Opinion

Visual sign phonology: insights into human reading and language from a natural soundless phonology

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Among the most prevailing assumptions in science and society about the human reading process is that sound and sound-based phonology are critical to young readers. The child's sound-to-letter decoding is viewed as universal and vital to deriving meaning from print. We offer a different view. The crucial link for early reading success is not between segmental sounds and print. Instead the human brain's capacity to segment, categorize, and discern linguistic patterning makes possible the capacity to segment all languages. This biological process includes the segmentation of languages on the hands in signed languages. Exposure to natural sign language in early life equally affords the child's discovery of silent segmental units in visual sign phonology (VSP) that can also facilitate segmental decoding of print. We consider powerful biological evidence about the brain, how it builds sound and sign phonology, and why sound and sign phonology are equally important in language learning and reading. We offer a testable theoretical account, reading model, and predictions about how VSP can facilitate segmentation and mapping between print and meaning. We explain how VSP can be a powerful facilitator of all children's reading success (deaf and hearing)—an account with profound transformative impact on learning to read in deaf children with different language backgrounds. The existence of VSP has important implications for understanding core properties of all human language and reading, challenges assumptions about language and reading as being tied to sound, and provides novel insight into a remarkable biological equivalence in signed and spoken languages.

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The newborn baby's extraordinary journey from an early sensitivity to the sounds of language in the world around it, to sounding out letters on the page en route to discovering meaning from print, has been a topic of intensive fascination and scientific study for the last half century. The maturation of this capacity progresses on a regular timetable, exhibits universal developmental periods, and occurs at break-neck speed in early life. By around ages 6–10 months, all hearing babies are well along their way to discovering the finite set of sound phonetic units and phonemic categories of their native language. With this, they will build all of the words and potentially infinite number of sentences in language over life.[1–4] The young baby's paradoxical tacit capacity to segment and categorize into stable discrete sound

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units the constantly varying linguistic stream is thought to be at the heart of this remarkable phonological capacity[5] and widely assumed to be utterly essential for healthy language learning, and, later, for masterful phonetic sound-to-letter decoding as a young reader.[1,2,6,7]

As the young child approaches reading, their early use of sound to decode meaning from print is regarded as obligatory for healthy and successful language learning, reading, and, ultimately, lifelong academic and social success. It has been suggested that early sound decoding in emergent readers is universal, and that it is even present in early readers whose written language is nonalphabetic such as Chinese.[5,6,8] *Yet, what happens to children who are born without access to sound?*

Until recently, it has been widely viewed that deaf children without access to spoken language will become poor readers and be academically challenged for life. However, recent scientific evidence challenges this dismal view. The brains of profoundly deaf people have been found to create an homologous level of phonological organization in the absence of sound.[3,9] Building on this and other vital developmental evidence, in this article, we offer a new hypothesis about the brain mechanisms from whence all phonology came and how it may contribute to successful reading in all children: The crucial link for early reading success is not between print and *sound*, but between print and the abstract level of language organization that we call phonology—signed or spoken. The human brain's capacity to segment, categorize, and discern linguistic patterning makes possible the capacity to segment all language, including language with the hands in signed languages and the tongue in spoken languages. Be it signed or spoken, phonological processing is the brain's basic computational skill of segmentation and categorization, optimally honed in early life with exposure to a natural language. This early computational skill later underlies the phonological segmentation and decoding that we see spanning all very early reading.

Because of the brain's propensity to segment and categorize the linguistic stream, hearing babies build their phonology from fragments of sound units from the spoken language around them. Similarly, we suggest that deaf babies build an equivalent phonological level of language organization[10] from fragments of visual units found in the visual language around them.[3,9,11–14] Moreover, as young readers, hearing children segment and categorize the linguistic stream into phonetic and syllabic units that are used in concurrent combination with their concert of linguistic capacities to aid them in creating connections (mappings) among phonological, orthographic, and semantic representations so vital for skilled reading.[15] Deaf children with an early age of exposure (AoE) to a visual sign language also segment and categorize the linguistic stream, but instead into sign phonetic and sign syllabic units, which we propose are the units used in creating connections (mappings) among sign phonological, orthographic, and semantic representations en route to becoming a skilled reader.[16]

To advance the above hypothesis, we draw together different strands of knowledge that have never been united, spanning the linguistic, developmental psycholinguistic, cognitive neuroscience, and reading literatures. Uniquely, we draw this knowledge together with emerging research that sign-exposed deaf early readers utilize a complex set of soundless visual sign-phonological units to facilitate print decoding (visual sign phonology, VSP). The combined strands of evidence converge on powerful universals underlying human language that are distinct from sound, the role of abstract phonological processing in all young reading children, and the looming role that VSP and VSP educational training can have to improve the lives of all young children and their acquisition of reading irrespective of their degree of deafness or upbringing. Another exciting consequence of our discussion is to decouple sound from language, and especially sound from reading, by using VSP as an example of successful reading despite the lack of exposure to sound.

Below our analysis is divided into four major sections: (1) Background, (2) Guiding Hypotheses, (3) Model, and (4) Conclusion. Throughout this work—and true to the basic neuroscience research and translational aims of the new discipline within which we reside, called Educational/Cognitive Neuroscience—we articulate how VSP may facilitate successful reading in all children (deaf and hearing). Of note, we offer an exciting new perspective that sound is not critical for successful reading, and articulate instead what is most key.

BACKGROUND

What is VSP?

