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Making sense of sensory language: Acquisition of sensory knowledge by individuals with congenital sensory impairments

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A B S T R A C T

The present article provides a narrative review on how language communicates sensory information and how knowledge of sight and sound develops in individuals born deaf or blind. Studying knowledge of the perceptually inaccessible sensory domain for these populations offers a lens into how humans learn about that which they cannot perceive. We first review the linguistic strategies within language that communicate sensory information. Highlighting the power of language to shape knowledge, we next review the detailed knowledge of sensory information by individuals with congenital sensory impairments, limitations therein, and neural representations of imperceptible phenomena. We suggest that the *acquisition* of sensory knowledge is supported by language, experience with multiple perceptual domains, and cognitive and social abilities which mature over the first years of life, both in individuals with and without sensory impairment. We conclude by proposing a developmental trajectory for acquiring sensory knowledge in the absence of sensory perception.

> “I know [sound] so well that it doesn’t have to be something that’s just experienced through the ears. It could be felt tactilely, or experienced as a visual, or even an idea.”
>
> – Christine Sun Kim, Deaf artist, *TED talk*
>
> “I am glad that I am not debarred from all pleasure in the pictures. I have at least the satisfaction of seeing them through the eyes of my friends. . . I am so thankful that I can rejoice in the beauties, which my friends gather and put into my hands!"
>
> – Helen Keller, *The Story of My Life*.

1. Introduction

Humans learn about the world through direct perceptual experience and through language. We can see that bananas are yellow or taste their sweetness directly. But we could also learn this perceptual information through language. If you’re told that “tamarillos” are egg-shaped fruits that can be red or orange, without ever seeing a tamarillo, you’ve learned about its appearance. However, language and perception are not equivalent sources of information, and it remains unclear the *extent* to which language is informative for learning sensory information in the absence of perception.

By examining how language encodes sensory information, as well as congenitally deaf[1] individuals’ knowledge of sound, and congenitally blind individuals’ knowledge of sight, we can gain insight into broader questions about how language relays sensory information, how the brain encodes it, and how children learn it.

In what follows, we 1) characterize the sensory information available in language, 2) detail the sensory knowledge of adults with sensory impairments, and 3) speculate on the developmental trajectory of sensory learning. We ask: **how could blind or deaf individuals learn about sight/sound through language?** In short, we propose that language plays a key role in the acquisition of sensory knowledge, and that children with and without sensory impairments follow largely the same developmental trajectory. For children with sensory impairments however, we propose two key differences: a larger role for the insights licensed by theory of mind (which in this case includes the insight that others have sensory experiences they lack), and a heavier reliance on linguistic context (rather than direct experience) to learn sensory language and information, with sensory language being learned through language structure, e.g. syntactic bootstrapping, similar to unobservable *hard words*, à la Gleitman et al. (2005).

1.1. Scope

Sensory impairment varies widely in cause, severity, and cultural or

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[1] “Deaf” with a capital D typically refers to cultural aspects of deafness, such as sign language use, whereas lower-case “deaf” refers to audiological status. Here we use “deaf” to refer to individuals with severe-to-profound hearing loss, and “Deaf” for instances specific to the culturally Deaf community.

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clinical implications. We generally limit our scope to a subset of the affected population: individuals born with severe-to-profound deafness or blindness, with no cognitive comorbidities, amplification devices, or corrective surgeries. Due to the importance of language input and processing within our proposed developmental pathway, for the deaf community, we try to highlight sign language research, as this provides a more parallel comparison to the blind population (who generally have full access to the spoken linguistic signal). Given the scarcity of sign language research on this topic, however, we supplement our review with data from deaf individuals using spoken language (generally after a period of linguistic deprivation) and note in-text when data come from individuals with reduced linguistic access. Selecting small subsamples from communities with diverse communication styles, sensory ability, and life experiences limits the generalizability of this work to the broader populations of deaf and blind individuals. We do this as an initial step to help isolate the role of language in developing sensory knowledge. Similarly, while cross-linguistic differences are relevant to the central questions we ask, they are not our focus (cf., Majid et al., 2018).

2. What sensory information is available in language?

This section describes the perceptual information available in the sounds, words, and structure of language, as well as linguistic strategies that convey perceptual content. One way language communicates sensory information is through dedicated words that describe perceptual experience, including sensory properties (e.g., “pink”, “bumpy”), perception (e.g., “see”, “hear”), and sensory experiences (e.g., “odor”). Sensory information can be quantified through sensory association word norms, whereby words are rated for how strongly they evoke each sense (e.g., visual, haptic, etc.; Lynott et al., 2020; Vergallito et al., 2020; Speed and Majid, 2017). Such norms reveal that the English lexicon, for instance, is biased towards communicating about sight, with relatively less representation for auditory and tactile information, and even less for taste and smell (Buck, 1949; Viberg, 1983, 1994; Evans and Wilkins, 2000; Winter et al., 2018). This visual dominance in the lexicon is relatively common across cultures and languages (cf. San Roque et al., 2015 for perception verbs; Majid et al., 2018 for sensation description, specifically color), though certainly not universal (Majid et al., 2018), with the relative ranking of other perceptual modalities less well-defined. For individuals born deaf or blind, English’s overrepresentation of visual and auditory terms (relative to smell and taste words) may be helpful in learning about those imperceptible domains; this is an empirical question which could perhaps be approached through leveraging the cross-linguistic variation in the codability of different perceptual modalities (e.g., color is very low in codability in Kata Kolok and Umpila, Majid et al., 2018).

While words can have meanings that elicit sensory associations, a word’s form can also *depict* sensory information, via iconicity. Iconicity captures the extent to which the perceptual form of language reflects its meaning. For instance, “moo” acoustically imitates the sound cows make, and the American Sign Language (ASL) sign for DRINK features a cupped hand tilting towards the mouth, visually representing the act of bringing a glass to the lips; these words are high in iconicity, while the English word “table” is not. Ideophones like “zigzag” and “splish-splash” are a subclass of highly-iconic, structurally-marked words that also make use of sound symbolism, articulatory symbolism, and timing (Blench, 2009; Dingemanse, 2012). Cross-linguistic work finds ideophones across sensory domains, though sound- and movement-related ideophones are most common across spoken languages, (Dingemanse, 2012).

Onomatopoeias iconically depict a range of auditory phenomena, including human noises (“hum”, “achoo”), animal calls (“squawk”, “ribbit”), and inanimate sounds (“snap”, “crackle”, “pop”). These words may act as a bridge between language and sound: Hashimoto et al. (2006) found that while separate brain regions were activated for processing animal sounds and (non-onomatopoeic) animal words (bilateral superior temporal sulcus and the left inferior frontal gyrus vs. left anterior superior temporal gyrus), onomatopoeias elicited more extensive activation, encompassing the superior temporal sulcus, inferior frontal gyrus, and superior temporal gyrus, with greater superior temporal sulcus activation than either the nouns or sounds. While onomatopoeias represent sounds iconically, they are influenced by language constraints. For example, Chinese frogs say “guo guo”, and Hungarian frogs say “brekeke”.[2] Phonotactic properties also influence the degree to which words from a given sensory domain can be iconic, such that auditory words in spoken language and visual words in signed languages tend to be more iconic than words from other sensory domains (Winter, 2017; Perlman et al., 2018); we return to this point in our proposed developmental trajectory.

