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Diverse language experiences in deaf infants and in hearing infants with deaf parents: 25 years of improved understanding and recognition

Evelyne Mercure [a,*], Rain Bosworth [b], Teodora Gliga [c]

[a] Goldsmiths, University of London, UK
[b] Rochester Institute of Technology, USA
[c] University of East Anglia, UK

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ABSTRACT

Most infants first encounter language through the words spoken in their environment. However, for a smaller number of deaf and hearing infants, language can be presented in different sensory modalities, including a visual-manual signed language (e.g. American Sign Language - ASL or British Sign Language – BSL) and an auditory-oral spoken language (e.g. English). Language acquisition trajectories for children exposed to both signed and spoken language are less understood and less recognised. For hearing children with deaf parents using sign language, recent research suggests that they develop a special case of bilingualism – bimodal bilingualism - which offers some advantages in early communication skills. In deaf children, it has now been clearly demonstrated that early exposure to sign language brings about gains in both the spoken and signed modalities, suggesting an amodal impact of language experience in infancy. The present review presents progress made in the last 25 years in understanding the impact of sign language experience in infancy. It will discuss potential neurocognitive mechanisms by which learning gains in one language modality can be transferred to the other language modality. The research data collected so far leave several questions unanswered and suggest many avenues for future research.

1. Introduction

Most babies are introduced to language by hearing the words and sentences spoken by their parents and others in their environment. However, for a smaller number of infants, the language present around them is produced in different sensory modalities, including an auditory-oral spoken language and a visual-manual signed language. This can be the case of hearing infants with deaf parents who use a sign language as their preferred mode of communication. It can also be the case of deaf infants who may be exposed to sign language while having reduced access to auditory spoken language. Some of these infants grow up to become fluent in languages of different sensory modalities and therefore develop a special case of bilingualism: bimodal bilingualism (for example, infants learning French and Langue des Signes Québécoise, LSQ, in Canada or those learning English and British Sign Language, BSL, or American Sign Language, ASL). Others may develop higher proficiency in one modality than the other as a result of differences in

* Correspondence to: Department of Psychology, Goldsmiths, University of London, London SE14 6NW, UK.
E-mail address: e.mercure@gold.ac.uk (E. Mercure).

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sensory access, in degree of exposure and/or in the fluency of the language models. Infants exposed to sign language represent a unique opportunity to study how experiences in the early years shape human development. Collectively, the different profiles of deaf and hearing infants exposed to sign language in the early years have tremendous potential to inform the processes of human communicative development, as well as the impact of early language deprivation and bilingualism on neurocognitive development.

The last 25 years have seen an enormous increase of interest for research on sign language and bimodal bilingualism. For example, the term bimodal bilingual was rarely used in publications before the year 2000 and its use exploded since 2010. Advances in research have happened in parallel and in interaction with many societal changes around the world that impacted the perception and reality of deaf and sign language using communities (Humphries et al., 2023; Tang, 2017). Universal screening for deafness has been established in many countries around the world, allowing identification of deaf infants in the newborn phase (Leigh et al., 2010). This early identification allows an earlier intervention, and, in some families, this can include early exposure to sign language. Early exposure to sign language was also encouraged by the fact that many sign languages around the world have received a better recognition of the fact that they are rich natural languages, leading to official recognition such as the BSL Act of 2022 in the United Kingdom (Adam et al., 2025). On the technological side, there has been a growing number of cochlear implant users especially in the early years, increasing access to auditory spoken language in many deaf infants (De Raeve et al., 2020; Nassiri et al., 2022; Peters et al., 2010). This has led to new profiles of language acquisition in some deaf infants, including infants acquiring language in both modalities as native users (Davidson et al., 2014; Rinaldi & Caselli, 2014).