VSP is the multidimensional development of the abstract level of language organization called phonology, here, in the visual modality. We already know from research in Linguistics—now spanning nearly 60 years of groundbreaking scientific discoveries—that phonology in signed languages and spoken languages are homologous levels of human language

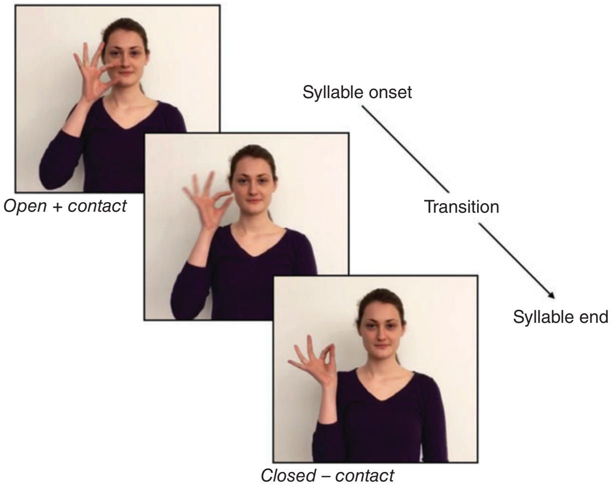

FIGURE 1 | Open/Closed (C-V) syllable structure for the ASL sign 'CAT.'[20]

organization. In spoken languages, linguists have defined phonology as being composed of a restricted set of meaningless sound units and the rules for combining them with which all the words and potentially infinite number of sentences in one's native spoken language are produced.[17] Pioneering studies by linguists have similarly mapped out sign language phonology, involving the finite set of surface phonetic units, the underlying phonemic categories from which they derive, and their combinatorial rules into syllables, signs, and sign sentences in signed languages, particularly American Sign Language.[18–20] These accounts from the discipline of Linguistics have contributed enormously to our understanding of the *phonological units and the rules for combining them in signers (adults and children).*

VSP is more than this. By uniting brain and behavioral discoveries, new biologically plausible theoretical explanations are possible, yielding three fundamental differences: (1) the fundamental units that comprise VSP, (2) the biological properties from whence it came, and (3) how it works.

What Fundamental Units Comprise VSP?

VSP comprises visual sign phonetic units, their underlying sign phonemic categories, and sign syllabic patterning—on these features only, VSP shares components of sign language phonology in Linguistics.[18–20] For example, a sign is built by combining *sign phonetic units* (a restricted set of units, e.g., handshapes, which in turn are derived from their underlying phonemic categories) into forms with movements that can be internal (e.g., change in handshape) or external (e.g., change in hand location). Such forms are combined into sequences of contrasting, rhythmically alternating hold/movement-like patterning to form the *sign-syllable*. For example, the hold/movement contrasting syllable sequences at the nucleus of signs is similar to the way that stop or 'close'-like properties of consonants (C) contrast with open-like sonorant properties of vowels (V) to form alternating close/open patterning in spoken C + V syllables at the nucleus of words (Figure 1). However, VSP is this and more. VSP also includes fingerspelling units and their patterning, and mouth units and their patterning.

Where Does VSP Come From?

At the heart of the biological level, VSP is the brain-based capacity to segment the linguistic stream, categorize it, and discern linguistic statistical patterning, and, crucially, the specific brain regions and systems that give rise to this segmentation–categorization pattern discerning capacity.[3,9] Of note, *this* is the central hypothesis we offer to answer the fundamental question: from whence does phonology come in our species? This powerful segmentation capacity is bound by a developmental maturational timetable from birth to approximately 7 years where the child passes through multiple peaked sensitivities for different-grain phonological units and their patterning. Yet, it is biologically open in that it can accept both sound and visual units. This segmentation capacity works in parallel with multiple levels of emerging linguistic knowledge. In this way, phonological development is both biologically constrained and biologically open and, in classical terms, involves 'bottom up' and 'top down' processes.[3,5,9,11,21,22] In addition to the discoveries of specific neural systems for highly abstract levels of language structure, the phonology in signed languages is not formed of sound units at all, but of silent, soundless units on the hands. Thus, the discovery of VSP is among the most noteworthy examples of neural resilience involving brain structure and function. It is a clear example of the computational power of the brain for processing abstract properties of language. Understanding VSP can result in new insights into the core components of human language despite radical variation in modality.

How Does VSP Work?

While the propensity to segment and categorize the linguistic stream is biologically driven, develops on a regular maturational timetable, and universal to the species, for any given child the units that comprise VSP can vary depending on the age and nature of first language exposure. To achieve optimal sign-phonological representations, a deaf child's exposure to the systematic rhythmic temporal patterning of a human visual sign language is biologically optimal if it occurs in the first months of life. In learning to read, this young sign-exposed deaf child's VSP (with segmentation and categorization abilities strengthened through experience with a natural sign language at the appropriate brain developmental sensitive periods), then maps this segmentation–categorization capacity when decoding visual orthographic letters and their patterning on the page, en route to deriving meaning from text. Next, we provide insights into how children may nonetheless benefit from VSP educational interventions and training who had not experienced such optimal early life natural language experience.

Multiple Types of Evidence Spanning Multiple Disciplines That Converge on the Existence of VSP

Developmental Psycholinguistics—Phonological Productions in Sign-Exposed Babies

Evidence has emerged from Developmental Psycholinguistics that converge with the above findings from Theoretical Linguistics. Researchers discovered that sign-exposed babies produce tightly constrained phonetic units on their hands homologous to CV alternating phonetic-syllabic vocal babbling in hearing babies, and on the identical maturational timetable (Figure 2).[3,9,11] Babies exposed to sign language produce a restricted subset of the total sign phonetic units found in their native sign language, in the same way that hearing babies produce a subset of the sound phonetic units in their spoken language in vocal babbling.[22,23] Most remarkable was that sign exposed babies were producing *syllables* on their hands. These units possess elementary open (similar to the vowel in spoken language) and closed (similar to the consonant) hand movement alternations, much like CV syllable structure. Subsequent neuroanatomical and neuroimaging studies by these researchers discovered that all infants are born with peaked sensitivity to rhythmic temporal, maximally contrasting and alternating units with specific rhythmic temporal patterning (neurally set to a narrow window of sensitivity of approximately 1–2 Hz[3,9]). This rhythmic temporal window of sensitivity roughly corresponds to units in the linguistic input about the size of a monosyllabic word/sign and is hypothesized to be the mechanism that makes possible babies' capacity to