Yet another way language iconically relays perceptual meaning is through phonesthemes, speech sounds that are associated with a sensory experience (e.g., Hinton et al., 1995; Schmidtke et al., 2014). For example, many English words beginning with “gl”– refer to shining or transient visual phenomena (e.g., “glitter”, “glisten”; Bergen, 2004). If individuals with sensory impairment are sensitive to these sound-meaning links, this would facilitate learning of sensory language, though to our knowledge this is yet to be empirically tested.

Relatedly, intuitions about certain sound-meaning relationships are largely consistent across individuals and cultures (e.g., high pitched sounds with smallness; voiced, labial sounds with roundness). This phenomenon is known as sound symbolism. For example, in the well-documented bouba-kiki task, participants readily associate the word “bouba” with a rounded shape and “kiki” with a jagged shape (Davis, 1961; Bremner et al., 2013). However, if learning sound symbolic relationships relies on *experiencing* associations between perceptual phenomena and language, sound symbolism may differ for individuals with sensory impairments. Prior work with deaf adults (using spoken language following prelingual deafness) tested on the standard visual/auditory bouba-kiki task (Gold and Segal, 2020) and blind adults tested with a haptic/auditory task (Fryer et al., 2014) finds weaker sound symbolic associations in these groups than in sighted and hearing adults. These findings are consistent with an experience-dependent account of sound symbolism (but also confounded with early linguistic deprivation in the case of the deaf group).

Alternative linguistic strategies complement dedicated language for perceptual experiences. For instance, source-based language uses the source of a percept or a similar percept to precisely identify a shade of color, sound, taste, smell, or touch by naming a known source (Plümacher and Holz, 2007, pg. 62–66), relying on shared common ground. For instance, describing something as “robin’s egg blue” would not identify the specific shade of blue for someone who has never seen the color of a robin’s egg. However, even without experiential common ground, source-based descriptions facilitate associations between the referent and the descriptor. The descriptor “robin’s egg blue” suggests to the listener that there is a consistent association between robins’ eggs and a shade of blue; the inference being that robin’s eggs must commonly be blue if sighted individuals can identify a blue with that descriptor.

Cross-sensory expressions, or *synesthetic metaphors* (cf., Day, 1996; Winter, 2018), are another linguistic strategy, wherein words typically associated with one sense describe another (e.g., “loud color”, “bright sound”). Intriguingly, cross-sensory expressions trigger neural activations associated with the *source* sense (e.g. vision for “loud color”; Lacey, Stilla, & Sathian, 2012; Citron and Goldberg, 2014; Pomp et al., 2018). This suggests that cross-sensory expressions facilitate connections between target and source perceptual domains. Likewise, for individuals with sensory impairments, cross-sensory expressions may help form associations between a perceptually accessible experience and an

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[2] Frogs who use American Sign Language sign: CROAK.

imperceptible one.

Finally, a great deal of information about word meanings (perceptual and otherwise) is carried not just by sensory language and the linguistic strategies discussed above, but across words' semantic and syntactic contexts in utterances and conversations more broadly. Regarding semantic context, research on distributional semantics highlights that meaning is, in part, constructed through the contexts in which words are used (Firth, 1957), finding that words that occur in semantically similar linguistic contexts tend to be semantically related (Lenci, 2008). Indeed, semantic representations derived from words' linguistic co-occurrences mirror human judgments of semantic similarity for perception verbs and animal appearances (Lewis et al., 2019; cf. Paridon et al., 2021 for related work). Regarding syntactic context, experiments find that syntactic cues can aid children in acquisition of color words, though in naturalistic input, non-ambiguous syntactic frames may be rare (Sandhofer and Smith, 2007). To provide another example, syntactic contexts like "I *glorp* that he did it" cue listeners that "glorp" is either a mental state verb or verb of perception. Thus, as is the case across other facets of meaning, aspects of sensory experience too are encoded in linguistic structure.

2.1. *Summary of sensory information in language*

While it is clear that language has many avenues for relaying perceptual knowledge that can complement, supplement, and potentially stand in for actual perceptual experience when it's unavailable, how often does such "helpful" language occur? Calculating the prevalence of such language is challenging, but on the whole the sensory linguistic phenomena like onomatopoeia appear relatively rare (See Table S1 for ballpark rates for English, where estimable). And yet, as we discuss next, deaf and blind individuals know a great deal about sound and vision. To us, this highlights the particular potency of information derived from structural aspects of language (as in the syntactic bootstrapping and distributional semantics examples above) for learning sensory information.

Progress identifying the balance of how much *linguistic structure in general* vs. *sensory linguistic phenomena in particular* contribute to sensory knowledge is stymied by missing empirical data on general rates of sensory language used by sighted and hearing individuals, but more critically, by those with sensory impairments, in both spoken and signed language contexts. Without analyses of the prevalence of sensory information in language in everyday interaction across these communities and particularly with child learners, a deeper understanding of the mechanisms by which language transmits sensory information remains out of reach. Fortunately, the advent of long-form naturalistic recordings is beginning to make first steps in such work possible (Campbell et al., 2021). Having laid out some ways language encodes perceptual information in principle, we next ask what perceptual information individuals with sensory impairments have acquired.

3. What do deaf and blind adults know about sight and sound?

3.1. *"Visual" knowledge in blind individuals*

Prior research has probed blind individuals' knowledge of visual word meanings, properties, and imagery, as we review below. Regarding meanings, results indicate that visual perception is not necessary for acquiring semantically-rich representations of visual words (Bedny et al., 2019; Landau and Gleitman, 1985; Minervino et al., 2018). For example, as part of a case study, Landau and Gleitman (1985) asked a blind adult to define visual verbs. Many of his definitions reflect accurate knowledge of visual word meanings. For example, "to fade" is defined as "to disappear gradually...sound or color would become less intense, become washed away so the color looks lighter...an object will fade as you get further back from it." In another task, blind and sighted participants were asked to rate the semantic similarity of verbs from different sensory domains (Bedny et al., 2019). For visual verbs, blind participants' responses were indistinguishable from those of sighted participants. In addition to accurate comprehension of literal uses of visual words, blind individuals also understand figurative uses of visual words (Minervino et al., 2018).

At the same time, sensory and semantic association word ratings do differ in blind and sighted adults. For instance, Kerr and Johnson (1991) find that for words whose referents could only be experienced visually (e.g., "shadow"), blind participants reported visual associations, but when the visual referent (e.g., "arm") could be experienced through another sense, blind participants described their non-visual associations more often than sighted participants did. Relatedly, Lenci et al. (2013) collected semantic feature norms from Italian-speaking blind and sighted participants. While there was considerable overlap across groups, blind participants produced significantly fewer perceptual properties than sighted participants overall (though split by modality was not provided). Taken together, these data suggest that although blind individuals define visual words similarly to sighted individuals, traditional sensory ratings of language by sighted participants (unsurprisingly) do not fully reflect the sensory experiences of blind individuals.

