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Date: 2021-07-30T00:00:00+00:00

Abstract

Auditory word recognition involves complex cognitive processing mechanisms. Blind individuals with visual deprivation exhibit certain auditory compensatory advantages in auditory word processing; however, due to the absence of visual experience, they demonstrate weaker semantic processing and comprehension of visually-related words (e.g., color words) compared to sighted individuals. Future research should categorize and discuss the visual relevance of vocabulary; conduct in-depth investigations into multiple levels including phonology, orthography, and semantics, as well as their neurophysiological mechanisms; develop auditory word processing models that align with the perceptual characteristics of blind individuals; and expand developmental research across different age groups. Ultimately, this will reveal the complete picture of the mechanisms through which visual experience deprivation influences auditory word recognition in blind individuals.

Full Text

The Effect of Visual Experience Deprivation on Auditory Word Recognition in Blind Individuals

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Abstract

Auditory word recognition involves complex cognitive processing. Blind individuals, whose visual channel is blocked, exhibit certain auditory compensatory advantages in word processing. However, due to the lack of visual input, their semantic processing and understanding of visually-related words (such as color terms) are weaker than those of sighted individuals. Future research should categorize words based on their visual relevance, investigate multiple levels including phonology, orthography, and semantics along with their neurophysiological mechanisms, develop auditory word processing models that conform to the perceptual characteristics of blind individuals, and expand developmental studies across different age groups. Ultimately, this will reveal the complete picture of how visual experience deprivation affects auditory word recognition in blind individuals.

Keywords: blind individuals, auditory word recognition, phonology, semantics, orthography

Language is one of the most complex cognitive abilities possessed by humans, serving as a crucial tool for expressing thoughts, communication, and learning. Possessing good language skills is essential for individual personality and socialization. Language acquisition and development are influenced by both genetic and environmental factors. Sighted individuals' language learning is based on intact vision—they can see changes in speakers' mouth shapes, facial expressions, and body movements during conversation, and they can see red flowers, green trees, and white snow. However, blind individuals (especially those with congenital or early-onset blindness) have blocked visual channels and lack vivid visual information input during language acquisition. From a human perspective, blind and sighted individuals living in the same physical and cultural environment have vastly different visual experiences. From an environmental perspective, it could also be understood that blind and sighted individuals live in physical and cultural environments with different visual characteristics.

The environment has a powerful shaping effect on individuals. Blind individuals with blocked visual channels undergo psychological and behavioral changes different from sighted people during environmental adaptation. Language is one of the most complex psychological phenomena and an important tool for communication and learning, with spoken language being even more critical for blind individuals with blocked visual channels. Are blind individuals, who rely more heavily on auditory channels, more advantaged in auditory speech processing, or does the lack of visual information create certain disadvantages? Moreover, what are the neurophysiological underpinnings of these changes in cognitive processing mechanisms triggered by visual experience deprivation? Exploring these questions helps us understand the complex influence mechanisms of environment on individual psychological development from the perspective of visual experience deprivation. Words play an important role in auditory speech comprehension, and understanding each word is a prerequisite for deeper comprehension. Therefore, this study focuses on exploring the influence mechanisms of visual experience deprivation on auditory word recognition in blind individuals. This paper first introduces the composition of auditory words and existing research on auditory word recognition in sighted individuals, then reviews previous literature on auditory word recognition in blind individuals, discusses the characteristics and mechanisms of auditory word recognition in blind individuals, and provides an outlook on future research directions in this field.

1.1 Composition and Processing Mechanisms of Auditory Words

Speech is a highly structured combination of sounds composed of basic speech units. Among them, the phoneme is the smallest unit of speech that can distinguish meaning. For example, in English, the word /home/ contains three phonemes: /h/, /o/, and /m/. In Western alphabetic writing systems, phonemes mainly include vowels and consonants. Vowels differ primarily in formants on spectrograms, while consonants have relatively more distinctive features, with voice onset time (VOT) being an important characteristic. In tonal languages (such as Mandarin Chinese), the smallest phonological units that can distinguish meaning include not only vowels (called finals in Pinyin) and consonants (called initials in Pinyin) but also tones. The primary cue for tone perception is the fundamental frequency contour. Mandarin Chinese has four tones with different pitch contours (Chao, 1948). For instance, /ma1/, /ma2/, /ma3/, and /ma4/ have the same initial-final structure, differing only in tone, yet they correspond to four completely different meanings—"mother," "hemp," "horse," and "scold." In short, phonemes in tonal languages consist of three types: vowels (or finals), consonants (or initials), and tones. People in different language systems combine phonemes into morphemes according to certain phonological and grammatical rules, which then form words. Words are the smallest units that can be used independently in language.

Words are combinations of phonology and semantics, simultaneously conveying grammatical and syntactic information. Words play an important role in auditory speech comprehension, and understanding each word is a prerequisite for deeper comprehension. For example, to understand the sentence "I love my country," one must first recognize each word contained within it. Individual lexical knowledge is organized and stored in the mental lexicon in the form of representations. Each word in the mental lexicon has an entry containing various information such as orthography, phonology, and semantics. During auditory word processing, individuals match the sound signals input by the auditory system with existing lexical representations (phonology-orthography-semantics) in the mental lexicon until the word is recognized and understood. Researchers call this process auditory word recognition or lexical access (this paper uniformly uses "auditory word recognition"). Auditory word recognition involves complex and refined cognitive processing. Based on extensive empirical research, psycholinguists have proposed many different theoretical models to reveal the processing of auditory word recognition, with the most representative being the Cohort model and the TRACE model.