Despite a recent increase in interest, sign language acquisition and bimodal bilingualism remain language acquisition profiles that are less understood in scientific communities and recognised in society than monolingualism or other forms of bilingualism in spoken language. A general lack of information about sign language acquisition and bimodal bilingualism may explain why deaf parents report experiencing prejudice and incomprehension from medical and educational professionals for their child's language acquisition profile (Chen Pichler et al., 2014; Lillo-Martin et al., 2023; St Clair et al., 2025). Beliefs that sign language exposure, in deaf and in hearing children, can lead to difficulties with language acquisition, especially in the spoken modality, are often expressed by professionals and researchers (Chen Pichler et al., 2014; Lillo-Martin et al., 2023; St Clair et al., 2025). This has led to variable access to many forms of signed communication, increasing the need to understand the developmental impact of this experience. With the turn of the new millennium, massive research efforts and investments has begun to create a better understanding of sign language acquisition and bimodal bilingualism, which has gradually diminished beliefs that learning two languages is "harmful" or confusing for children (see Bialystok (2009) and Genesee (2016) for reviews of positive, negative and neutral effects of bilingualism).

This quarter century review aims to address how experience of sign language in the early years influences trajectories of language and neurocognitive development in hearing and deaf individuals. It will mainly address the following question: how does learning language in one sensory modality influences the acquisition of language in a different sensory modality? How does this relationship interact with the child's hearing status? It will begin by presenting recent literature on language development in hearing infants with deaf parents. Next the literature on the impact of sign language experience in deaf children will be reviewed. It will then discuss potential mechanisms through which learning gains in one language modality can be transferred to the other language modality. Finally, this review will discuss questions that remain to be addressed or answered about sign language acquisition and bimodal bilingual experiences in infancy and avenues for future research in the field.

2. Language development in hearing children exposed to sign language from their deaf parents

If deaf parents use sign language as their preferred mode of communication, their hearing child is likely to develop bimodal bilingualism. A signed language (such as LSQ, BSL or ASL) is likely to be used by the deaf parents to and around the child in the home; while a spoken language (for example, spoken French or English) can be used by relatives, peers, teachers, the wider hearing community, media, and in some instances, by the deaf parents themselves. Because of their different experience of language in two sensory modalities, this population represents a unique opportunity to study experience-dependent plasticity in human development.

Early studies on hearing children of deaf parents (also known as CODAs – Children of Deaf Adults) usually focused on spoken language development, often ignoring the sign language experience of the child and their bilingualism. These early studies aimed to assess the speech and spoken language development of hearing children with deaf parents compared to hearing children with hearing parents, and they reported a higher prevalence of difficulties in the former (Sachs et al., 1981; Schiff & Ventry, 1976). However, these findings are very likely to be confounded by a direct comparison of bimodal bilinguals to monolinguals instead of to children of hearing parents exposed to two spoken languages (unimodal bilinguals, exposed to English and Spanish for example). With the lack of a unimodal bilingual comparison group, it is impossible to tell if differences can be specifically attributed to bimodal bilingualism or to bilingualism in general. In sharp contrast with these early studies, the first studies focusing on sign language development suggested that the early acquisition of signed vocabulary may be accelerated compared to monolingual norms of spoken language development (Orlansky & Bonvillian, 1985) and English vocabulary may be increased in bimodal bilinguals compared to monolinguals (Daniels, 1993).

2.1. Early communication

Even before a baby has produced their first word or sign, their language acquisition profile is influenced by sign language experience. One demonstration of this early influence was found in the manual babbling of infants with deaf parents. Hearing 6-to-12-month-old infants exposed to sign language produced rhythmic hand movements that were not present in infants exposed to spoken language only, but were similar to canonical vocal babbling in its age of acquisition and its communicative function (Petitto

et al., 2004). Moreover, a bimodal language experience may also influence early receptive communication skills in hearing infants with deaf parents. In a recent study, bimodal bilingual infants between 4 and 8 months demonstrated increased receptive skills as assessed by the Mullen Scales of Early Learning compared to bilingual infants of hearing parents (Mercure et al., In press). These early communicative skills were not specific to any language modality and included skills such as smiling in response to a communication attempt or engaging in a peek-a-boo game. It may be that the infant's experience of communication in two language modalities encourages flexibility in communication strategies, leading to broad advantages in the development of social communication in the first year of life (Mercure et al., In press). By 1-to-3 years of age, bimodal bilinguals also develop pragmatic language differentiation for the two language modalities they are exposed to and a sensitivity for the modalities used by different communication partners. Indeed, language productions from preschool bimodal bilinguals include more words when addressed to a hearing person and more gesture and sign language when addressed to a deaf person (Kanto et al., 2015; Lillo-Martin et al., 2014).