Another way to study blind individuals' visual knowledge is by querying their representations of how visual properties (e.g., color, brightness, etc.) are associated with objects or other properties. For instance, across several studies asking participants to rate color similarity (e.g., "how similar is green to blue?"), roughly half of blind participants' color similarity judgments were consistent with sighted participants, while the rest diverged (Marmor, 1978; Saysani et al., 2018; Shepard and Cooper, 1992). When asked how they acquired this knowledge, blind adults reported no formal training in color relations, with the exception of science class lessons on the color spectrum. Instead, participants recalled learning color relationships through conversations with sighted people about fashionable color coordination or "chance conversations in which colorful objects and events like rubies and sunsets were discussed." (Marmor, 1978). These results demonstrate that some color knowledge readily emerges without visual perception (Marmor, 1978; Saysani et al., 2018; Shepard and Cooper, 1992).

Extending these results, Saysani et al. (2021) recently asked participants to judge colors' similarity, as well as rate color terms along several semantic scales (e.g., happy—sad, cold—hot). On many of the scales, blind participants resembled sighted participants, though there were notable individual differences. Blind individuals who produced accurate color similarity judgments tended to also have semantic associations for color that more closely resembled sighted individuals (e.g., *blue is cold/red is hot*; Saysani et al., 2021). Saysani and colleagues interpret these results as evidence for distributional semantics (i.e. how color words occur in language) as a driver of blind individuals' color knowledge. Supporting the idea that color words distributional semantics supports color knowledge in both blind and sighted participants, a follow-up study found that both groups' color-semantic ratings (e.g. where "orange" falls on a scale of happy—sad) in this task were predicted by word embeddings from a corpus of spoken and written English (van Paridon et al., 2021), though this effect was stronger for sighted participants. For the blind participants, this relationship was mediated by the presence of highly salient examples (e.g., "snow" for "coldness is white"). These results license two conclusions: (1) spoken language co-occurrence statistics capture color-semantic associations regardless of access to vision, and (2) tracking the contexts in which highly salient words occur may turn out to help blind individuals acquire associations between color and other dimensions of meaning, though empirical work is necessary to test this proposed mechanism.

Examining visual knowledge from a different angle, Kim et al.

(2019a), (2019b) tested congenitally blind adults' knowledge of visual properties (i.e., size, height, color, texture, and shape[3]) of animals. When asked about animal appearance, blind and sighted adults largely performed similarly with regard to size, height, texture, and shape, with a subset of blind participants producing indistinguishable judgments from the sighted adults. Blind participants performed least accurately for color, but still produced many accurate color judgements. Adding support for the role of the distributional structure of language in perceptual representations, further analysis showed that the semantic representations acquired by associative learning algorithms exposed to natural language (which are based on the distributional structure of language) correlated significantly with both blind and sighted participants' performance, but in this case more so for the blind group (Lewis et al., 2019). These results again highlight the role of distributional semantics in relaying visual information, perhaps especially for blind individuals. That said, blind and sighted participants' ratings were more similar to each other than to the model, suggesting that human mental computation here goes beyond the model's predictive capacity. How precisely word co-occurrence drives knowledge is still a matter of debate, with strong arguments supporting both a 'lower level' associative learning component alongside a 'higher level' inferential one (Lewis et al., 2019; Kim et al., 2019a, b).

Blind individuals also demonstrate sophisticated understanding of color stability (Kim et al., 2020). In one task, blind and sighted participants were asked about color consistency (e.g., "If you picked two *lemons*/*cars* at random, how likely are they to be the same color?"). Blind participants' color consistency ratings mirrored those of sighted participants. When participants were asked *why* objects have those colors, participants' responses again were similar across groups. These results suggest that rich causal knowledge of color is separable from specific object-color associations.

Although blind individuals demonstrate rich, detailed knowledge of the color or appearance of common objects (Kim et al., 2020; Kim et al., 2019a, b; Landau and Gleitman, 1985), they appear to weigh this information less heavily than sighted individuals in, e.g. semantic similarity judgments. For instance, in a semantic similarity task consisting of fruits, vegetables, and household objects, blind participants were less likely than sighted to use color as a basis for semantic similarity (Connolly et al., 2007; e.g., sighted participants were more likely than blind to group red objects as semantically similar).

What should be surprising is not that blind individuals (who by definition have never had direct perceptual access to visual properties like color) perform less well on tasks of visual property knowledge than sighted ones, but that they perform surprisingly similarly to sighted adults given only indirect access to visual information. As reviewed above, blind individuals have acquired visual knowledge about associations between properties (e.g., that cold is blue; Saysani et al., 2021), the appearance of many objects and animals (Kim et al., 2019a, b; Kim et al., 2020), and how stable object color is for different categories (Kim et al., 2020). This in turn raises the possibility that sighted individuals too rely to a great degree on indirect routes like language co-occurrence statistics and inferences licensed by language in concert with directly perceivable input to build their color knowledge.

While the studies above suggest that blind individuals readily conceptualize visual properties, this may be distinct from the ability to visualize these properties with the *mind's eye*, through visual imagery (i.e. the representation of visual images generated in the absence of retinal input; Roland and Gulyás, 1994). In studies of sighted individuals, imagery is often evaluated by eliciting ratings of the subjective intensity of imagery evoked by various words, or by asking individuals to memorize then recall high-vs. low-imagery words (the former being better remembered; Paivio, 1971). Using these same dependent variables, blind adults report experiencing visual imagery, though less than sighted adults (e.g., Cornoldi, 1979; Zimler, 1983). More specifically, when asked about the type of imagery elicited by different words, for words that one might assume rely on direct visual experience (e.g., rainbow), both blind and sighted individuals reported the imagery modality as "visual" (Craig, 1971; Marmor, 1978; Cornoldi, 1979). For multisensory stimuli however, blind individuals are more likely than sighted to describe the imagery modality as non-visual (e.g., reporting tactile or auditory imagery for rose), whereas sighted participants would be more likely to report visual imagery in these multisensory cases. Moreover, on some recall tasks, blind participants show a modest boost in recall for high-visual imagery words compared to low-visual-imagery words (Craig, 1971), similar to sighted adults. These findings suggest that even visual imagery (at least as measured by the operationalizations above) can emerge without direct perception.