The Cohort model (Marslen-Wilson & Tyler, 1980; Marslen-Wilson & Welsh, 1978) is the first theoretical model for auditory word recognition in psycholinguistics. In the Cohort model, auditory word recognition includes three stages: access, selection, and integration. First, in the access stage, auditory input of phonological information simultaneously activates a series of candidate word cohorts in the mental lexicon, whose word-initial information matches the input phonological information. The second stage is lexical selection. As input phonological information increases, candidate words that do not match the features of the newly input phonological information are removed. This process repeats until only one candidate word that completely matches the input phonological information remains, achieving recognition of the target word. The first two stages belong to pre-lexical processing, while the integration stage occurs at the lexical level. In the integration stage, individuals extract the semantic and syntactic features of the target word and integrate them into the context.

The TRACE model (McClelland & Elman, 1986; McClelland & Rumelhart, 1981) is a connectionist interactive model. This model divides the auditory word recognition system into three hierarchical levels from low to high: the feature layer, phoneme layer, and word layer. Each level contains multiple recognition units. Different recognition units within the same layer are mutually inhibitory, while relationships between different layers are facilitative and bidirectional. When auditory speech signals are input, phonological representation units in the feature layer are first activated, which further activate related phoneme representations and lexical representations in the phoneme layer and word layer. As input stimuli continuously increase, the activation levels of recognition units at each level undergo dynamic changes. The word that matches all input features has the highest activation level and is thus recognized. Auditory word recognition begins at the bottom feature layer, transmitting phonological information bottom-up. Simultaneously, higher-level information also influences lower-level processing, meaning lexical information also affects pre-lexical processing.

Both the Cohort model and TRACE model acknowledge that auditory word recognition is a process of matching phonological input with mental lexicon representations and that the process includes pre-lexical phonological processing and lexical-level semantic processing. The difference is that the Cohort model considers auditory word recognition a unidirectional bottom-up process and emphasizes the importance of word-initial information, while the TRACE model acknowledges the influence of higher-level information on lower-level processing, believing that both bottom-up and top-down processing coexist in lexical recognition. Currently, the TRACE model' s hypotheses about auditory word processing have received broader research support.

1.2 Auditory Word Processing in Sighted Individuals

Many previous studies on auditory word processing in sighted individuals have found that both phonological and semantic variables modulate auditory word processing. Studies using priming paradigms have found that when primes and targets are semantically unrelated but share initial syllable phonological similarity (e.g., /zaotui-zaofan/), participants' performance in judging whether the target is a real word is worse (lower accuracy, longer reaction time) than for targets that are semantically unrelated and phonologically different from the prime (e.g., /shouduan-zaofan/) (Huang et al., 2016; Huang et al., 2014). This result indicates that phonological information is activated during auditory word recognition. Semantic information is also activated in auditory word recognition. For example, research has found that low-frequency concrete words are easier to recognize than low-frequency abstract words (James, 1975), words with more meanings are easier to recognize than words with fewer meanings (Hino & Lupker, 1996), and participants show better recognition performance (higher accuracy, shorter reaction time) for targets semantically related to primes than for semantically unrelated targets (Huang et al., 2016; Huang et al., 2014). Furthermore, low-level phonological features also influence high-level semantic extraction and integration processes. ERP studies have found that targets sharing initial syllables with primes (e.g., /zaotui-zaofan/) elicit larger N400 effects than targets with different initial syllables from primes (e.g., /shouduan-zaofan/) (Huang et al., 2016). The N400 represents semantic extraction and/or integration processes (Kutas & Hillyard, 1980; Kutas & Hillyard, 1984; Kutas & Federmeier, 2011). Therefore, this result demonstrates that low-level phonological features have a bottom-up influence on high-level semantic processing.

Additionally, individuals' reading experience (Frith, 1998; Seidenberg & Tanenhaus, 1979; Qu & Damian, 2017) and task type (Huang et al., 2016) have top-down modulating effects on auditory word processing. Individuals need to master the connection between phonology and semantics when acquiring spoken language, and when learning to read, they must also match visual symbols (orthography) with phonological and semantic representations (Chen et al., 2016). Frith (1998) suggested that individuals' experiences learning to read and write may affect their spoken language processing. Evidence supporting this hypothesis includes the influence of orthographic variables on spoken word processing, such as orthographic consistency (the degree of consistency between orthography and phonology mapping) and orthographic neighborhood density (the number of words differing by only one letter from the target word), which affect individuals' auditory word processing. The most prominent evidence for orthographic factors affecting auditory word recognition may be the orthographic consistency effect, which refers to similar orthography facilitating individuals' judgments of auditory words. Specifically, participants show shorter reaction times when judging orthographically inconsistent word pairs (e.g., /tie-rye/) than consistent word pairs (e.g., /tie-pie/) (Seidenberg & Tanenhaus, 1979). Using ERP technology, researchers observed that N400 response amplitudes elicited by prime-target pairs with similar orthography (e.g., /beef-reef/) were smaller than those elicited by orthographically mismatched pairs (e.g., /sick-reef/) (Perre, Midgley, & Ziegler, 2009). The orthographic consistency phenomenon has been widely verified in alphabetic language systems with high phonology-orthography matching (Chéreau, Gaskell, & Dumay, 2007; Miller & Swick, 2003; Pattamadilok et al., 2007; Pattamadilok et al., 2009; Taft et al., 2008; Ventura et al., 2004; Ventura et al., 2008; Ziegler, Petrova, & Ferrand, 2008). Recent studies have also found orthographic consistency effects in logographic systems (such as Chinese) with relatively lower phonology-orthography matching (Chen et al., 2016; Qu & Damian, 2017; Zou et al., 2012). The orthographic consistency effect in auditory word recognition reflects the top-down influence of reading and writing experience on auditory word recognition.