2.2. Vocabulary

Studying vocabulary acquisition in bilingual children is more complex than it could initially seem. Indeed, for children exposed to two spoken languages, vocabulary measured in one language is usually smaller compared to a monolingual control group or monolingual norms (Byers-Heinlein et al., 2024; Poulin-Dubois et al., 2013; Siow et al., 2023; Stolarova et al., 2016). However, vocabulary measured in one language does not include words bilingual children would know in other languages, and this measure therefore represents an underestimate of the child's full lexicon. When a measure of total vocabulary is created by adding the words known in one language to the words known in another language, unimodal bilinguals have larger expressive and receptive total vocabularies compared to monolinguals (Byers-Heinlein et al., 2024; Siow et al., 2023). Alternatively, when measuring conceptual vocabulary as the number of concepts for which the child knows at least one label in either language, unimodal bilinguals have similar receptive (Byers-Heinlein et al., 2024; Siow et al., 2023) but smaller expressive vocabularies compared to monolinguals (Byers-Heinlein et al., 2024; Core et al., 2013; Siow et al., 2023). It is therefore crucial to take the complexity of the bilingual experience into account when studying vocabulary acquisition in bimodal bilinguals.

Regarding bimodal bilinguals' vocabulary, some studies compared their development to monolinguals and found similar vocabulary size. Indeed, vocabulary development measured at 16 and 20 months did not differ from monolingual norms in each language modality in a child exposed to ASL and English (Brackenbury et al., 2006). The fact that this child received only 20 % of their language input in spoken English suggests that a relatively small degree of exposure to spoken language might be sufficient to follow monolingual trajectories of vocabulary acquisition in bimodal bilinguals and informs debates about the quantity of input needed for early language development (Bergelson et al., 2023).

A recent study of a larger group of bimodal bilinguals with varied exposure to spoken and signed language modalities compared their trajectory of vocabulary acquisition to monolinguals' and unimodal bilinguals' (Mercure et al., In press). As a group, bimodal bilinguals did not differ from monolinguals in English vocabulary at 15-months, 24-months and 7-years. In contrast, children exposed to two or more spoken languages (unimodal bilinguals) had smaller receptive and expressive vocabulary than monolinguals at 24-months. This finding is congruent with robustly observed effects of unimodal bilingualism on vocabulary size when measured in a single language (Byers-Heinlein et al., 2024; Poulin-Dubois et al., 2013; Siow et al., 2023; Stolarova et al., 2016), but suggests that the impact of bimodal bilingualism may be smaller than that of unimodal bilingualism on vocabulary acquisition in the spoken language of the majority. Moreover, English and BSL vocabulary sizes were positively correlated at the individual level, which suggests that bimodal bilingual acquisition does not interfere with vocabulary development in the majority spoken language (Mercure et al., In press). It remains unclear how vocabulary acquisition in one modality interacts with or contributes to vocabulary acquisition in the other. Cross-modal learning of concepts and its contribution to language learning across modalities will be further discussed in Section 5.

2.3. Grammatical development

At the level of grammatical development, it is also important to recognise the interaction of the two languages within a bilingual learner, sometimes leading to grammatical structures that differ from those of monolinguals of either languages (Chen Pichler et al., 2014; Grosjean, 2010). Recent research suggests that bimodal bilinguals' development in the preschool period is consistent with what would be expected of unimodal bilingual children and does not reveal any negative impact of bimodal bilingualism on grammatical development. For example, in their spontaneous production of spoken English, 2-to-5-year-old bimodal bilinguals demonstrated similar mean length of utterance in English and similar accuracy in their use of English grammatical morphemes compared to monolinguals (Goodwin, 2016). More bimodal bilinguals had Z-scores below the monolingual mean than predicted by chance on vocabulary diversity, mean length of utterance and index of productive syntax (Goodwin & Lillo-Martin, 2023). However, they were not more likely to show a clinically-relevant difference with the monolingual mean (1.5 standard deviation below the mean) on vocabulary and mean length of utterance, and only slightly more likely to do so for syntax. This finding in syntax may be influenced by the production of spoken utterances using the word order used in sign language (Chen Pichler et al., 2014; Lillo-Martin et al., 2016; Pichler, 2009), and is not surprising given what is known about grammatical development in unimodal bilinguals (Grosjean, 2010). It is however interesting to note that while grammatical development in the spoken language can be influenced by sign language learning in the early years, influences of the spoken language on the signed modality become more important from school-age years (see Chen Pichler et al. (2014) for a full discussion of findings including from older children).