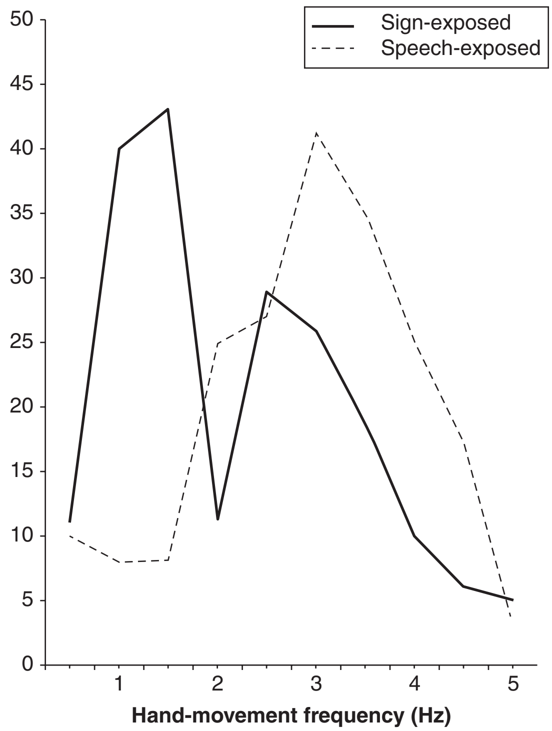

FIGURE 2 | Distribution of the frequencies of sign-exposed and speech-exposed babies' movement segments, clearly indicating that the sign-exposed group of babies was producing two distinct types of hand activity (babbling and nonlinguistic motoric activity).[3,9]

discover their native language's phonetic-syllabic building blocks of language from the constantly varying linguistic stream. Moreover, deaf children's other universal language milestones occur on the identical timetable as hearing children; babbling (~6–10 months), first word/sign (~12 months), two-word/sign combinations (~18 months), morphological embellishments (~22–24 months), and beyond.[11,22,24] Semantic meanings and concepts in deaf children learning a sign language follow the same development as hearing children.[23,25]

Petitto and colleagues have described how the above processes are possible by suggesting a 'lock and key' match between the biological tuning of specific brain tissue and the structure of human language. The structure of human language contains these bite-sized meaningless phonetic-syllabic units as its elementary building blocks, while the infant's brain contains tissue that is tuned to find these units salient.[21] Petitto et al.[21,27] have hypothesized that the primary brain system in human infants and adults for the processing of phonology is located in the superior temporal gyrus (STG, especially the Planum Temporale). This same tissue permits the baby to crack into the cacophony of sights and sounds and find the restricted set of phonology units with which

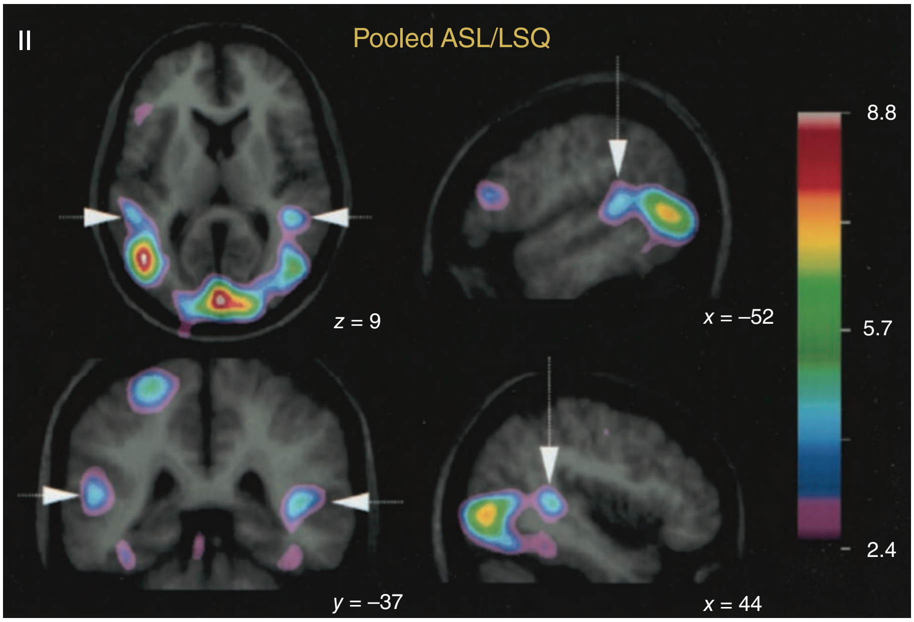

FIGURE 3 | PET MRI data for pooled comparison including all conditions in which signs or linguistically organized phonetic-syllabic nonsigns were presented compared with baseline for all deaf participants. Results indicate phonological processing in the STG for deaf signers.[26]

they may tacitly perform distributional and statistical analyses and build the units and structure of their native language.[22,26]

There is one caveat. Natural language exposure should optimally begin at birth, irrespective of whether it is signed or spoken because the STG and its related brain systems are a vital time-sensitive brain network with a narrow window for optimal integration into neural systems that make possible human language production and perception.[1,3,9,11–13,21]

Cognitive Neuroscience—Biological Equivalence of Phonology in the Brains of Deaf and Hearing People

Neuroimaging studies of adults have discovered that phonological representations in signed and spoken languages are represented in the same brain sites and regions.[27–29] For example, the sound-based phonological processing identified in the left STG had been thought to be specialized for unimodal, sound-based phonological systems, yet deaf signers recruited these regions for processing meaningless signed syllables[27] (Figure 3). Additionally, morphometry studies of primary auditory cortex in deaf and hearing brains showed equal gray and white matter volumes even though there was no auditory afferentation into these brain sites in deaf individuals (Figure 4),[30] providing support for the hypothesis that the STG is not dedicated exclusively to sound. Instead, the tissue remains active, processing specific rhythmic temporal patterning found in all languages due to these deaf participants' exposure to sign language and the shared rhythmic phonological patterning in signed and spoken languages.