3.1.1. Neural plasticity and concept representations in blind and sighted adults

Comparing the brains of blind and sighted individuals highlights differences in neural organization in response to differences in perceptual experience. For instance, the occipital cortex of congenitally blind vs. sighted individuals demonstrates an enhanced response to *non*-visual stimuli (Van Ackeren et al., 2018; Amedi et al., 2003, 2005; Bedny et al., 2011; Sadato et al., 1996; Mattioni et al., 2020), and particularly relevant here, linguistic stimuli (Kanjlia et al., 2019; Lane et al., 2015; Bedny et al., 2011). In spite of this neural reorganization, blind individuals' concept representation is still remarkably similar to sighted individuals'. Indeed, when blind individuals are presented with objects in an accessible modality (i.e., sound, touch) their neural responses are locationally similar to those of sighted individuals who visually perceive the same objects. In these cases, functional brain organization does not rely on visual input. Such parallels also exist in blind adults' activation in "visual" word form area for auditorily- or tactilely-presented text (Kim et al., 2017; Striem-Amit et al., 2012; Reich et al., 2011). As further evidence of blind individuals' refined sensory knowledge, their neural representations don't simply collapse concepts they can or cannot perceive: they exhibit differentiated responses in the anterior temporal lobe for concepts that are, for them, imperceivable, perceivable, abstract, and concrete (e.g. rainbow, rain, freedom, and cup, respectively; Striem-Amit et al., 2018). Taken together, this research suggests that just as behavioral work highlights the cross-modal and linguistic routes to perceptual knowledge in blind individuals, so too does the neuroscientific literature highlight parallels in brain activation that reflect multiple pathways to perceptual knowledge, encoding, and representation.

3.2. "Auditory" knowledge in deaf individuals

In contrast to the literature on visual knowledge among blind individuals, auditory knowledge among deaf individuals is relatively unexplored. We next review this limited literature, specifically with regard to knowledge reflected by sign language representation, auditory imagery, and rhyming ability. Given the sparsity of research in this area, we also touch briefly on representations of sound in Deaf literature as a proxy for auditory knowledge for the deaf population more broadly.

Knowledge of sound is embedded in the structure of signed languages, which are formed organically by Deaf communities. To demonstrate this point cross-linguistically, over half of the English-language words rated "highly auditory" in sensory association norms (e.g. "loud"; Lynott & Connell, 2020) appear in a multilingual sign language dictionary.[4] More concretely, the concepts LOUDNESS,

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[3] While properties like texture can be haptic as well as visual, most adults (sighted or blind) have not felt (e.g.) a hippopotamus.

[4] 45/74 words that were rated (by hearing adults) above 4.75/5 on the auditory scale of the Lancaster Sensorimotor Norms were listed in the online sign language dictionary Spread the Sign, often appearing in many of the 42 signed languages represented in the dictionary.

SILENT, and MELODY have translation equivalents in 15, 23, and 25 sign languages, respectively (Spread the Sign, 2021). At a coarse level, this shows that auditory concepts are represented in languages for the deaf (Spread the Sign, 2021). Zooming in on American Sign Language, recent work by Emmorey and colleagues (*in press*) presented native deaf ASL signers with sound stimuli via tactile vibrations felt through their hands through a balloon that was touching an audio speaker at maximum volume. Participants were asked to describe the sounds in ASL. Deaf signers in this study described 95% of the sounds presented. Common strategies included fingerspelled words (e.g., R-U-M-B-L-E, B-U-Z-Z-I-N-G, B-E-E-P; 5% of responses), source-based descriptions (e.g., GUITAR, HONK-HORN; 15% of responses), dedicated sound vocabulary (e.g., LOUD, HIGH, QUIET; 28% of responses), and classifier descriptions (e.g., CL: hooked 5 handshape opens wide (used to describe a loud sound); 37% of responses). These classifier constructions, the most common strategy for depicting sound in ASL, are particularly interesting because they represent a way for deaf signers to productively (and iconically) describe pitch, volume, and duration of a novel sound (Emmorey et al., 2022). Signs referencing sound are also anatomically iconic: across nearly 3 dozen sign languages (including sign language isolates like Kata Kolok), HEAR and other sound-related concepts are overwhelmingly produced near the ear (Östling, Börstell, & Courtaux, 2018; de Vos, in preparation). Similar patterns of sound expression (i.e., *translating it from an inaccessible modality (auditory) to an accessible modality (visual, tactile)*) can be found in Deaf literature and music (Rosen, 2007; Cripps et al., 2017). In literature, congenitally deaf authors often use cross-sensory descriptions of sound (Rosen, 2007), e.g. expressing rhythm as tactile vibrations of stamping feet (Clark; Rosen, 2007) or throbbing heartbeats (Kessler; Rosen, 2007). Signed music uses varied handshapes and vertical and horizontal movement to express pitch variation (Cripps et al., 2017).

In addition to auditory knowledge of the world at large, many congenitally deaf individuals learn spoken language as a second language, and acquire knowledge of spoken language sound structure. This is seen in studies showing that deaf individuals can generate rhyming word pairs at above chance rates (Hanson and McGarr, 1989). Deaf individuals' rhyme judgements appear to rely at least partially on orthography and lipreading, since the sound itself is inaccessible. Notably, reliance on orthography during rhyme judgements is not unique to the deaf population: individuals with and without hearing loss respond more quickly and accurately to orthographically similar rhymes than dissimilar ones (e.g., "blue/clue" vs. "blue/two"; Seidenberg and Tanenhaus, 1979; Lipourli, 2014; Rudner et al., 2019).

On the other hand, deaf and hearing individuals appear to take different approaches to encoding and organizing information based on its auditory properties: compared to hearing peers, deaf participants report experiencing less auditory imagery ("hearing in one's head") in response to spoken language auditory words (e.g., "trumpet"; Marchant, 1984). For hearing individuals, connecting a word to perceptual experience through auditory imagery can boost memory of auditory-related words. Deaf individuals do not show an auditory imagery boost: across multiple studies, deaf individuals recall fewer words than hearing individuals from (spoken word) lists of auditory-related words (Marchant, 1984; Craig, 1971; cf., Heinen et al., 1976). This suggests that unlike hearing participants, deaf individuals may not be using auditory imagery (either as much or at all) to organize word lists. The cause of this divergence, however, is not clear. It may reflect that deaf individuals lack auditory feature knowledge of spoken words (which may be their second language), that deaf individuals possess knowledge of auditory features of spoken words but do not form lexical-semantic networks that facilitate retrieval based on auditory properties, or that other word features may be more salient for deaf individuals and interfere with auditory-based lexical retrieval. Parsing out these options requires further empirical work probing component spoken language knowledge, and lexical network structures in deaf individuals, with potential sequelae for lexical organization more generally.

Electrophysiological data shed further light on how deaf participants process auditory information. For example, during (written English) rhyme judgements, deaf participants produce ERPs that are largely similar in polarity, location, and timing to those of the hearing participants, suggesting that the neural processes underlying spoken language sound structure knowledge are similar across groups (MacSweeney et al., 2013). While these results are intriguing and important, spoken language accounts are insufficient for capturing neural representations of deaf individuals' sound knowledge. Combining some of the behavioral methods above, such as presenting "high-auditory-imagery" vs. "low-auditory-imagery" word lists (e.g., Marchant, 1984; Craig, 1971) or presenting sounds tactilely and asking participants to provide a sign language description (e.g., Emmorey et al., 2022), with neural methods, could help illuminate the neural networks supporting auditory concepts in deaf individuals. While, given the dearth of prior work, any hypotheses would be somewhat speculative, we might expect to find weaker neural responses to auditory concepts, perhaps with greater recruitment of haptic regions than in hearing adults.