One aspect of bimodal bilingual bilingualism that differs from unimodal bilingualism is the possibility of using code blending.

While unimodal bilinguals can switch from using one language to another, across or within sentences, bimodal bilinguals have an additional set of articulators that allows the simultaneous production of words and signs. A high degree of code-blending is used by preschool hearing children of deaf parents (Lillo-Martin et al., 2016; Pichler, 2009; Van den Bogaerde & Baker, 2005), with these productions following a form similar to the one used by their mothers (Van den Bogaerde & Baker, 2005). The production of code-blended utterances offers an interesting window into the interactions between the language modalities.

In conclusion, recent data suggest that hearing bimodal bilinguals develop language following similar early milestones of acquisition as described for monolinguals and unimodal bilinguals, and learning a signed language does not interfere with learning a spoken language. However, it remains unclear how the development of the two modalities interacts. Observations of positive correlations between BSL and English vocabulary and of bimodal bilingual advantages in early communicative skills suggest that positive transfers operate between the two modalities but research remains scarce on the mechanisms of these transfers across language modalities. These questions will be discussed further in Section 4.

3. Language development in deaf infants exposed to sign language

Language experience in deaf infants varies widely depending on the child's hearing profile, the parents' hearing status and preferred mode of communication, as well as the communicative strategies adopted by the family. About 95 % of deaf infants are born to hearing parents (Mitchell & Karchmer, 2004). Approximately 30 % of hearing parents report using sign language to communicate with their deaf infants while the majority of hearing parents use spoken language only (Stine, 2019), and only 1–2 % of deaf children worldwide receive formal education in sign language (Haualand & Allen, 2009). Deaf children whose families do not use sign language may have delayed or reduced exposure to their first language (L1) prior to audiological intervention. Exposure to sign language may provide the necessary access to language in deaf infants, at least until spoken language input is viable and while audiological intervention and cochlear implant treatment is in progress.

There is huge variability in the type, quantity and quality of sign language experiences in deaf infants. A small proportion of deaf infants are exposed to fluent models of sign language from their deaf parents who already use a natural sign language such as ASL, BSL or LSQ. On the other hand, hearing parents without experience of sign language prior to their child's identification as deaf cannot immediately provide a fluent model. Learning a sign language, as learning any other natural language, requires a huge investment of time and effort, and novice sign language learners are unlikely to provide fluent models in the early years. Moreover, there are many different forms of manual communication that can sometimes be included under the umbrella of 'sign language'. These include sign languages with their own phonology, vocabulary and grammar that naturally emerged in deaf communities around the world (ASL, BSL, LSQ etc). It can also include systems created to supplement spoken language comprehension, such as sign-supported speech (where signs are used to clarify content words in spoken language sentences), manually coded English (in which all morphemes of a spoken sentence are represented manually) and cued speech (in which the manual components represent phonological information only). For all these reasons, language experiences in deaf infants are extremely diverse with some infants receiving and accessing fluent models in two language modalities, while others have reduced access or exposure to fluent models in one or more modalities, and yet others have reduced access to language per se.

The last 25 years have seen huge controversies in the perceived advantages or disadvantages of sign language exposure for deaf children. On one side of the debate, sign language experience, has been perceived as encouraging cross-modal plasticity in the brain and leading to a 'visual takeover' of auditory areas that could limit the acquisition of spoken language post-implant (Champoux et al., 2009; Giraud & Lee, 2007; Kral & Sharma, 2012; but see Campbell et al. (2014) for a review of limitations and data not supporting this theory). In line with this hypothesis, Geers et al. (2017) measured English speech intelligibility, receptive skills and reading skills in children with cochlear implants and found that those who received more input in sign language were showing poorer spoken language performance than children with less or no sign language experience. This data was interpreted by the authors as an indication that sign language experience negatively impacts spoken language development in these children, despite many confounds in the study. It is crucial to note that the children exposed to sign language in this study were a mixed group, receiving sign input of various types, quantities and qualities. According to the authors' inclusion criteria, many so-called "signing" families in this study did not actually use a natural sign language such as ASL, but rather a language system that is artificially constructed (e.g., sign-supported speech or manually-coded English). Since these very different types of language experiences were not differentiated in this study, it is impossible to know what would have been found if only bimodal bilinguals with exposure to fluent ASL and English were included in the signing group. Moreover, Hall et al. (2019) pointed out that children's proficiency in spoken language is likely to influence the decision to introduce and use sign language with a deaf child, creating a self-selection bias in the research design. Finally, this study did not consider skills a deaf child may have in sign language and the fact that for some of these children, English might have been their second language. In this respect, the study confounded fluency in English specifically with proficiency in the dominant language, which may or may not have been English.