Also relevant is the finding that both ASL signs and fingerspelled words activate classic left hemisphere areas associated with phonological and semantic processing including left frontal and temporal cortical regions[31] (Figure 5). Fingerspelled words and printed words revealed overlapping activation in the occipito-temporal region known as the visual word form area (VWFA), the left medial temporal gyrus (MTG), and the left anterior temporal lobe. This pattern of overlap suggests a shared lexical-semantic processing network for sign language fingerspelling and written word recognition underlying reading English print, which may support mapping between orthographic forms and fingerspelling.

Reading—A Common View of the Role of Sound Phonology and Learning to Read

Children acquiring spoken language use multiple cues when learning to read. Building on the sounds of their native language, young hearing children map sounds onto printed letters to discern meaning, particularly in languages that use alphabetic writing systems. However, regardless of a language's orthography (e.g., English or Chinese), it is argued that early reading builds on children's phonological knowledge of words, their parts, and their patterning regularities. Hearing children may also use visual orthographic regularities derived from both the shape of letters and the sequence and patterns

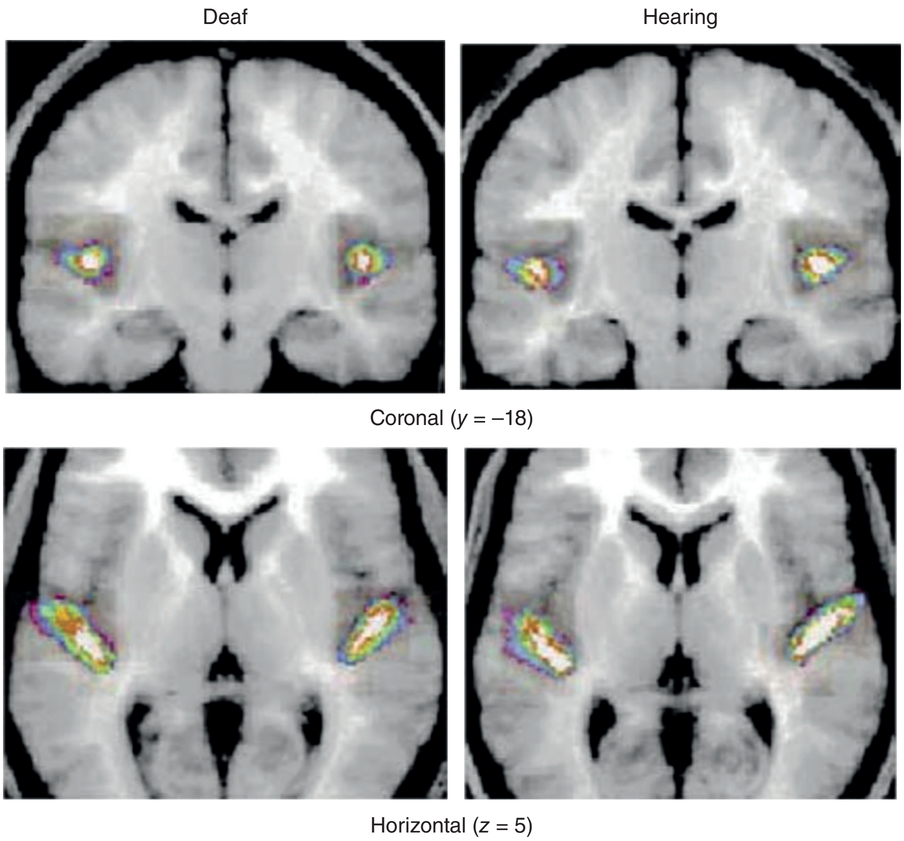

FIGURE 4 | Voxel-based morphometry analyses showing preservation of gray and white matter volumes in deaf participants' in primary auditory tissue, Heschl's gyrus, and secondary auditory tissue, STG/planum temporale, compared with hearing participants. Gray matter volumes show that the location, extent, and variability are the same across both groups (deaf and hearing). Results indicate that the development and maintenance of auditory tissue does not depend on auditory language experience.[30]

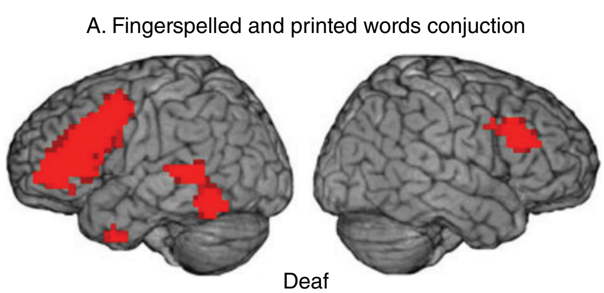

FIGURE 5 | Conjunction maps projected onto a template brain, showing overlapping regions of activation for fingerspelled words and printed words in deaf readers.[31]

of letters on the page (i.e., orthographic patterns). For some high-frequency words in alphabetic languages, children may go from the word's visual shape directly to meaning (as in the printed letters c + a + t to the idea of the small furry animal that we call 'cat').[15,32,33] Other cues may be relevant. Articulatory mouth gestures associated with pronouncing English words may contribute to reading. Additionally, the reading process—as well as the reading brain—changes over development. Children move from a greater propensity to engage phonological decoding (until age ~7–8 years) to a greater propensity to engage relational meanings and world knowledge en route to comprehending complex text (after age ~8 years). This behavioral transition in reading occurs with striking concomitant brain changes.[5,34] All these cues are important, but as we will now discuss, the evidence for VSP's existence does not support the assumption that sound is obligatory in reading.