Although speech is primarily considered an auditory experience, visual channel input also plays a very important role in speech perception. Speakers' mouth movements can provide listeners with information about temporal and phonetic features of acoustic signals, which can be used to decode speech signals (Yehia et al., 1998; Grant & Greenberg, 2001; Chandrasekaran et al., 2009). Individuals can use speakers' articulatory mouth movements, facial muscle activities, and expressions as "visual information" to form continuous visual perception, compare and connect it with lexical representations stored in the mental lexicon, and thereby understand what the speaker is saying. This process is also called "lipreading" (Summerfield, 1992; 朴永馨, 2006; 徐诚, 2013). The influence of visual information on speech perception has been widely confirmed. For example, researchers have found that when visually presented mouth articulation movements (i.e., visual information) are consistent with auditory speech information, they can enhance speech perception abilities in both normal-hearing adult and child participants (Knowland et al., 2016; Lusk & Mitchel, 2016; Sumby & Pollack, 1954). Inconsistent visual information interferes with individuals' speech perception, such as the McGurk effect, where presenting participants with the visual articulation of /ga/ while simultaneously presenting the auditory stimulus /ba/ results in participants reporting hearing /da/ (McGurk & MacDonald, 1976). Studies on hearing-impaired individuals with damaged auditory channels have found that they mainly rely on visual information for speech perception (雷江华 & 方俊明, 2005), and lipreading helps hearing-impaired populations form phonological representations and interacts with lexical knowledge (赵英 et al., 2020). The influence of visual information related to lipreading on speech perception reflects the top-down effect of visual perceptual experience on auditory speech processing.

Previous research findings on auditory word processing in sighted individuals support the theoretical construction of the TRACE model, which posits that auditory word recognition includes pre-lexical phonological processing and lexical-level semantic processing, with both bottom-up and top-down processing occurring simultaneously. Individuals' lexical knowledge is stored in the mental lexicon in the form of orthography-phonology-semantics representations, with phonological, semantic, and corresponding orthographic features of words all modulating the auditory word processing. Auditory word recognition is the process by which individuals match speech signals with existing phonology-orthography-semantics representations in the mental lexicon. The lack of visual experience may change the phonological, orthographic, and semantic representations in blind individuals' mental lexicon, and the processing mechanisms of auditory word recognition in blind individuals may differ from those of sighted individuals. So, what are the specific manifestations of differences between blind and sighted individuals in auditory word recognition, and are these differences quantitative or qualitative? Below, this study will discuss previous research related to auditory word recognition in blind individuals.

2.1 Compensatory Effects in Speech Perception in Blind Individuals

Sensory compensation theory posits that a deficit in one sensory channel may cause individuals to rely more on other intact sensory channels, thereby optimizing the function of these intact channels and producing advantageous compensatory changes (Kupers et al., 2011; Hötting & Röder, 2009). Vision, hearing, touch, and smell are important sensory channels for humans. Blind individuals have blocked visual channels and cannot use them to perceive the world, thus relying more on non-visual sensory channels such as hearing and touch to obtain information about their surroundings. Blind individuals also more actively use these intact sensory channels to acquire information in social life (such as listening to audiobooks and news). As the saying goes, "use it or lose it." Blind individuals' adaptive changes to the environment enable them to develop stronger abilities to perceive and process auditory information.

Previous researchers have observed many auditory compensatory phenomena in congenitally and early-blind participants. For example, researchers have found that blind individuals have better pure tone pitch discrimination ability (Arnaud, Gracco, & Menard, 2018; Gougoux et al., 2004; Wan et al., 2010), pitch rhythm classification ability (Rammsayer, 1992), auditory temporal interval discrimination ability (Rammsayer, 1992), noise gap identification ability (Muchnik et al., 1991), auditory stream segregation ability (Boroujeni et al., 2017), and sound spatial localization ability (Gougoux et al., 2005; Lessard et al., 1998) than sighted individuals.

Blind individuals' auditory compensatory advantages are also reflected in speech perception. The most prominent is that congenitally blind adults can process and understand speech information presented at ultra-fast speeds (16-22 syllables/second), far exceeding the speech presentation speed that sighted participants can generally accept (6-8 syllables/second) (Dietrich, Hertrich, & Ackermann, 2013a, 2013b; Moos & Trouvain, 2007). Moreover, Gordon-Salant and Friedman (2011) found that older blind participants had better perception abilities for fast speech than older sighted participants under both quiet and noisy conditions, with no significant difference between older blind participants and young sighted participants.

At the syllable and phoneme levels, blind individuals also show certain auditory compensatory advantages. Hugdahl and colleagues (2004) used a dichotic listening test procedure to directly measure and compare blind and sighted individuals' processing abilities for consonant-vowel (CV) syllables. The experiment included 14 congenitally or early-blind Finnish-speaking participants and 129 Finnish sighted participants. The experiment had three conditions: asking participants to attend only to right-ear stimuli, only to left-ear stimuli, or no special requirement. The results showed that overall, blind participants correctly reported more syllables than sighted participants, indicating better speech perception abilities in blind participants. Moreover, when asked to attend to left-ear stimuli and report only what was heard in the left ear (right hemisphere processing), the blind group performed significantly better than the sighted group, suggesting that blind individuals' right hemisphere has better processing ability for speech information than sighted individuals. Ménard and colleagues (2009) observed that blind participants had better perception abilities for native language vowels than sighted participants when studying the relationship between perception and production of French vowels in blind and sighted individuals. A recent study also found that adult blind participants had smaller discrimination thresholds for native language vowels than sighted participants, meaning blind individuals are more sensitive to native language vowels (Arnaud, Gracco, & Menard, 2018).