On the other side of the debate, a growing body of evidence suggests that bimodal language input represents a positive approach to education leading to optimal language development outcomes for deaf children. While data on language development in infancy is rare, studies with older children and adults often focus on early experiences and are therefore relevant to better understand the impact of sign language experience in the early years. In this context, it is interesting to note that deaf adults who received fluent sign language exposure in their early years can develop highly proficient reading levels in the spoken language of the majority (Stringer et al., 2024) and show rapid word retrieval in English (Bosworth et al., 2021). Moreover, children with CI acquiring ASL as a native language from their deaf parents have English language proficiency that is comparable to hearing bimodal bilingual children and exceeding scores reported for children with CI who were implanted at a similar age and used their CI for a similar duration (Davidson et al., 2014). In

another study, one deaf child with CI exposed to Italian Sign Language from an early age demonstrated vocabulary comparable to hearing peers in spoken Italian (Rinaldi & Caselli, 2014). The child predominantly used Italian Sign Language before receiving their CI and then gradually shifted towards spoken Italian. Taken together, these data suggest that exposure to fluent models of sign language in infancy not only leads to the development of a strong first language, but also scaffolds the (later) development of spoken language in deaf children.

Recent data suggest that even non-native use of sign language by hearing parents could lead to benefits in the development of spoken and signed language. Indeed, sign language exposure, and especially prolonged exposure, was found to associate with better post-CI outcome in spoken language development, phonological memory and nonverbal working memory (Delcenserie et al., 2024). Moreover, deaf infants with hearing parents, exposed to sign language before 6 months had ASL vocabulary similar to that of deaf infants acquiring sign language from their deaf signing parents (Caselli et al., 2021). ASL vocabulary in 4-year-old deaf children with hearing parents was also significantly predicted by their parent's proficiency in ASL (Berger et al., 2024). This relationship was not observed in infancy and toddlerhood, suggesting that the fluency of the model grows in importance with increased child's age. Finally, positive correlations between ASL and English vocabulary sizes were found in 8-to-60-month-olds deaf children with hearing parents (Pontecorvo et al., 2023). This finding is concordant with similar findings observed in hearing bimodal bilinguals (Mercure et al., In press) and suggests that transfers of gains in learning vocabulary may operate across language modalities or that efficient vocabulary acquisition across modalities depend on similar neurocognitive mechanisms.

Taken together, these studies suggest clear benefits for early bimodal exposure in deaf children. They demonstrate that fluent models in sign language lead to optimal outcomes in both language modalities, as well as in cognitive development. Less fluent models of sign language from parents who are learners of the language can also offer benefits to the child's communicative development in both modalities. The findings suggest that benefits of language development can transfer from one modality to the other. The next section of this review is aiming to explore the potential mechanisms of transfer of this benefit across language modalities.

4. Mechanisms of amodal language transfer

The evidence reviewed above suggest interactions between spoken and signed language development in the developmental period. In hearing infants, sign language experience leads to benefits in broadly defined early communication skills in the first year of life. It has also been observed that spoken and signed language vocabulary correlate with each other. In deaf infants, there is clear evidence that early access to a signed language benefits spoken language development. All these findings point to learning gains being transferred across sensory modality, but the mechanisms of these transfers remain unclear. The following section will discuss three potential amodal transfer mechanisms that are beginning to be investigated. For each of these mechanisms we ask whether there is empirical and/or theoretical support for their development depending on early language access and for transfer across modalities.