GUIDING HYPOTHESES

Overarching Hypotheses

The guiding hypotheses in this article are that early segmentation and categorization of the linguistic stream, and the capacity to discern linguistic patterning, are brain-based capacities present at least from birth in all human children. The segmentation–categorization pattern discerning capacities develop and change over time on a maturational timetable across early life, most optimally require the presence of early language experience for the most healthy development to advance, give rise to what we call 'phonology' (and phonological knowledge), and is optimal to healthy human language learning and early reading in all children. Another key hypothesis is that sound is not necessary for these capacities to mature. Sound is not necessary for phonological knowledge to develop. Instead, the presence of natural language *patterning* in early life is key, and experienced in rich socially-contingent linguistic interactions. Consequently, strengthening early segmental capacities in all children is crucial. In particular, strengthening competence in visual sign phonological segmentation in a sign language is a crucial and foundational building block for language and reading success in young deaf children—be it through early natural sign language exposure in the home or through intensive early educational training in ASL phonological awareness and segmentation (more below). We further hypothesize that this will benefit all deaf and hard-of-hearing children, and possibly even hearing children, regardless of whether they have deaf or hearing parents, are exposed to sign natively or have no sign exposure, or if they receive speech training, or any combination in between.

The paradigm shift that we seek to impart is that exposing a young deaf child to VSP —irrespective of having deaf parents who sign—will nonetheless promote their reading mastery. We seek for science to extend the positive brain and language growth that happens in native signers to all deaf children, so that good reading skills are a part of *all* deaf children's lives.

Specific Hypotheses in Our Model of Early Reading

Reading is the result of multiple processes. Neither VSP nor sound phonology are sufficient for healthy reading but this phonological level of language processing, common to all human languages, is fundamentally necessary to the knowledge and skills that will be brought to bear on learning to read in the emergent reader (see Refs 13,21 for an expansion of the following theoretical account for all children). Beginning with the discovery of the essential building blocks of human language and within the most optimal sensitive period of human development, knowledge of VSP permits the child to discover concurrently other core parts of their language—that is, to 'find' the vocabulary words or signs in the linguistic stream, find the language's smallest meaningful parts that modulate meanings (morphology), build strong word or sign meanings (semantics and categorical relations), gain strong experience with discerning and manipulating the relations among meanings (syntax), and discover how manipulation of their arrangement conveys variations in meaning (discourse and pragmatic relations). These multiple levels of language organization contribute language comprehension and world knowledge to young children's reading success. However, the strong assertion offered here is that it is the human phonological level of language organization, be it sign phonology or sound phonology, which plays a major role in early reading.

MODEL

Overview of Model

Next, we articulate a model for how VSP may facilitate reading in all children (deaf and hearing), with the following specific hypothesis at its core: Universal Phonology (UP)—the human phonological capacity does not require sound, but in both signed and spoken languages—is built from the brain's segmentation, categorization, and pattern-discerning capacities, constitutes the essential capacities from which all human phonology arises, and is of central importance to all early reading.

We provide a testable model of the hypothesized relationship between the young signing child's discovery and knowledge of VSP and its ultimate discovery and decoding of print to derive meaning. The model is our hypothesis of the relationship between the phonological level of language organization of a sign language and the processes and analyses that children engage to arrive at successful reading of the printed word. Our model draws from the essential architecture of a now classic model of reading, Harm and Seidenberg[15] (see Figure 6). We do this to emphasize the basic universality of core processes that are vital to reading success in all world languages. Despite controversies surrounding Seidenberg and colleagues' model since its articulation in the 1970s, most contemporary models have preserved the core elements of its fundamental structure—phonology, orthography, and semantics—the trilogy of processes argued to be vital to reading. They especially assert that phonology is key to the early reading process and we are in agreement on this important point. The difference lies in what existing models and our model assume to be the 'beginning.' While Harm and Seidenberg and most contemporary models assume that sound is most basic to early reading, we do not.

To summarize, in the proposed VSP model of decoding processes underlying word recognition in

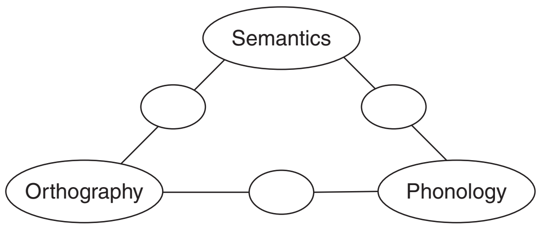

FIGURE 6 | Harm and Seidenberg's model of reading.[15]

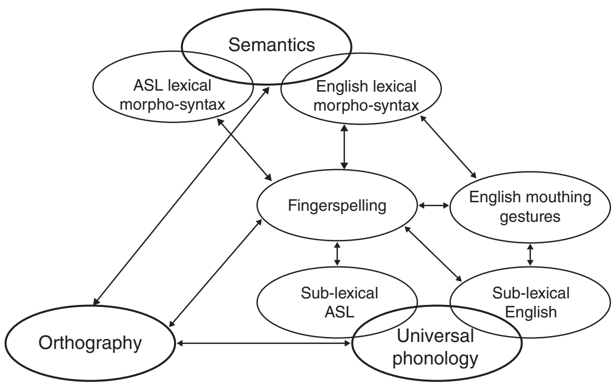

FIGURE 7 | A model of the core components of reading in young sign exposed deaf children. The model identifies the relations among Universal Phonology, the sub-lexical level of language organization, inclusive of a soundless visual sign phonology, and the multiple components hypothesized to be involved in deriving meaning from print in the emergent reader.