Unlike Western alphabetic writing, tonal languages (such as Chinese) include tones in addition to vowels and consonants. Chinese researcher Cao Jieqiong (2004) measured Chinese blind students' syllable perception abilities. The study recruited 84 blind students from Shanghai School for the Blind (10 third graders, 10 fifth graders, 10 first-year middle school students, 5 second-year middle school students, and 9 first-year high school students, divided into totally blind and low vision groups) and ten sighted students from regular schools at each corresponding grade level. Participants needed to judge whether two or three syllables they heard were the same. The results showed that younger blind children (ages 9 and 11) had lower accuracy in speech discrimination than sighted children of the same age, while older blind children (age 13) had higher accuracy than their sighted peers. This result indicates that blind children' s speech perception abilities improve with age, revealing different effects of visual experience deprivation on blind children' s speech perception across age. The researcher also reported that by age 16, the accuracy of the three groups was similar, possibly due to ceiling effects in the behavioral test tools for this age group.

Speech perception is the foundation of speech processing. Western alphabetic writing research has found that blind individuals have better consonant-vowel syllable discrimination abilities and more sensitive vowel perception abilities, and the lateralization advantages of speech perception in blind individuals also differ from those of sighted individuals. Phonemes in tonal languages (such as Chinese) include initials, finals, and tones. Currently, research on speech perception abilities of blind individuals in tonal language environments is relatively scarce, and we do not yet understand the neuroplastic changes in brain mechanisms underlying phoneme perception in blind individuals in tonal language cultures. Research on speech perception of blind individuals in tonal language cultural environments needs further deepening. Additionally, phonemes are the smallest units that can distinguish meaning. In auditory word recognition, blind individuals' more optimized phoneme processing abilities may have a bottom-up influence on word-level processing, which subsequent research could explore. Furthermore, the impact of visual experience deprivation on blind individuals' speech perception and processing may change over time, making it necessary to conduct developmental studies using multi-level research methods including behavioral and cognitive neuroscience approaches to reveal how visual experience deprivation affects individual speech perception and processing with age.

2.2 Compensatory Effects in Auditory Word Processing in Blind Individuals

Blind individuals' auditory compensation phenomena are also reflected in other speech abilities. In many spoken memory tasks, congenitally blind participants perform better than sighted participants, such as in short-term memory and long-term recall (Amedi et al., 2003; Pasqualotto, Lam, & Proulx, 2013), word recognition (Amedi et al., 2003; Röder, Rösler, & Neville, 2001), serial word order (Raz et al., 2007), and working memory as represented by digit span (Tillman & Bashaw, 1968; Smits & Mommers, 1976; Hull & Mason, 1995; Withagen et al., 2013). Röder and Rösler (2003) found that congenitally blind participants had better memory abilities for environmental sounds (including animal sounds, human voices, traffic sounds, etc.) than sighted participants, suggesting that congenitally blind individuals may have better physical encoding abilities for sounds. Occelli and colleagues (2017) compared congenitally blind participants with age- and education-matched sighted participants on spoken tasks (including spoken word memory, spoken phonological fluency, spoken semantic fluency, and spoken working memory) and spatial tasks (spatial memory and spatial imagination). The results showed that the blind group performed better than the sighted group on all spoken tasks, while there was no significant difference between the two groups on spatial tasks. This indicates that blind individuals have more optimized spoken memory abilities rather than general memory advantages.

In lexical processing, researchers have found that blind participants judge auditory words faster than sighted participants (Röder, Demuth, Streb, & Rösler, 2003; Schild & Friedrich, 2018). Röder and colleagues (2003) used semantic priming and grammatical priming paradigms, asking German-speaking congenitally blind and sighted adults to listen to prime-target word pairs, where primes were adjectives and targets included both real nouns and pseudowords. The researchers also manipulated semantic relatedness (related or unrelated) and grammatical congruency (matched or mismatched) between adjectives and nouns in real word pairs. Participants needed to judge whether the heard target was a grammatically correct German word. The results showed no significant difference in error rates between the two groups. However, blind participants' judgment speeds for targets were faster than sighted participants under all experimental conditions. Moreover, all participants showed shorter reaction times in semantically related and grammatically matched conditions than in conditions with only semantic relatedness or only grammatical matching, demonstrating grammatical and semantic priming effects. However, these semantic and grammatical priming effects did not differ significantly between the two groups. This result suggests that blind and sighted individuals seem to use semantic and grammatical relationships between prime-target pairs to the same degree to facilitate their behavioral judgments. Therefore, the researchers believe that blind individuals' fast speech processing abilities seem not to be strongly related to more refined semantic or grammatical analysis but may mainly result from their more optimized speech perception and analysis abilities.

In another study, Schild and Friedrich (2018) used a word onset priming paradigm to compare behavioral responses and electrophysiological signal changes in auditory word recognition between adult blind and sighted participants. In the experiment, participants were presented with prime stimuli (word-initial phonology) and target stimuli (whole word phonology), with two conditions: phonologically same and phonologically different between prime and target. The study found that blind participants' auditory word judgment speeds were faster than sighted participants, with blind individuals' faster reaction speeds evident under both experimental conditions. However, the study found no significant differences in EEG responses between the two groups. The researchers believe these results indicate that during auditory word recognition, blind and sighted individuals have similar processing speeds for phonological encoding and semantic matching. Blind individuals' faster behavioral judgments may be because they do not need to integrate visual cues, while sighted individuals need to integrate stored visual-auditory information in memory during auditory word recognition, resulting in longer reaction times.