For understanding developmental trajectories, it is important to understand what adultlike perceptual knowledge looks like in these populations, thereby making the underrepresentation of deaf adults in this literature especially glaring. This requires research both in sign language communities (full language access) and individuals who use spoken language (less language access). Such work would help us better understand the role of language access in acquiring sensory knowledge, as well as provide information about whether insights gleaned from one population (blind vs. deaf) may generalize. Expanding sign language research in sensory language specifically would help illuminate the role of language modality in sensory learning. How much does it matter if the majority of language users have a sensory impairment? Emmorey et al.'s investigation into the language of perception in ASL is an important start, but we need corpus-based evidence: how common is auditory language in naturalistic sign language input for deaf individuals? Do signed languages distributionally contain auditory information in the same way that spoken languages are thought to contain visual information (e.g., van Paridon et al., 2021; Lewis et al., 2019)? These empirical questions await further research.

3.3. Sensory knowledge summary and synthesis

Across the literature, we find many examples of detailed perceptual knowledge of inaccessible senses. Individuals with sensory impairments have concepts that draw both on their own accessible perceptual experiences (e.g., Rosen, 2007; Kerr and Johnson, 1991) as well as linguistically-learned associations with the inaccessible sensory modality (e.g., MacSweeney et al., 2013; Bedny et al., 2019; Kim et al., 2020). Blind participants' sensory knowledge on multiple tasks (Saysani et al., 2021; Kim et al., 2019a, b) is strongly correlated with distributional statistics in language, and the inferences this may license (van Paridon et al., 2021; Lewis et al., 2019; Kim et al., 2019a, b). On other tasks, blind adults report learning some of the sensory information from sighted people's descriptions (e.g., Marmor, 1978), while deaf authors discuss reading about sound (Rosen, 2007).

The evidence above also suggests that some sensory knowledge involves compensation with accessible sensory domains. For instance, sign language representations of sound are often iconic, depicting anatomical, haptic, or temporal aspects of audition/sound (Emmorey et al., 2022; Östling et al., 2018; de Vos, in preparation). Similarly, blind adults reported more multisensory imagery than sighted participants (Kerr and Johnson, 1991). Properties with some sensory redundancy (e.g., volume and rhythm for deaf individuals; shape and size for blind individuals) also seem more readily learned than properties without sensory redundancy (e.g., spectral properties for deaf; color for blind). More concretely, blind participants are more accurate on shape/size than on color (Kim et al., 2017), and deaf participants are more accurate on rhyme judgements when rhymes aligned with orthography (Rudner et al., 2019). These behavioral results dovetail with findings that blind individuals' neural activity in response to auditorily- or tactilely-presented stimuli closely resembles sighted individuals' neural responses to *seeing* the same stimuli (Striem-Amit et al., 2012; Reich et al., 2011).

Given the sparsity of research on auditory knowledge in deaf individuals, it remains unclear to what extent blind individuals' relationship to the visual modality parallels deaf individuals' relationship to the auditory modality. Outside of observations of sign languages, and Deaf literature and music, much of the sound knowledge literature focuses on spoken English, which for many deaf individuals is a second language. Therefore, many open questions remain about deaf individuals' knowledge of auditory properties. In the past, research on blind and deaf individuals has been limited by the density of eligible participants in a given geographic area, or to surveys which could be mailed out or completed online. However, recent improvements in online testing, eyetracking, and screenreading technology hold particular promise for collecting more robust data from these special populations.

While we currently lack sufficient data to draw robust comparisons between learning about sight and sound, evidence of auditory knowledge in deaf individuals and visual knowledge in blind individuals suggests that across sensory domains, individuals with sensory impairments can perform indistinguishably from typically-sensing individuals on a number of *sensory knowledge* tasks (cf. analogous results in the domain of smell, Speed et al., 2021). The next step for such research is to figure out what mechanisms underlie this similar performance, i.e. whether indistinguishable results arise from insufficiently sensitive measures, universal processes, or compensatory mechanisms in individuals with sensory impairments. Another important avenue for progress in this domain is to consider the learning trajectories of children, to which we now turn.

4. Acquiring sensory knowledge in imperceptible domains

As discussed above, both language and experience in other modalities appear critical for perceptual knowledge in those with sensory impairment. But little is known about the *process* of acquiring this knowledge, in part due to low incidence of profound congenital sensory impairment (Gilbert and Awan, 2003; CDC, 2019). We propose factors that may facilitate learning sensory information in an inaccessible domain and developing an adultlike understanding of sensory language, both in the earliest stages of language development and thereafter. For language development in infancy we highlight roles for **language access** (particularly early word learning, iconicity, joint attention, and linguistic structure); for sensory learning in preschool into early childhood we highlight the role of **theory of mind**, alongside abilities that could **extend sensory knowledge** (namely literacy, sensory redundancy, and taxonomic knowledge). We draw on the developmental literature for these skills, highlighting data from children with sensory impairments. Finally, we propose a developmental trajectory for attaining sensory knowledge for individuals born deaf or blind.

4.1. Language access with sensory impairment

For children to take advantage of how language encodes sensory information, they must be proficient language users. Given full perceptual access to the linguistic signal (i.e., sign language for deaf children, spoken language for blind children), children with sensory impairments can unquestionably achieve language fluency on track with typically-developing peers (Mayberry et al., 2006; Blamey and Sarant, 2011; Landau and Gleitman, 1985; Pérez-Pereira, 1999; Bigelow, 1990).

How might children begin learning language to describe their environment? Children with typical hearing/vision learn their first words through linguistic, social, and perceptual cues, and everyday interactions (Smith, 2000; Fisher and Gleitman, 2002; Tomasello, 2001). Cross-linguistically, first words tend to be concrete, highly-frequent nouns with stable perceptual features, like “foot” and “banana” (Bergelson & Swingley, 2012, 2015; Bergelson and Aslin, 2017; Tincoff & Jusczyk, 1999, 2012; Kartushina and Mayor, 2019; Parise and Csibra, 2012; Frank et al., 2021; Benedict, 1979). As children mature and encounter more language input and everyday experience, they are able to make increasingly complex inferences about word meaning (Bergelson, 2020; Bohn et al., 2021; Meylan and Bergelson, 2022).

However, if high word frequency and perceptual consistency are necessary for initializing the lexicon, this process may be disrupted for children with sensory impairments. For deaf children in a spoken language household, the speech signal is inaccessible, so there are many fewer linguistic tokens from which to build associations. Accordingly, deaf children who receive access to a signed language typically achieve language proficiency, while deaf children learning spoken language (without sign language access) tend to experience language delays (e.g., Svirsky et al., 2000). Consideration of the varying lengths of language deprivation that DHH children often experience in spoken language households (Hall, 2017) may help disentangle the relative contributions of language and experience to sensory knowledge acquisition.