early reading development (see Figure 7), all children begin their journey to reading in the bottom right node, with the universal capacity to segment and categorize the linguistic stream that renders them with tacit knowledge of the sublexical structure of their native language, (be it ASL or English). Multiple cues may couple with visual sign or spoken language sublexical structure and related processes (depending on the native language of exposure, sign or speech, or both), inclusive of English mouthing gestures and fingerspelling, with both mouthing gestures of English words and fingerspelling also contributing to the development of mapping between English and ASL lexical morpho-syntactic structures as well as orthographic encoding and decoding. In this model, VSP makes possible the segmentation of print, even though the print is built from a sound-based language. Here, ASL lexical morpho-syntactic knowledge is facilitating semantic and orthographic mappings in English and is equal to the contribution of English lexical morpho-syntactic knowledge to reading. Crucially, both ASL and English lexical morpho-syntactic knowledge draw on common semantic knowledge in the same way that young bilinguals' dual lexicons share a common semantic store.[25,35]

Universal Phonology

Universal Phonology (UP) is the universal capacity to segment and categorize the linguistic stream, which renders the restricted set of sublexical units and their patterning regularities/structure (what we call 'phonology') with which one's native language(s) is built. At the biological core of UP, and all that we refer to as phonology for the human brain, is the predisposition of the species to segment the linguistic stream into parcels at the size of phonetic-syllabic units, and to analyze their categories and distribution. Segmentation processes are vital, transcend modality (hand or tongue) and will occur normally in development as long as natural language input is early and systematic.[1,26,27] Moreover, segmentation and related processes that give rise to the phonetic units of language in infancy are governed by specific brain sites and systems (phonetic-syllabic analyses take place primarily in the left STG, particularly the Planum Temporale[27]) and mature on a strict maturational timetable in early childhood.[21] Thus, in our model, early reading draws on the brain's core segmentation processes of the linguistic stream that we call here UP, processes that are not dependent on sound.

While the underlying processes of segmentation and categorization are universal, the specific units will be different as per the natural language input and writing system, and this does influence the processes in learning to read. As McQuarrie and Parrila[36] suggest, different mapping units may invoke different processes that are maximally efficient for different learners. For hearing children, the most relevant phonological contrasts, patterning, and mapping units may be sounds and the letters on the page. Likewise, we suggest that for the deaf child whose lexicon is patterned on VSP contrasts, patterning, and mapping, the computational capacity experienced through visual sign language acquisition may render the most relevant unit of mapping to be skill in visual units as they are mapped with visual orthographic segments on the page. More research is needed, but after considering the existence of VSP, our answer to the question of whether sound segmentation is obligatory in reading would have to be no, it is neither obligatory nor necessary.

The Mapping Problem

Like Harm and Seidenberg, many contemporary studies suggest a direct sound phoneme-to-letter mapping route to be essential for children learning to read.[37,38] The lack of sign phonemes with 1-to-1 mapping to the orthography of a spoken language with an alphabetic writing system, has rendered a point of argument in the field that can be called 'the mapping problem.' The argument is that VSP cannot help deaf children because, for example, the ASL phonemic handshape used to form the sign CAT (see Figure 1), bears no relationship to the English letter 'c' on the page. By contrast, the English phoneme [k] maps in a more consistent manner to the letter 'c' in the printed word 'cat.' Here, the phoneme [k] and the letter 'c' is said to have a shallow phoneme-to-letter mapping and thus facilitates the association and retrieval of word meanings; hence the traditional view that sound phonology is essential to early reading success. We suggest that this view of the mapping problem is wrong and represents a failure to recognize that sound-to-letter (sound to print) mapping is not obligatory for reading acquisition—neither in English, nor is it universal to reading in other world languages.

The direct sound phoneme-to-letter view has garnered criticism regarding the hearing child reader. If regularity of sound-to-letter mapping is required, then we should find 'deep' orthographies to be comparatively unreadable as compared to 'shallow' orthographies. This is not the case.[39] Whereas the mapping between sounds and letters in deep alphabetic orthographies are not in a one-to-one relationship, (e.g., the word *yacht* in English), only shallow alphabetic orthographies are in a direct sound-to-print mapping and represent only one writing mechanism found in the world (e.g. Italian and Welsh, with English having a combination of deep and shallow orthographies). There are other languages with nonalphabetic logographic writing systems, like Chinese, in which children nonetheless learn to read. Although there are phonological cues in Chinese characters, they are not in a strict sound-to-character mapping nor are they systematic and predictable. Thus, models of reading that require strict sound mappings are problematic even for hearing children. Interestingly, this observation does not mean that phonological awareness is not important in the young early Chinese reader, as researchers have found a significant positive correlation between early phonological awareness and early Chinese reading success,[40,41] providing intriguing support for our hypothesis that it is segmentation affordances that are key and not whether sound is mapped to characters (or letters) 1:1 on the page. Furthermore, computational modeling studies of reading acquisition in English and Chinese support the view that learning to read in any language involves the statistical learning of flexible mappings among meaning, spelling, and phonological units, rather than a direct and obligatory mapping of sound on print.[42,43]

In summary, we suggest that the mapping problem is not a problem at all. The fact that spoken language sound phonetic-syllabic units can loosely or tightly match letters, and that signed language sign phonetic-syllabic units have an even looser match to the letters on the page, is not key. Instead, it is the child's early life experience with linguistic segmentation and related processes that is key and that permits the child the profound insight that letters on the page are 'standing for' segmentable units of language. In support of this hypothesis, a positive correlation between ASL phonological awareness and reading development in English has been observed in signing deaf children and adults.[44,45]