The above research results on speech processing in blind individuals show that compared with sighted individuals, blind individuals have better spoken memory abilities and also show certain advantages in auditory word processing. In auditory word processing, researchers consistently find that blind participants judge auditory words faster than sighted participants, but explanations for this phenomenon are controversial. Röder et al. (2003) believe that blind individuals' fast speech judgment abilities may result from their more optimized speech perception and analysis abilities, while Schild and Friedrich (2018) suggest that blind individuals may have faster judgment speeds because they do not need to integrate visual cues during speech processing. Auditory word recognition includes pre-lexical phonological processing and lexical-level semantic processing. Blind individuals rely more on and use speech information more frequently in daily life, and this increased use and practice may enable them to better utilize internal speech information. Speech information includes both basic to complex phonological information such as duration, amplitude, pitch, phonemes, phonological units, syllables, and intonation, as well as various semantic and grammatical information such as word meaning, word frequency, word form, syntax, and linguistic context in which words appear. In other words, blind individuals' faster lexical recognition abilities may be related to their processing and utilization of phonological information and related semantic-grammatical information in spoken words, and the importance of these types of information for auditory word recognition may also differ. These are questions that remain to be resolved in research on auditory word processing in blind individuals. Additionally, due to differences in phoneme composition between tonal and non-tonal languages, cross-cultural research and comparisons in multiple language cultures are necessary to explore universality and specificity. Furthermore, the influence of visual experience on blind individuals' auditory word processing and related factors may also change over time. Therefore, to comprehensively reveal the complex processing mechanisms of blind individuals' auditory word recognition advantages, developmental studies are also necessary.

2.3 Semantic Understanding of Words in Blind Individuals

Grounded Cognition Theory posits that sensation and cognition are not isolated, and that individuals' cognition is closely related to sensory experience. Modal simulation (Barsalou, 1999; Decety & Grèzes, 2006; Goldman, 2006), bodily states (Barsalou, 2003; Lakoff & Johnson, 1980; Smith, 2005), and situated action (Barsalou, 2003; Barsalou, Breazeal, & Smith, 2007; Glenberg, 1997; Prinz, 1997; Rizzolatti & Craighero, 2004; Robbins & Aydede, 2008; Smith & Semin, 2004; Yeh & Barsalou, 2006) are the foundations of cognition. Individuals' knowledge representations are based on their sensory experiences and stored in sensory association cortices (Barsalou et al., 2003; Martin, 2016; Simmons et al., 2007). Some words used by humans have certain "visual" characteristics (referred to in this study as visually-related words), such as spatial orientation words, shape words, visual verbs (observe, gaze, glance, gaze into the distance), color words (red, green, black, milky white, watermelon red, coffee color), etc. These visually-related words contain sighted individuals' understanding and definitions of the world. Blind individuals (especially congenitally and early-blind individuals) lack direct visual perceptual experience of the world, and their understanding and representation of these visually-related words may differ from those of sighted individuals. Based on Grounded Cognition Theory, it can be inferred that visual experience deprivation may have some adverse effects on blind individuals' semantic representation and understanding of visually-related words.

In this research field, early educational psychologist Cutsforth (1932, 1951) first proposed the concept of "verbalism." He pointed out that some words used by blind individuals are meaningless to them, such as color words and light words (for related research on verbalism, see review Rosel et al., 2005). However, more research has found that visually-related words are not meaningless to blind individuals, who have some understanding of these words and can use them correctly in context (Landau & Gleitman, 1985; Piskorska, 2008). For example, Piskorska (2008) reported that three 11-12-year-old blind children could effectively distinguish and use a series of words representing "beauty" (pretty, beautiful, handsome, and cute). They all considered the description "Eggs are beautiful" to be incorrect, and among the four words "big," "fast," "small," and "cute," they identified "cute" as most different from the other three. These results indicate that blind children can meaningfully understand and use some visually-related words from an early age.

Although blind individuals have some understanding of visually-related words, their degree of understanding and representation characteristics differ from those of sighted individuals. Previous researchers have used word association tasks or word definition tasks to explore blind individuals' word understanding and semantic representation. McGinnis (1981) divided visually-featured words into three categories: (1) color words; (2) verbs with visual references (look, stare, etc.); (3) verbs with visual reference features used in slang (understand, imagine, etc.). The researcher compared blind and sighted participants' use of visually-related words in word association tasks and found that blind participants used visually-related words less than sighted participants. The researcher suggested this might be because blind participants have smaller vocabularies of visually-related words or less refined semantic representations of visually-related words than sighted participants. In another study, Vinter and colleagues (2013) asked congenitally blind, late-blind, and sighted children to define and explain five categories of common words: people, animals, objects that can be touched but not manipulated (such as trees and houses), objects that can be touched and manipulated with hands (such as toothbrushes and glasses), and things that are not solid but can be felt through contact (such as rain and sun). By coding and analyzing participants' spoken materials, the researchers found that sighted children had more descriptions of sensory features than the other two groups. Congenitally blind children used more auditory and tactile features in their descriptions than sighted and late-blind children, while sighted children used more visual features than congenitally blind children. This result indicates that blind children' s lexical representations contain more tactile and auditory representations and fewer visual representations. Additionally, researchers found that adult sighted participants mainly classified "fruits and vegetables" vocabulary based on color features, while blind participants did not actively use color strategies when classifying these words (Connolly, Gleitman, & Thompson-Schill, 2007). Landau and Gleitman (1985) conducted a longitudinal study of a 4-year-old congenitally blind child and found that the child could interpret "look" as "touch with hands" and understand "seeing" as "perceiving an object at a certain distance from the speaker." When blind children were asked "why they think spring is beautiful," they answered "birds singing," "warm weather," and "like the smell of spring," but unlike sighted children, they did not mention colorful flowers and new leaves, using hearing, touch, and smell to experience and understand "beauty" (Piskorska, 2008).