For blind children, referents that may be perceptually consistent for a sighted child (e.g., *bird, moon*) are not visually accessible. While it is in principle possible that experience in other modalities may compensate for part of what is typically learned through hearing or sight, not all information is “transferrable” (e.g. color for blind individuals doesn't have haptic correlates). This may explain why some studies find early vocabulary delays in blind individuals, though the literature on this topic is both limited in sample size and mixed in its conclusions, with some studies reporting early vocabulary delays (McConachie, 1990; Landau and Gleitman, 1985), and other studies reporting age-appropriate vocabulary (Bigelow, 1990; Nelson, 1973; Mulford, 1988). Summarily, both blind and deaf infants likely have fewer perceptually accessible instances from which to learn about the world, and how language functions within it; this is compounded further when full language access is not available (i.e. for deaf children without sign language input).

4.1.1. Role of iconicity in learning words' meanings

Across spoken and sign languages, iconic words are easier learned than non-iconic words (Imai et al., 2008; Laing, 2017; Perry, Perlman, & Lupyan, 2015; Thompson et al., 2012; Caselli and Pyers, 2017; Vinson et al., 2008; Tolar et al., 2008; Ortega et al., 2014; see Ortega, 2017 for a sign language review). This learning advantage may facilitate word learning for deaf and blind children just as it does for sighted and hearing children. More concretely, Imai and Kita (2014) propose a *sound symbolism bootstrapping hypothesis,* which asserts that iconic representations scaffold infant's realization that words/sounds can be associated with meaning, helping particularly with learning those iconic forms, but later applying that referential skill to non-iconic forms. In turn, this may indirectly support the eventual learning of inaccessible sensory information e.g., by limiting the unknown words in a given utterance.

However, we find it relatively unlikely that iconic words support acquisition of inaccessible sensory information directly for two reasons. First, iconicity generally depicts the same modality that language is relayed in, e.g. the ASL sign STIR *looks* similar to the action it notes while the spoken English word “pop” *sounds* similar to the explosive action it denotes (Perlman et al., 2018). Thus, the predominant modality of iconicity does not facilitate learning about the inaccessible sense (vision for blind individuals, sound for deaf individuals.) While sign languages do feature many iconic signs for sound, the particular aspects of sound being depicted are often visual, anatomical, or tactile, i.e. the aspects of sound that deaf individuals have direct access to (Emmorey et al., 2022, Östling, Börstell, & Courtaux, 2018; de Vos, in preparation*)*.

Second, although iconic words are learned earlier across languages and language modalities, it is not until toddlerhood that children reliably recognize associations between word form and word meaning (Namy, 2008; Tolar et al., 2008; Suanda et al., 2013), even for perceptually accessible referents. Newport and Meier (1985) proposed that younger children lack the world knowledge that would help them interpret the connection between the word and its meaning (e.g., MILK in ASL references the action of milking a cow, which is likely quite unfamiliar to infants). This challenge in recognizing word form and word meaning associations would only be compounded for inaccessible sensory meanings.

On the other hand, iconic words are often marked. In spoken language, onomatopoeias and ideophones tend to be phonologically and morphosyntactically marked (e.g., Dingemanse, 2012), and in sign languages, classifier constructions (which comprise a large proportion of ASL sound descriptions, Emmorey et al., 2022) are also marked. Iconicity in infant directed speech and sign are particularly salient. In naturalistic interactions, mothers produce iconic word forms with higher pitch, wider pitch variability, and longer duration than other words in infant-directed speech (Laing, 2017). In sign too, mothers iconic signs with larger movements, repeated movements, and longer duration (Perniss et al., 2018). If learners with sensory impairment are sensitive to this markedness and saliency, it could, in principle, yield the inference that a word form is likely to resemble a sensorily inaccessible referent. Whether this is the case is an open empirical question.

4.1.2. *Can joint attention support learning imperceptible words?*

Around 12–14 months, typically-developing infants show a qualitative improvement in word learning (Bergelson, 2020). One social strategy that comes online at this time is joint attention. During joint attention, parent and child simultaneously focus on an object or event and share awareness that the other person is focusing on the same thing. Joint attention has been linked to concurrent and subsequent language learning (Tomasello and Farrar, 1986; Naigles, 2021).

While joint attention is a critical social foundation for language, it generally relies not just on purely *social* interaction, but on the coordination of linguistic and perceptual information. It is thus perhaps unsurprising that joint attention develops on different timelines for deaf and blind children (Prezbindowski et al., 1998; Bigelow, 2003; Lieberman et al., 2014) relative to hearing and sighted peers. Joint attention coordination is particularly remarkable in a sign language context, wherein deaf children learning sign language must learn to rapidly switch visual attention between their caregiver's signs and the referent during joint attention (Lieberman et al., 2014; MacDonald et al., 2018). This frequent shifting of the gaze comes online by 16–24 months of age (Lieberman et al., 2014; MacDonald et al., 2018). Its precursors are detectable as young as 7–14 months, when deaf infants of Deaf signing parents show enhanced gaze following over hearing children of hearing parents at (Brooks, Singleton, & Meltzoff, 2020). The situation diverges in the context of deaf children learning spoken language from a hearing parent, wherein caregivers have more difficulty establishing joint attention (Nowakowski et al., 2009), and parent-child dyads spend less time in joint attention than their hearing peers (Prezbindowski et al., 1998; Depowski et al., 2015). This again highlights the interaction of language access and other facets of cognitive, social, and linguistic learning.

In blind children, joint attention is coordinated tactilely and often delayed relative to sighted peers (Pérez-Pereira, 1999; Bigelow, 2003), though further research with larger sample sizes is still needed. Blind children of course cannot see an object offered to them, and typically exhibit delays in reaching for objects relative to sighted children (Bigelow, 1986), thereby delaying the acquisition of tactile joint attention. Taken together, the literature suggests that while modality and language experience influence the timeline of joint attention, blind, deaf, and typically-sighted/hearing children do exhibit joint attention within the first two years of life (Prezbindowski et al., 1998; Bigelow, 2003; Lieberman et al., 2014).

In typically-developing children, while joint attention is viable for concrete objects, it is harder to coordinate attention to something abstract. This, as well as the lack of perceptual consistency for abstract words, may explain why abstract words are largely acquired later than concrete words (Bergelson and Swingley, 2013; Frank et al., 2021). For children with sensory impairments, by hypothesis, ascertaining the meaning of sight and sound words may be similarly difficult: for such children, joint attention cannot be coordinated to something only the caregiver can perceive. Thus, the facilitatory role of visual joint attention may not be readily leveraged by blind or deaf children for learning about how language links to the inaccessible sense. That said, how joint attention in other modalities (e.g. tactile joint attention) may support learning about the inaccessible sense remains an open area of inquiry. At the same time, focusing on perceptible objects and properties can certainly still facilitate word learning. Indeed, in a study of three blind infants, Bigelow (1987) observes that blind children's earliest words pertain to touch, taste, and smell, i.e. their own highly consistent and frequent experiences. Ongoing work is investigating whether these findings hold with a larger N (Campbell & Bergelson, 2022).