4.1. Language in any modality helps develop the language network in the brain

Research carried over the last 25 years have clearly demonstrated that early sign language access in deaf infants leave a long-lasting impact on the structural and functional development of the brain, which could facilitate the acquisition and processing of signed and spoken languages as the child grows. One reason for this may be because spoken and signed language share neural substrates. Just before the turn of the century, neuropsychological studies with patients revealed somewhat surprisingly that sign language was mainly processed in left lateralised language areas (Corina et al., 1999; Poizner et al., 1987). These findings challenged the view often held at the time that perceived language only through the lens of speech. The fact that classical language areas process language regardless of the sensory modality in which it is presented became clearer with further neuroimaging studies with adult fluent signers (see MacSweeney et al. (2008) for a review).

This is in contrast with how differently the adult brain processes language in individuals without full access to language in the early years (see Mayberry and Kluender (2018) for a review). These were often individuals who were not diagnosed with congenital deafness until later in life and spent their first few years in environments with inaccessible speech, learning ASL in late childhood or teen years. When viewing sign language stimuli, their brain activation patterns showed reduced involvement of language areas but increased involvement of sensory-perceptual areas of the visual cortex (Mayberry et al., 2011). This pattern of activation clearly contrasts with activation for sign language observed in hearing adults learning ASL as an additional language (L2) later in life (Ferjan Ramirez et al., 2014), or hearing adults acquiring a new spoken language as an L2 (Indefrey, 2006). In all studies of L2 learning in individuals with full access to an L1 from birth, the pattern of activation predominantly involves left lateralised language areas, without the increased activation in sensory-perceptual areas observed in deaf individuals with late L1 acquisition. These findings suggest that early language experience while the brain is in a phase of maximal plasticity is required to establish the classical neural network for language.

Infant studies also reveal that the brain recognises and processes natural languages differently from other stimuli from early life, regardless of their sensory modality and the infant's experience of different modalities. Mercure et al. (2020) showed some consistency in how the brain processes spoken and signed language in hearing infants with and without experience of sign language. Berent et al. (2021) further demonstrated that hearing infants exposed only to spoken language showed similar brain activation patterns in response to a rule learning paradigm presented in signed and spoken language, but not when presented in non-linguistic stimuli.

The neuroimaging literature therefore suggests that the benefits of sign language exposure in deaf infants may act through the development of a neural architecture advantageous for language learning in any modality. The exact biological means by which language experience impacts the structural and/or functional development of the brain in infancy remains unclear but could involve the development of connectivity between brain regions involved in language processing. Indeed, Fibla et al. (2023) have demonstrated

that hearing 30-month-olds exposed to more language input in their home environment had more myelin in white matter tracks closely involved in language processing – the arcuate fasciculus and the superior longitudinal fasciculus. In deaf individuals, late L1 learning also affects the development of the arcuate fasciculus (Cheng et al., 2019). Many questions remain about the development of the language network in the brain. For example, what characteristics of the sign language exposure (type, quantity and quality of sign language experience) influence the development of the neural architecture? Also, is the development of language networks in the brain accelerated by bimodal language exposure in hearing bimodal bilinguals without delayed exposure to an L1?

4.2. Language in any modality trains non-linguistic abilities that are prerequisite for further language learning

The idea that some of the benefits of early exposure to SL may train transferable abilities such as memory and attention is only recently gaining traction. Again, confounded research had for a long time suggested the opposite. Two decades ago, the auditory scaffolding hypothesis was put forward to explain difficulties in language development in some deaf infants that received CI later in life. This hypothesis suggests that hearing loss impairs the development of general cognitive abilities related to the processing of temporal and sequential patterns, which are key for subsequent language processing (Conway et al., 2009). Conway and collaborators observed difficulties in visual sequence learning (Conway, Pisoni, et al., 2011) and motor sequencing (Conway, Karpicke, et al., 2011) in 5- to 10-year-old deaf children with CI, which correlated with standardised measures of spoken language development. More recently, differences in temporal and sequential pattern processing were also observed in the first year of life. Monroy et al. (2019) found that deaf infants were slower to habituate to visual stimuli than hearing infants and that visual habituation correlated with spoken language development measures. Moreover, deaf infants pre-CI did not demonstrate evidence of visual statistical learning, while hearing infants of the same age and deaf toddlers with CI did (Monroy et al., 2022). However, an alternative explanation to these findings is that it is the language deprivation that can accompany hearing loss, especially in a non-bimodal language environment, that negatively impacts the processing of temporal and sequential patterns, rather than deafness itself. Conway, Pisoni, et al. (2011) note that, in their study, "several of the children had been exposed to Signed Exact English" which is a system of manual communication that aims to mirror English vocabulary and grammar but is not a natural language. In contrast, deaf native signers exposed to a natural sign language (ASL) were found to have better visual learning of spatial-temporal sequences than hearing non-signers (Giustolisi & Emmorey, 2018). In a similar manner, non-verbal working memory and executive functions were initially claimed to be negatively affected by deafness (Burkholder & Pisoni, 2003; Hauser et al., 2008). However, like for sequencing skills, reduced access to language may be more to blame than auditory deprivation per se (Hall et al., 2018). Indeed, differences between deaf and hearing children in working memory and executive function tasks were mostly eliminated when deaf children were exposed to fluent models of sign language in the early years (Hall et al., 2018; Marshall et al., 2015).