Orthographic–Phonological–Semantic Pathway

The model indicates that orthography and meaning are mediated by UP, while classic models view phonology exclusively as sound-based and playing a major role in early reading.[8,15] Theories of orthographic mapping in early reading support developmental milestones based on and triggered by phonemic awareness and phonemic knowledge.[46] Some have argued that the printed text is equivalent to phonological representations.[47] However, McQuarrie and Parrila[36] have argued that orthography is not equivalent to auditory language information in the hearing child. Furthermore, in their 'Functional Equivalence Hypothesis,' they regarded VSP and sound phonology to be functionally equivalent, with both having a facilitative impact on the child's visual segmentation of orthography. Morford et al.[48] provide support for the functional equivalence of sign and spoken phonology relative to printed text on the page. In a cross-language activation task with varying rapid presentation rates, they found that deaf ASL-English bilingual readers showed the identical cross-language activation as observed in all bilinguals. Here, the ASL-English bilinguals directly and automatically accessed ASL phonological forms while reading English orthographic forms prior to lexical access—a striking finding given the radically different form of ASL phonology vis-a-vis English phonology.

Morphology and Morpho-Syntax

The model indicates that VSP (which arises from UP) provides the foundation for developing rich morphological and morpho-syntactic awareness. Cross-language literacy studies have discussed the concept of morphological transfer. This has been shown for developing bilinguals who use languages with similar orthographies[49] and different orthographies.[50] The studies are relevant for sign-print bilingualism because there are few one-to-one correspondences between a phonetic form in ASL and the form as written in English (fingerspelling would be the exception). Early natural sign language experience, and consequent early visual sign phonological knowledge, provides a mechanism to discover morphological structure in printed words. During the early reading and metalinguistic awareness period (age ~4 years), children's knowledge of sign inflections allows them to build translation equivalents with the English graphemes that represent the inflections. A child's internal phonological segmentation of the word also strengthens mappings between words and their meanings that build schemas, which may strengthen lexical memory (storage) and permit stronger lexical retrieval. VSP sensitivity provides the child insight into how the mental lexicon is structured and its constituent parts.[36,51] Stronger vocabulary (mental lexicon) builds stronger world knowledge and comprehension skills vital to reading success.[52–57]

Orthographic–Semantic Pathway

Our model corroborates the classic observation that the orthographic-semantic link may be a quicker pathway in activating a semantic representation as compared to the ortho-phono-semantic pathway.[15] However, we found that this is so for older hearing children and adults who are skilled readers, but less so in younger hearing and less skilled readers.[5,34] Bélanger and Rayner[58] found that deaf adult skilled readers have a larger visual window of viewing, read larger chunks of sentences, and encode characters quicker, than hearing adult skilled readers, and experience less regressions (revisits to old words), which implies a stronger ortho-semantic pathway than other routes.

Predictions

Several intriguing predictions follow from our model.

(1) A deaf child with VSP exposure, either most optimally from birth/early life in the home, and/or in educational training or intervention programs in early schooling, *will develop VSP knowledge* (to segment, categorize, and discern patterning regularities enabling the discovery of the abstract level of language organization called phonology). As is commonly seen in young hearing children with various language issues, intensive therapeutic language interventions can and do show great success. For example, hearing children who demonstrate difficulties with language or phonological segmentation, and who then receive intensive training on rhythmic temporal and phonological segmentation, do show better segmentation abilities which leads to better language and reading outcomes.[8] Thus, we predict that these types of exposure to VSP, in combination with other powerful higher cognitive capacities (e.g., association/mapping) and concurrent emerging linguistic knowledge, will facilitate the child's capacity to segment, categorize, and discover the patterning regularities of print en route to meaning.

(2) All deaf and hard-of-hearing children with early VSP exposure *will show fundamental advantages in reading* compared to those without early VSP exposure. For example, a deaf child prior to receiving a cochlear implant may have partial access to sound units and their patterning. This reduced access to language in the absence of early VSP exposure until the CI surgery (typically occurring at 10–18 months) is after or near the end of the peak sensitive period for phonological development (6–14 months)[1–4] and can result in lifelong attenuation of phonological processing abilities. As support for this view, deaf and hard-of-hearing individuals who acquired signed language later in childhood continue to experience a sign-phonological 'bottleneck,'[59,60] which results from language exposure occurring after the critical or sensitive period. This causes their ASL phonological skills to remain weak and nonnative despite having many years to develop abilities in ASL. Furthermore, deaf signers from deaf parents are more than twice as likely to be skilled readers than deaf signers from hearing parents.[61] Together, this predicts that late exposed signers will have weaker reading skills than early signers because their weaker phonological segmentation abilities impede reading processes.

(3) The model predicts that children (deaf or hearing) receiving both speech and sign training *will gain powerful bilingual language processing advantages* involving the brain's capacity to segment and categorize the linguistic stream that have been observed in young bilinguals acquiring two spoken languages.[21] Decades of research have demonstrated that hearing children with early age of first bilingual language exposure (AoE), (ages < 4–5 years) have specific language and reading advantages that persist over life,[5,34,35,62–65] which is predicted to be seen in children receiving speech and sign from early life. By contrast, the model predicts that deaf infants receiving only monolingual spoken language input will miss out on these important benefits, and, in conjunction to insufficient access to speech sounds, will render them with weaker phonological segmentation skills which will have a deleterious impact on

segmentation of orthography and mapping to meaning in early reading. Interestingly, this is precisely what Allen and colleagues have found.[66]

We further predict that the bilingual language and reading advantages will extend to other subsets of deaf children, all of whom are 'bilingual,' including deaf children with early sign language exposure, whereupon their first exposure to the other majority language (e.g. English) is through print, called 'sign-print bilinguals' (e.g., through early book sharing and reading activities).[67] For other deaf children with early sign language exposure, some are also receiving speech training in English. Some receiving sign may have varying degrees of hearing, thereby permitting them a degree of access to English sounds. The predictions offered by our model suggest that these bilingual children's entry into reading should be facilitated both because they had early natural language experience through sign language and/or direct instruction in VSP,[68] and thus they will pick up 'the bilingual advantage,' especially as observed in other bilingual children and reading.[69] By contrast, there are large groups of deaf children who are provided little or no early exposure to an accessible natural sign language (or direct VSP instruction in early life), and instead receive exclusive training in speech. These children are *monolingual* deaf children at risk for 'minimal language experience.' Minimal language experience in children has been shown to have a devastating impact on their capacity to learn language and achieve normal reading and literacy skills.[70–74] The present model predicts a difficult and later route into reading that could have been ameliorated with early visual language exposure.