4.1.3. *Tracking linguistic structure to learn meaning*

As children continue to build the lexicon through the first few years of life, knowing some of the words in an utterance narrows the space of plausible meanings of unknown words (e.g. "Daxes cry" suggests that whatever a "dax" is, it's animate). For children with sensory impairments, understanding more of the perceptually-accessible words may reduce ambiguity for imperceptible referents. More broadly, for typically-developing children, distributional information—information gleaned from how words pattern with one another— is argued to be more important for learning the meaning of abstract words relative to concrete ones (Vigliocco, Meteyard, Andrews, & Kousta, 2009; Gleitman et al., 2005), since the latter lack clear, perceptually-consistent referents. By hypothesis, the same kind of distributional information (particularly at the semantic and syntactic levels) may be useful for deaf and blind children learning auditory and visual words.

At the semantic level, typically-developing children are sensitive to word co-occurrence regularities by toddlerhood (Matlen, Fisher, & Godwin, 2015; Unger, Savic, Sloutsky, 2020), and these statistical regularities shape semantic knowledge (Savic, Unger, & Sloutsky, 2020; Unger, Savic, Sloutsky, 2020). Given the availability of sensory information in language statistics (Lewis et al., 2019; van Paridon et al., 2021), linguistic regularities could be a rich source of information for deaf or blind children. For example, through hearing color words used almost exclusively to describe concrete objects, blind children might infer that color is a physical property (see Landau and Gleitman, 1985).

Tracking syntax also helps children acquire meaning (e.g., Gleitman, 1990). Across many studies, young children have been found to capitalize on aspects of syntactic structure (e.g. verb arguments, discourse coherence, number and distribution of noun phrases and function words, knowledge of some words in the sentence, etc.) to make inferences about word meaning (Waxman and Booth, 2001; Gleitman, 1990; Fisher et al., 2019; Havron et al., 2019; Ferguson et al., 2014; Babineau et al., 2021; Naigles, 1990). For example, upon hearing, "The duck and the bunny are kradding" vs. "The duck is kradding the bunny", " typically-developing children infer that the first case describes an intransitive event while the latter is transitive, i.e. the syntactic structure lets children infer which event the new verb "kradding" refers to (Naigles, 1990).

This type of strategy (known as syntactic bootstrapping) alongside related linguistic inferences like inferring animacy of a new noun based on the verb it's used with (Ferguson & Waxman, 2014) likely helps children with sensory impairments learn meanings as well. For example, verbs of perception ("to see", "to hear") are transitive and generally pertain to concrete objects that are present in the scene (though not always). Likewise words like "red" and "high-pitched" are adjectives that can only be applied to concrete objects – combining these semantic and syntactic clues helps constrain the possible meaning space for inaccessible sensory language as children accumulate linguistic experience. Landau and Gleitman (1985) document the syntactic and environmental contexts of the verbs “look” and “see” in the language input for one blind child, and demonstrate that while environmental cues like object presence do not disambiguate between “look” and “see”, the distribution of syntactic frames for the verbs differentiate them from each other and from other common verbs in early input.

Taken together, we propose that as long as children receive full linguistic access, early word learning unfolds similarly for children with and without sensory impairment. Namely, first words are likely to be concrete, perceptually accessible objects in children’s environment with contingencies between the word and its referent. Joint attention may help children with this process by providing referentially transparent learning instances, as long as children’s accessible modalities are kept in mind. As children build up their vocabulary, they can increasingly use distributional and syntactic regularities to infer the meaning of new words, perceptible and imperceptible. Notably, the types of mechanisms underlying more abstract word learning in typically-developing children (e.g. syntactic bootstrapping) may be particularly useful for children with sensory impairment to learn about modalities they don’t directly experience.

4.2. Theory of mind and perceptual experience

Blind and deaf children are not alone in needing to deduce unobservables. Over early childhood, children must realize that other people’s mental states and perceptions are different from our own. This ability is referred to as Theory of Mind. (Henry et al., 2013; Premack and Woodruff, 1978). As early as 12 months, typically-developing infants demonstrate knowledge of what another person can or cannot see based on their visual perspective (Liszkowski, Carpenter, & Tomasello, 2008; Sodian and Thoermer, 2008). Around 4 years of age, typically-developing children can use information about other people’s sensory access to reason aloud about their mental states (Schmidt and Pyers, 2011).

For deaf or blind children to understand that sight and sound are physical properties that sighted and hearing people can perceive while they cannot, they must appreciate that other people’s perceptions differ from their own. It is unclear whether the timeline for Theory of Mind development differs for children with sensory impairments. On false belief tasks, children with sensory impairments often show Theory of Mind delays relative to typically-developing peers, though the genesis of these delays differs. For deaf children, language access plays a facilitating role in Theory of Mind acquisition, such that deaf children with delays in language access show corresponding delays in Theory of Mind development (Pyers and Senghas, 2009; Schick et al., 2007). Deaf children learning sign language from birth may even show an *advantage* over typically-developing spoken language peers, perhaps due to the perspective shifting required in many sign languages (Courtin, 2000). Theory of Mind development in blind children as measured on false belief tasks appears delayed relative to sighted children (McAlpine and Moore, 1995; Minter et al., 1998; Peterson et al., 2000), although the origins of this difference are not linked to language access (as they are in the deaf population).

However, false belief tasks are notoriously complex (Saxe, 2013), and often invoke more advanced social cognition than just an awareness of differences in perception (e.g., Liszkowski, Carpenter, & Tomasello, 2008). If understanding others’ sensory abilities relies on first-hand sensory experience (e.g., Meltzoff, 2007), then blind children and deaf children should exhibit delays specific to others’ visual knowledge and auditory knowledge respectively. If language, in addition to first-hand world experience, supports understanding of others’ sensory abilities (e.g., Gopnik and Wellman, 2012), then we would not expect modality-specific differences for these groups – though language-deprived deaf children may exhibit delays across modalities. Schmidt and Pyers (2014) tested these competing hypotheses directly by probing orally-educated deaf and hearing children’s awareness of others’ sensory access. Children watched two experimenters, one of whom was blindfolded, and one of whom wore headphones, peer into or listen to a box containing a toy animal; children were asked to state whether the informant (based on their sensory access) knew which animal was in the box. Hearing participants demonstrated earlier mastery of this task than deaf participants (~3–5 years old in hearing group vs. 5.5–6.8 years old in deaf group), but neither group showed a difference based on modality. This suggests that while deaf children were delayed in their understanding of others’ sensory access (perhaps due to language inaccessibility) they exhibited no specific deficit for understanding hearing as a knowledge source. For blind children, in one case study, Landau and Gleitman (1985) document how a blind child (3;4 years) differentially applied visual verbs to herself and to her sighted mother,[5] contrasting her mother’s visual access with her own. Additionally, by 4;6 years, when asked to retrieve an object based on color, the child would ask a sighted adult for help selecting the correct objects, further demonstrating a socially nuanced understanding of vision. Examples like these suggest that as early as preschool age, blind children can understand that sighted individuals experience visual phenomena differently than they themselves experience. Taken together, this work suggests that knowledge of others’ sensory access can be guided and modulated by language experience.