The interaction between language acquisition and the development of attention control and memory, is an area of growing interest in developmental research (Schroer & Yu, 2023; Spencer et al., 2025), and likely to shed light on the benefit conferred by early exposure to sign language in deaf infants. Research is also required to clarify the impact of a bimodal bilingual language experience on cognitive development in hearing infants with deaf parents.

4.3. Language in any modality trains pragmatic and communicative abilities

In the first year of life infants learn that language is intended for communication, and that it refers to objects, people and events in the world. Very young infants seem able to already identify linguistic from non-linguistic stimuli, both in the auditory and visual modality. For example, six months old sign-naïve hearing infants attended differently to linguistic versus non-linguistic body actions (Bosworth et al., 2022), to natural versus reversed signed sentences (Bosworth & Stone, 2021) and to well-formed lexicalised fingerspelled words compared to ill-formed (Stone et al., 2018). These early sensitivities to language stimuli and attentional biases were lost by 11 months in the absence of sign language exposure (Bosworth & Stone, 2021). We propose that, with continuous early access to sign language, these biases may be maintained in deaf infants and might support attention to amodal aspects of linguistic content in a spoken language, later on. Future research is required to more precisely characterise the nature of amodal information infants use to identify a signal as being communicative or linguistic.

During their first year of life infants also gradually discover which bodily movements are used as referential signals (e.g. gaze shifts, pointing). By one year of age, hearing infants expect that, when used together, words and other cues such as pointing and gaze shifts, co-refer, i.e. refer to the same object (Gliga & Csibra, 2009). Around the same age, they make use of co-occurrence between a familiar communicative cue and a new cue to endow the latter with referential meaning (Wu et al., 2011). A recent study showed that deaf infants from deaf families show significantly more consistent gaze following than hearing infants from hearing families (Brooks et al., 2020). This advantage may be conferred by the frequent co-occurrence of referential signals such as gaze shifts and pointing. Frequent exposure to gaze shifts and pointing, which in SL can be lexicalised (e.g. pointing to a location to mean there) might facilitate learning of gaze following. Future research should test whether these differences are explained by an advantage conferred by co-occurrence between signed labels and referential signals as well as whether they further lead to an advantage in using referential cues when learning a spoken language, in bimodal bilinguals.

5. Looking ahead to the next 25 years…

The last 25 years have provided major improvements in our understanding and awareness for early bimodal bilingualism in hearing and deaf children, but the research data collected so far leave several questions unanswered. One rarely addressed question is the role

that conceptual knowledge may have in the transfer from one language to another. Early sign language exposure may help build abstract semantic concepts, and this knowledge of the world could then be accessible to support the acquisition of a new language, independent of its modality. The bidirectional link between language and conceptual learning is now supported by 20 years of experimental evidence. It has been robustly demonstrated that providing children with object names, whether spoken (Althaus & Westermann, 2016; Waxman & Markow, 1995) or signed labels (Novack et al., 2021) helps them learn new categories. Once category knowledge is established, labelling only one exemplar of this category is sufficient to generalise this label to other category members (Pomiechowska & Gliga, 2019). In deaf children, this opens the possibility that spoken language benefits from early access to sign language because categories learned by exposure to the former (i.e. as a result of parents providing signs for common objects) may later serve as substrate for spoken word-generalisation, speeding up vocabulary acquisition. This is suggested by the fact that vocabulary development correlates across modalities in deaf and hearing children exposed to spoken and sign language (Mercure et al., In press; Pontecorvo et al., 2023). It is still unclear if the same or different concepts tend to be acquired across language modalities and how sign learning interacts with word learning. If conceptual transfer occurs in children exposed to sign language, spoken vocabulary acquisition would be faster for words that were already part of the child's signed vocabulary. This prediction remains to be tested in future research.