Based on the above discussion, we can see that blind individuals use non-visual perceptual pathways such as hearing, touch, and smell to understand and represent some visually-related words, such as words representing "beauty"(Piskorska, 2008) and words representing concrete objects (Vinter et al., 2013). This study refers to these words that can be perceived through other sensory channels as "weak visually-related words." For weak visually-related words, the difference between blind and sighted individuals may mainly manifest in different representation dimensions, with their degree of understanding of these visually-related words possibly being similar. In other words, visual experience deprivation may not affect blind individuals' degree of understanding of these words that can be understood through other perceptual pathways. However, among visually-related words, there are some more special words that can only be directly perceived and experienced through vision, such as color-related words and light-related words. This study refers to these as "strong visually-related words." Visual experience deprivation may cause blind individuals greater difficulty in understanding and processing strong visually-related words. Taking color words as an example: color is a sensory experience produced by light waves acting on the human eye. It is silent, tasteless, and untouchable, and can only be directly perceived through the visual channel. Blind individuals with blocked visual channels cannot directly perceive color and can only learn color knowledge through non-visual pathways (such as hearing others' descriptions). In a recent study, Kim and colleagues (2019) compared animal appearance knowledge between congenitally blind and sighted participants using a series of tests including ranking (volume and height), classification (shape, skin texture, and color), difference finding (shape), and feature selection. The results showed that although the two groups' performance on most tasks had slight differences, they were highly similar. The biggest difference between the two groups came from the dimension most easily perceived by sighted individuals: color.

Previous researchers have conducted many explorations around blind individuals' color concepts. In an early case report, Landau and Gleitman (1985) pointed out that a blind child could correctly name the colors of some objects at age four. Connolly and colleagues (2007) reported that 8-13-year-old blind children could name the colors of most common objects. Chinese researchers have conducted more detailed studies on the timing of blind children' s acquisition of color words (张积家 et al., 2008; 时琴琴, 2011). 张积家 and colleagues (2008) used 11 basic color words (including black, white, red, orange, yellow, green, blue, purple, brown, gray, and pink) as experimental materials to measure the acquisition order of basic color concepts in 85 elementary and middle school blind students (58 congenitally blind and 27 late-blind). The criterion for acquiring a color concept was being able to name objects with that color. The results showed that the acquisition order of color concepts in blind children differed from that of sighted children. Late-blind children had higher acquisition rates for "white" and "purple" than congenitally blind children, and middle school blind students had higher acquisition rates for "brown" than elementary school blind students. 时琴琴 (2011) also studied blind children' s acquisition rates for 11 basic color words. The results found that blind children' s acquisition order for color words was roughly the same as sighted children, with higher acquisition rates for black, white, red, and green. However, elementary school blind children had lower acquisition rates for "brown" than sighted children, and middle school blind students had lower acquisition rates for eight basic colors excluding red, blue, and green than sighted children.

Research on the mental representation of color concepts in blind individuals has found that blind individuals' mental representations of color concepts are highly similar to those of sighted individuals—both conform to Newton' s color circle

规律, with red adjacent to orange, yellow between orange and green, followed by cyan and blue, and purple between blue and red (Marmor, 1978; Shepard & Cooper, 1992; Saysani, Corballis, & Corballis, 2018). However, there are certain differences in the size and distribution of color cognitive space between blind and sighted participants, and there is also considerable individual variation within the blind group (Shepard & Cooper, 1992; Saysani, Corballis, & Corballis, 2018). Additionally, Chinese researchers have found that sighted children' s color classification dimensions include a cool/warm color classification dimension, which blind children do not form (张积家 et al., 2008; 时琴琴, 2011).

In addition to basic color concepts and object color knowledge, researchers have also explored blind individuals' understanding of metaphorical meanings of color words. Some case reports indicate that a congenitally blind child knew that color words could only be used to describe concrete objects (such as cats and dogs) but not abstract concepts like ideas or stories (Landau & Gleitman, 1985). Another blind child believed that "blue" was a boy' s color, while "red or pink" were girls' colors (Bedny & Saxe, 2012). Barilari and colleagues (2018) compared cross-modal association abilities between early-blind and sighted participants from two countries. In the experiment, participants needed to answer three questions: (1) "Is a lemon fast or slow?" (2) "Is a rock sour or sweet?" (3) "Which is heavier, yellow or red?" The researchers analyzed participants' responses using chi-square tests. The results showed that both blind and sighted participants were more inclined to think that "rocks are sour" and "red is heavier than yellow," but there were significant group differences between the two groups in color-weight associations. This research indicates that early-blind groups also have some color association knowledge, but to a lesser degree than sighted individuals.

Chinese researcher 时琴琴 (2011) also conducted a series of explorations on blind individuals'color association knowledge. In one experiment, the researcher asked elementary blind children, middle school blind children, and sighted children (wearing blindfolds) to compare white and black objects placed in each hand to determine which was heavier. Choosing black scored 1 point, choosing white scored 0 points, and thinking they were the same scored 0.5 points. The results only found that middle school participants' scores were higher than elementary school participants, with no differences found between sighted and blind children (时琴琴, 2011). In another experiment (时琴琴, 2011), the researcher used a priming paradigm, auditorily presenting related color association word pairs (such as red-festive) and unrelated color association word pairs (such as red-tranquil) to sighted and blind children, asking them to judge whether they knew the second word in each pair. The researcher recorded and analyzed participants' reaction times. The results showed that all participants had significantly shorter reaction times for related word pairs than for unrelated word pairs, demonstrating a color association priming effect. Moreover, middle school students had shorter reaction times than elementary school students, possibly because as age increases, individuals have more color association knowledge and stronger representations, making them more effective at utilizing association relationships in color association judgments. However, this study did not find significant group differences between blind and sighted children, possibly because the researcher only analyzed reaction time, a behavioral indicator with limited sensitivity.

