviated Scale of Intelligence; [2] t-score norm is 50 (*SD* = 10); [3] EOWPVT: Expressive One Word Picture Vocabulary Test

Table 2

Participant characteristics of Deaf and Hard of Hearing sample

	DHH Group N=75
Age of Onset	
Born Deaf	61 (81%)
Deafened before age 5 years	14 (19%)
Cause of deafness*	
Genetic	31 (41%)
Illness	9 (12%)
Premature birth	11 (15%)
Unknown	35 (47%)
Family deafness	
One or more deaf parent	20 (27%)(14 children also had a deaf sibling)
Deaf sibling only	11 (15%)
Hearing Loss in better ear	
Mild-Moderate (30-69 dB) Mean (39dB)	11 (15%)
Severe (70-94 dB) Mean (81dB)	19 (25%)
Profound (>95dB) Mean (106dB)	45 (60%)
Amplification	
Hearing Aids	44 (59%)
Cochlear Implants	31 (of these 9 had bilateral implants)
Communication preference	
British Sign Language	22
Spoken English	40
Sign Supported English	13
Educational setting	
Specialist deaf day school	16
Specialist deaf residential school	8
Mainstream schools with specialist unit	23
Mainstream schools with no specialist provision	28

* some families gave more than one cause of deafness

Table 3

Executive function and expressive vocabulary (raw scores): Means and standard deviations (in parenthesis) by Group and Assessment Time, and Results from Mixed ANOVAs

		Time 1			Time 2		Group				Time			Group x Time		
Construct	Assessment	*N* (% missing)	Deaf (*N* = 75)	Hearing (*N* = 82)	Deaf	Hearing	*F*	*df*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Planning	ToL (additional moves)	150 (5)	29.62 (16.32)	26.11 (15.63)	21.97 (17.66)	18.57 (10.16)	2.71	1,148	.10	.02	34.45	<.001	.19	.002	.97	.00
Inhibition	Simon task (interference)	145 (8)	-16.87 (16.12)	-12.33 (14.42)	-10.02 (16.06)	-8.33 (14.95)	2.47	1,143	.12	.02	11.2	.001	.07	.78	.38	.01
Switching	Children's Colour trail test (interference)	152 (3)	38.47 (18.45)	26.93 (15.34)	30.36 (17.86)	24.64 (13.05)	7.89	1,150	.006	.05	52.97	<.001	.26	2.15	.14	.01
Visuo- spatial cognitive fluency	Design fluency (total)	157 (0)	19.11 (7.87)	20.82 (6.2)	24.95 (7.89)	27.21 (7.69)	3.46	1,155	.07	.02	139.3	<.001	.47	.82	.60	.01
Working memory	Odd one out (total)	156 (1)	8.29 (4.31)	10.31 (4.72)	11.37 (4.12)	12.51 (4.57)	10.79	1,154	<.001	.07	91.68	<.001	.37	.06	.80	.00
Working memory	Spatial span backwards (total)	157 (0)	4.99 (2.14)	6.04 (1.92)	6.29 (3.1)	7.05 (1.54)	11.35	1,155	.001	.07	57.59	<.001	.27	.93	.34	.01
Expressive vocabulary	EOWPVT (adjusted)	156 (1)	64.43 (19.93)	87.06 (15.21)	77.76 (19.56)	100.38 (13.55)	73.11	1,154	<.001	.32	310.27	<.001	.67	.00	.99	.00

Note. Constructs highlighted in bold represent significant Group differences (Hearing > Deaf)

Table 4

Model results: cross-lagged parameter estimates

Model	Path	*B*	β	*SE*	*p*
Tower of London (planning)	EF T1 → LA T2	.01	.01	.04	.83
	LA T1 → EF T2	-.03	-.05	-.05	.62
Simon task (inhibition)	EF T1 → LA T2	-.04	-.03	-.86	.34
	LA T1→ EF T2	.13	.18	.08	.03
Colour trails (switching)	EF T1 →LA T2	-.04	-.04	.05	.46
	LA T1→ EF T2	-.16	-.26	.08	.001
Design fluency (visual-spatial cognitive fluency)	EF T1→LA T2	.11	.04	.04	.33
	LA T1→ EF T2	.10	.28	.06	<.001
Odd one out (working memory)	EF T1 → LA T2	.05	.01	.05	.80
	LA T1→ EF T2	.05	.21	.08	.006
Spatial span-backwards (working memory)	EF T1 → LA T2	.34	.04	.05	.51
	LA T1→ EF T2	.02	.23	.08	.002

Note. EF = executive function; LA = language (expressive vocabulary). Beta estimates represent standardized regression coefficients. Paths in bold represent significant *p* values.

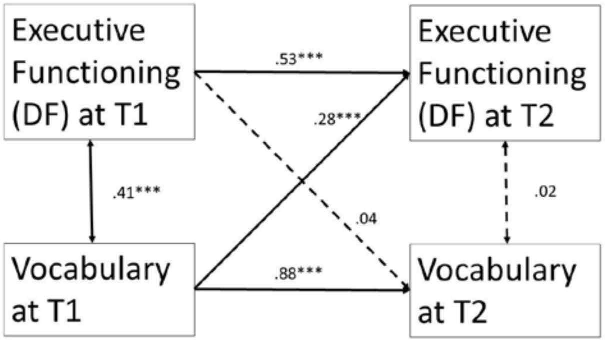

Figure 1. Cross-Lagged Model for Design Fluency Subtest (visual-spatial cognitive fluency)