How might this understanding of others’ knowledge connect to the sensory learning process for children born deaf or blind? By hypothesis, children with sensory impairments may initially learn sensory information as an abstract property, only later surmising that sighted/hearing people’s perception is different from their own. Thus, Theory of Mind may be a prerequisite for adultlike comprehension of sensory terms. As this develops, children may begin to understand that sight and sound words actually apply to physical properties that are imperceptible to them. We hypothesize that as these socio-cognitive skills develop, blind and deaf children undergo a qualitative shift in understanding sensory words as terms initially deemed abstract are surmised to be imperceptible to them but not others.

4.3. Using world knowledge to extend sensory knowledge

Books and other written media are likely a particularly rich source of sensory information for individuals with sensory impairments. Literature, particularly fiction, contains more sensory-rich words than conversational speech (van Paridon et al., 2021; Winter et al., 2018). In order to access sensory information from books, captions, and internet sources, children must develop literacy, but the process of reading development differs somewhat for children with sensory impairments. Blind children are generally taught to read using braille (Argyropoulos and Papadimitriou, 2015; Emerson, Holbrook, & D’Andreas, 2009) and can also access the written word through text-to-speech software. In contrast, deaf children often experience literacy delays relative to hearing peers (Kyle and Cain, 2015; Wauters, van Bon, & Tellings, 2006; Qi and Mitchell, 2012). However, once children with sensory impairments develop literacy, reading can further boost their learning of sensory content.

Taxonomic information may be particularly helpful for extending sensory knowledge in well-structured domains (e.g., how animals are related). Data from blind adults suggests that blind individuals rely *more* on taxonomic information than sighted individuals for appearance judgments (Kim et al., 2019a, b). Given that the use of taxonomic knowledge as a basis for generalization is in place by preschool in typically-developing children (e.g. Gelman, 1988), children with

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[5] When the blind child was instructed to see an object, she would explore it tactilely, but when asked to let a sighted person see it, she would instead hold the object up for them rather than bring it to them for tactile exploration, correctly understanding that sighted people can see at a distance, while she cannot. By contrast, when asked to let a sighted person touch an object, she would bring it closer to them (Landau and Gleitman, 1985).

sensory impairments too may leverage taxonomic knowledge to generalize sensory properties to novel objects, particularly as their world experience, academic learning, and/or literacy skills develop.

In addition to linguistic and social information, perceptual information from the other senses might aid in developing sensory knowledge as well. For deaf individuals, some tactile information is naturally available as a property of the sound-making event such as the floorboard vibrations of footsteps. Deaf individuals can also see how hearing individuals react to sounds (e.g., covering ears; turning head towards sound) and infer sound information from other people's actions. For blind individuals, size or shape information for certain objects can be felt through touch. Children with typical hearing and vision readily integrate multimodal cues in learning from infancy onwards (e.g., touch and vision in object categorization, Bahrick et al., 2004). For individuals without sensory impairments, perceiving multimodal cues simultaneously may be sufficient for learning contingencies between sensory modalities. However, because individuals with sensory impairments cannot *perceive* synchrony between the inaccessible sense and the accessible sense, linguistic input may highlight its existence, particularly once the child has gained a basis of language skills and Theory of Mind abilities more broadly. For example, parents may tell a deaf child "Feel the vibrations! This is really loud!" After learning patterns for how the inaccessible property relates to the accessible property, children with sensory impairments may be able to extend that rule to new instances of the sensation.

4.4. Proposed trajectory for acquiring sensory knowledge

As laid out above, children with sensory impairments likely begin by building up a vocabulary inventory of perceptually accessible words through direct experience with the world and people within it just as typically-developing children do. As their vocabulary knowledge grows, they can increasingly make use of distributional statistics and syntactic frames to understand the meanings of sensory words. Concurrently, children's developing social and cognitive abilities facilitate the awareness that sighted and hearing people's perceptions are different from their own. This may allow them to infer that sensory properties are distinct from abstract properties. Explicit information about relevant sensory dimensions may be particularly helpful in this regard, in an educational context where e.g. instruction in taxonomic structure in domains of natural kinds, and literacy can boost sensory knowledge.

Thus far, we have not speculated on differences in learning *between* individuals born deaf vs. blind. We would be remiss not to reiterate the importance of language accessibility in this process. While blind individuals generally have full auditory access to spoken language from birth, many deaf children are born into spoken language households (Mitchell and Karchmer, 2004), where the language input is inaccessible. Language deprivation is associated with delays in cognitive, social, and of course, linguistic skills, both those relevant for learning perceptual information, and others (Campbell, MacSweeney, & Woll, 2014; Hrastinski and Wilbur, 2016; Kronenberger et al., 2013; Hall et al., 2019). But if we assume that blind and deaf individuals receive accessible language from birth, would their learning trajectories and knowledge differ? This depends in part on whether the auditory information contained in the distributional properties of signed input parallels the visual information of spoken input. At a coarse grain of analysis, we expect many parallels for deaf and blind learning of auditory and visual knowledge to hold. Indeed across domains of cognitive neuroscience, increasing evidence points to interleaved attentional networks and memory networks for visual and auditory information. For instance, short term memory recruits 'visual' or 'auditory' areas for remembering stimuli of the opposite modality (Michalka et al., 2015). This underscores the roles of cross- and inter-modal perception and attention (Shinn-Cunningham, 2008), and demonstrates that the brain can flexibly adapt even 'dedicated' perceptual areas to process stimuli in another modality. How this plays out in the case of learning sensory information with a sensory impairment remains an important open question.

5. Conclusions

Individuals born profoundly blind or deaf grow up without access to sight or sound, yet by adulthood demonstrate remarkable knowledge of perceptual information that they have never experienced. This astounding feat is made possible by language, alongside perceptual experiences in other modalities, and cognitive and social development.

Language encodes sensory information in phonemes, words, phrases, and structure. Individuals born deaf or blind possess knowledge of vision and audition that often parallels the sensory knowledge of individuals without sensory impairments both in behavioral measures and neural underpinnings. But how they acquire it remains largely unknown, and quantifying the contributions of language and sensory experience in attaining sensory knowledge is a complex endeavor that awaits future work.

Our proposed developmental trajectory for the acquisition of sensory knowledge by those with sensory impairment lays the groundwork for answering these questions. This in turn has implications for clinical and educational interventions for children with sensory differences. More broadly, understanding how blind and deaf individuals learn about vision and audition without direct perceptual experience stands to clarify the role of language, cognition, and social interaction in relaying perceptual information for all individuals, in turn facilitating a deeper understanding of both the flexibility and limits on reorganization of the human mind.

Author contributions

Erin Campbell: Conceptualization, Writing – original draft, Writing-Reviewing and Editing, Funding acquisition **Elika Bergelson:** Conceptualization, Supervision, Funding acquisition, Writing- Reviewing and Editing

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Appendix A. Supplementary data

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