The above research on blind individuals' understanding of visually-related words shows that blind individuals with visual experience deprivation can also acquire and understand some visually-related words. However, unlike sighted individuals, blind individuals tend to use non-visual features (such as tactile, auditory, and olfactory) to represent and understand visually-related words (such as words representing concrete objects and words representing "beauty"). Previous studies have mostly used qualitative analysis or behavioral research paradigms to explore differences in semantic representation dimensions of visually-related words between blind and sighted individuals, with less exploration of differences in semantic processing and understanding degree. This study hypothesizes that for words that can only be directly perceived through vision (such as color-related words and light-related words), blind individuals with visual experience deprivation may show greater differences in understanding and processing compared to sighted individuals. Therefore, when studying the processing mechanisms and neurophysiological basis of auditory word recognition in blind individuals, it is necessary to classify and discuss words based on their visual relevance, such as dividing words into non-visually-related words (such as kindness, wisdom), weak visually-related words (such as water cup, computer), and strong visually-related words (such as color words, light words). The influence of visual experience deprivation on semantic processing and understanding of auditory words in blind individuals may vary depending on the words used. Discussing this issue can help us deeply understand the relationship between sensation and cognition, as well as the relationship between matter and consciousness. Currently, there is relatively little research on the degree of understanding of visually-related words in blind individuals, and existing research is mostly at the behavioral level. We still do not understand its neurophysiological mechanisms, and further in-depth exploration of this field is needed.

3 Neuroplastic Changes in Word Processing in the Blind Brain

The brain is the physiological basis for various psychological phenomena and behaviors in humans. The changes in speech perception and speech processing in blind individuals due to visual experience deprivation also have certain neurophysiological underpinnings. Researchers have used cognitive neuroscience research techniques such as event-related potential (ERP), functional magnetic resonance imaging (fMRI), and transcranial magnetic stimulation (TMS) to explore adaptive changes in blind individuals' brains, finding some neuroplastic changes in brain structure and function related to language processing in blind populations.

At the speech processing level, Jafari and Malayeri (2014) compared differences in brainstem-evoked potentials between congenitally blind and sighted participants when listening to pure tone stimuli and speech stimuli (/da/ with 40 ms duration). The results showed that compared with sighted participants, blind participants had larger amplitudes and shorter latencies in brainstem-evoked potentials elicited by speech stimuli, while there were no significant differences between the two groups in brainstem-evoked potentials elicited by pure tone stimuli. The researchers believe these results indicate that congenitally blind participants have superior neural representation of speech stimuli at the brainstem level compared to sighted participants. The advantage in brainstem-level speech representation in congenitally blind populations has also been observed in blind children (ages 8-12) (Jafari & Malayeri, 2016). Additionally, researchers have found that during ultra-fast (16 syllables/second) speech processing, blind participants show stronger activation in the left prefrontal cortex and temporoparietal cortex than sighted participants, and blind participants' right primary visual cortex and left fusiform gyrus also participate in ultra-fast speech perception (Dietrich, Hertrich, & Ackermann, 2013a, 2013b; Hertrich et al., 2009). During ultra-fast (16 syllables/second) speech perception, blind participants show stronger phase synchronization in auditory cortex than sighted participants, and blind participants' right hemisphere visual cortex activity is correlated with syllable onsets in ultra-fast speech (Hertrich, Dietrich, & Ackermann, 2013).

At the lexical processing level, researchers have found that when generating verbs to nouns presented in Braille and auditorily, congenitally blind participants, in addition to activating frontal language areas like sighted participants, also show activation in early visual cortex (Burton et al., 2002a; Burton et al., 2002b). The phenomenon of visual cortex activation in blind participants during verb generation tasks is also evident in second language learning (Ofan & Zohary, 2007). Auditory word processing includes both low-level phonological processing and high-level semantic processing. Burton and colleagues (2003) further distinguished whether the adaptive changes in visual cortex during auditory word generation in blind individuals reflect semantic processing or phonological processing. The researchers recruited three groups of participants: sighted, early-blind, and late-blind, asking them to listen to a series of related words and attend to words with the same semantics (semantic task) or words with the same rhyme (phonological task) according to requirements. The results showed that the semantic task produced stronger activation in the left inferior frontal gyrus, while the phonological task produced stronger activation in bilateral inferior parietal lobes and posterior left inferior frontal gyrus in all three groups. However, only blind participants showed activation in occipital, temporal, and parietal visual cortex regions, and this activation in blind participants was more inclined toward the semantic task. The researchers believe that blind individuals' visual cortex participates in auditory speech processing, and this visual cortex activation is mainly related to semantic processing.

In another study, Noppeney et al. (2003) found that both early-blind and sighted participants showed activation of the left fronto-temporal core semantic extraction system during auditory word processing. Meanwhile, early-blind participants also showed additional activation in striate cortex, reflecting adaptive changes in semantic extraction responses due to visual experience deprivation. Other researchers used TMS to create temporary virtual lesions in blind participants' visual cortex and found that blind participants made more semantic errors than phonological errors in verb generation tasks (Amedi et al., 2004), and repetitive stimulation of blind participants' occipital cortex interfered with their Braille reading (Cohen et al., 1997). Additionally, researchers have found that the activation degree of blind participants' occipital cortex is correlated with their spoken memory performance (Amedi et al., 2003).