To fully explain the benefit of early sign language access for later spoken (and signed) language proficiency, we identified several pre-requisite learning gains that may be transferred from one communication modality to another. For the field to move forward, thorough measuring and reporting of infants' language experience history and further development of standardized sign language fluency measures are needed so that we can examine the relationship between language input and later language development (Hall & De Anda, 2021). Very few of the studies we cited, from the past 25 years, report on children's natural sign language experience and even fewer use this measure as predictors of language development. This is likely to change due to a growing understanding of the importance of early access to language in any modality. It will also change with the development of new tools that better capture varied experiences, such as multi-lingual communicative development inventories and sign language specific parental reports (D-LEAT, Hall & De Anda, 2021).

Finally, a majority of current work focused on the direct impact of early sign language exposure on infant neurocognition. Yet, less understood is how early access to sign language in deaf children influences children indirectly through increased parental awareness of what makes communication with a deaf child successful and increased parental confidence. Studies of parent-child play have shown that deaf-deaf and hearing-hearing parent-infant dyads use different strategies for establishing communication. From the first months of life, deaf parents reposition their infants so that they face each other and use gentle touch to grab attention (Koester & Lahti-Harper, 2010). They also follow more into the infant's attention focus rather than trying to re-direct their attention (Curtin et al., 2021). These strategies result in more time spent in joint attention and more turn-taking (Curtin et al., 2021). As deaf infants gain access to spoken language, post CI, they will likely still benefit from these adaptations. For example, giving infants more time to orient to objects before labelling them, something deaf parent of deaf infants do (Curtin et al., 2021), is likely to lead to more successful learning in both signed and spoken language. In addition, establishing and experiencing successful communication with deaf babies, using spoken or sign language, is likely to increase parental confidence and enjoyment of interaction. Parental self-efficacy measures reveal positive correlations between a deaf child's language skills and parental beliefs about their ability to support their child's spoken language development, their abilities to use strategies to support communication and their active involvement in their child's intervention (Davenport et al., 2025). Access to signed communication earlier on may lead to increases in parental self-efficacy which are likely to transfer into more confidence in supporting later interaction through signed or spoken language. We anticipate that, as the field moves forward, and as more parents are given access to sign language themselves, these aspects of interaction will become central to research into sign language and bimodal bilingualism.

Taken together, the data reviewed suggest that early bimodal language experiences leave a lasting impact on the child's neurocognitive and communicative development with some gains in one language modality being transferred into advantages in the other modality (see summary in Fig. 1). The study of infants with sign language experience reveals that multidisciplinary work is required for a better understanding of the bidirectional relationships between language, communication, perception, cognition and the brain in human development.

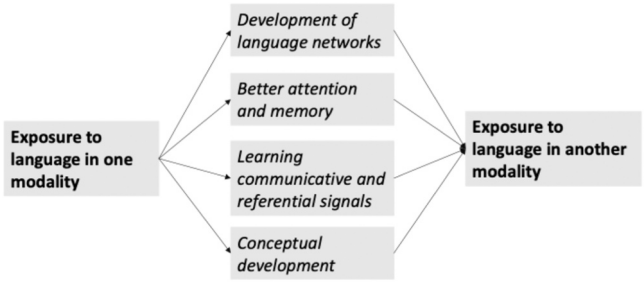

Fig. 1. Putative mechanisms to explain the transfer of learning gains across language modalities.

CRediT authorship contribution statement

Rain Bosworth: Writing – review & editing, Writing – original draft, Conceptualization. **Teodora Gliga:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Evelyne Mercure:** Writing – review & editing, Writing – original draft, Conceptualization.

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Data Availability

No data was used for the research described in the article.

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