(4) A surprising prediction involves hearing children. *Hearing children* with select reading difficulties *will benefit from visual segmentation training in VSP*. Many young hearing children have difficulty reading and may show reading improvement with early visual segmentation training drawn from VSP to discern meaning from the visual letter patterning (orthography) on the page. It is further predicted that hearing children with select reading challenges may even show a reading *facilitation* as compared to other hearing children learning reading with sounds because these children do not have to switch modalities. Unlike standard reading training that goes from sound segmentation to visual letter patterns, another pathway into reading for these children may be achieved by going from the visual to visual—visual segmentation afforded by VSP training to visual letter patterning and decoding on the page. It is an intriguing open research question.

Fingerspelling as a Source of Visual Phonological Information

Fingerspelling is a system of handshapes to represent each letter of the alphabet. Hearing children learn the phonological and semantic mappings from spoken words to print through various strategies, such as language play with phonological awareness activities and alphabet spelling and letter matching games. Similarly, in bilingual approaches to deaf education, practice with sign language phonetic and phonemic units (e.g., handshapes and sign syllables), sign language phonology (e.g., phonological awareness activities,[45,68]) and fingerspelling, are often used in conjunction with print to aid in the learning of letters/word-meaning couplings.[75,76] A common practice in deaf education is to engage in 'chaining,' such as producing an ASL sign, BALL, fingerspelling B-A-L-L, pointing to the printed word, 'ball,' repeating the sign BALL, and using BALL in an ASL sentence.[77] Here, English becomes a 'shallow orthography' with 1:1 correspondence between fingerspelling and printed letters/words, which, via chaining, is linked to semantic meanings, as well as being embedded in the sign stream as lexical items. Thus, fingerspelling as one among the multiple components of VSP, may provide three types of beneficial visual experience for the young deaf reader: visual segmentation experience through early exposure to (1) VSP segmentation from a natural sign language, (2) visual fingerspelling segmentation, and its correspondence to (3) visual orthographic letter segments and their patterning on the page. Confirming many deaf educators and parents' intuitions about fingerspelling in education, fingerspelling skill is highly correlated with reading and vocabulary skills.[16,76,78,79]

CONCLUSION

In this study, we offered a new hypothesis about the brain mechanisms from whence phonology in human language came and how it may contribute to successful reading in all children. We suggest that phonology derives from the brain's biological capacity to segment the linguistic stream, categorize it, and discern linguistic-statistical patterning, and we offer support for this hypothesis through neuroscience research showing homologous participating brain regions and systems underlying phonology, be it on the hands in signed languages or on the tongue in spoken languages.[22,27,28,44]

We articulate the fascinating features of VSP from the natural sign language, ASL (sign-phonetic and sign-syllabic units and their patterning, in addition to fingerspelling and mouthing patterning). Perhaps our most controversial conclusion is that VSP serves the identical role in early reading acquisition as sound phonology. A child with early exposure to sign language develops normal phonological knowledge, enabling segmentation and categorization skills, which, in turn facilitates early decoding of English print in young deaf readers, similar to young monolingual and bilingual readers.[63,80] We specifically suggest that VSP facilitates the development of strong and automatic mappings among English phonological, semantic, and orthographic representations based on the child's strong underlying visual phonological segmentation skills, which are made possible most optimally through visual language exposure or VSP-based instruction in early life.

We have also proposed the hypothesis that sign-exposed deaf children, and all children instructed in VSP, may develop a visual modality advantage. These children move from visual segmentation of natural language sign-phonetic units to visual segmentation of orthographic letters and patterns on the page. Added to this hypothesized advantage is a second advantage made possible by exposure to fingerspelling. Here, deaf children may go from the fingerspelled letter in sign to a direct mapping and segmentation of the printed words on the page. Together, fingerspelling and ASL sign phonological awareness may strengthen phonological-orthographic mapping, thereby enabling the development of skilled reading in deaf children and adults who use sign language; the radical prediction here is that bilingual deaf children may be better readers than their age-matched hearing monolingual peers.

Much additional research is needed to understand the role of VSP in young deaf children's acquisition of reading as only hypothesized in our model. Here, we hope to stimulate serious discussion of the existence of VSP, and its potential for powerful positive impact on reading success in young children.

The mere existence of young sign-exposed profoundly deaf children who are outstanding readers of English compels us to ask *how is this possible?* Our strongest conclusion concerns the essential nature of language in our species: Sound, per se, is neither crucial for normal human language acquisition, nor for masterful reading. Instead, to the above question we answer with research showing striking cross-modal evidence of the human brain's sensitivity to specific maximally contrasting, rhythmic-temporal patterning at the core of human language phonological structure and its biological capacity to segment, categorize, and discern linguistic patterning.[3,5,9,11,13,14,27,35] The existence of VSP has exciting and important implications for all language learning, all reading, the biological equivalence of signed and spoken languages, and the essential properties of human language in the brain of our species. This knowledge can radically alter our understanding of how to best promote language learning and reading in children for generations to come.

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