Cognitive neuroscience researchers have also explored the neural basis of how blind individuals' brains represent different types of words semantically (Bottini et al., 2020; Striem-Amit et al., 2018; Wang et al., 2020). Striem-Amit et al. (2018) used fMRI technology to study how congenitally blind individuals process words they cannot directly perceive (such as "rainbow," "red"). The researchers divided experimental words into four categories based on blind individuals' perceptual characteristics, from abstract to concrete: (1) words blind individuals cannot directly perceive (such as "rainbow," "red"), (2) classic abstract words (such as "fairness"), (3) words blind individuals can perceive (such as "rain"), and (4) words referring to concrete objects (such as "cup"). By comparing blind individuals' brain activation states when processing these categories of words, the researchers found that blind individuals' dorsal anterior temporal cortex is more sensitive to unperceivable lexical concepts, the lateral anterior temporal cortex is more sensitive to abstract lexical concepts, and the middle anterior temporal cortex tends to be more sensitive to perceivable lexical concepts. Wang et al. (2020) used a population comparison experimental design to compare similarities and differences in neural representations of color knowledge between congenitally blind (or early-blind) and sighted participants. They found that both blind and sighted groups showed activation in the left dorsal anterior temporal cortex, while the ventral occipito-temporal color perception area was only activated in sighted participants. Other researchers have found that in sighted participants, perceptually similar color words or action words induced adaptation phenomena in the posterior occipital cortex, which overlaps with brain regions known to represent low-level visual features in perceptual domains, while early-blind participants showed stronger adaptation phenomena in the temporal cortex for perceptually similar words (Bottini et al., 2020). The researchers believe that blind participants may rely more on lexical-semantic coding to represent perceptual knowledge (Bottini et al., 2020). The above studies consistently show that blind individuals' processing and representation of words they cannot directly perceive (such as color words) mainly occur in the temporal cortex. Sighted individuals' temporal cortex is an important component of the language processing network, leading to the speculation that blind individuals may rely more on linguistic information coding to represent such lexical knowledge.

Sighted individuals have an important visual word form area (VWFA) in the reading network, located in the left ventral occipito-temporal cortex (vOTC). In sighted individuals, the VWFA mainly participates in recognition of words and letter shapes (Cantlon et al., 2011; Cohen et al., 2000; Dehaene et al., 2010). However, some researchers have found that blind participants also show activation in the vOTC when reading Braille (a tactile script) (Buchel et al., 1998; Burton et al., 2002a; Reich et al., 2011; Sadato et al., 1996). Blind participants' vOTC activation when reading Braille is stronger than when touching meaningless patterns, and the response is strongest in the region corresponding to the VWFA in sighted individuals' anatomical structure (Reich et al., 2011). So, does blind individuals' "VWFA region" only participate in Braille form recognition in the mental lexicon like sighted individuals' , or does it also participate in high-level complex semantic-grammatical processing? Kim and colleagues (2017) used fMRI technology, asking congenitally blind and sighted participants to complete two experimental tasks: (1) word reading (Braille for blind participants, print for sighted participants), and (2) listening to sentences with different grammatical complexities (same for both groups). The results showed that only in blind participants did the VWFA region corresponding to anatomical structures respond to both visually presented words and spoken sentences with different lexical and grammatical complexities, indicating that blind individuals' VWFA participates in both Braille processing and high-level grammatical processing, while sighted participants'VWFA is insensitive to grammatical structure. However, automatic activation of word forms stored in the mental lexicon cannot be excluded when processing auditorily presented sentences, making Kim et al.' s (2017) conclusion that the VWFA participates in grammatical processing based on its activation during sentence processing not rigorous enough. Sigalov and colleagues (2016) studied the function of blind individuals' VWFA using a visual-auditory sensory substitution technology that can transmit letter shape features, comparing brain activity changes in congenitally blind participants when reading meaningful and meaningless words. They found that in early processing stages (letters), early auditory cortex and visual cortex were activated, while in later processing stages (words), both VWFA and bilateral dorsal intraparietal lobes were activated for words, and VWFA preferentially participated in letter and word form processing rather than subsequent semantic processing tasks. This result indicates that even with only short-term sensory substitution experience, form processing dominates over semantic processing in blind individuals' VWFA region. Words are stored in individuals' mental lexicon in the form of phonology, semantics, and orthography. Blind individuals use the Braille system dominated by touch for written expression and reading, and Braille reading experience may lead to the formation of Braille word form representations in blind individuals' mental lexicon. Blind individuals may have automatic activation of Braille forms during word processing. Future research needs to further examine the role and mechanism of blind individuals' VWFA in auditory word processing.

Sighted individuals' left prefrontal cortex and temporal cortex are mainly responsible for language processing. Blind individuals' occipital visual cortex participating in language processing expands rather than replaces the function of the original left fronto-temporal classic language areas. In language processing, blind and sighted participants' classic language areas have similar functional performance, and the visual cortex related to language processing in blind populations shows the same lateralization as the prefrontal language functional areas. Compared with sighted participants, blind individuals' occipital visual cortex activity has close connections with prefrontal language networks (Lane et al., 2015; Liu et al., 2007; Watkins et al., 2012), and blind participants' left prefrontal language area has stronger functional connectivity with the thalamus (Bedny et al., 2011). Memory and attention abilities also play important roles in speech processing and comprehension. Burton et al. (2014) found that compared with sighted individuals, early-blind participants had stronger functional connectivity between occipital visual cortex and brain regions related to cognitive control of memory and attention, indicating that blind individuals' visual cortex may be integrated into episodic retrieval and attention-related functional systems for non-visual events. However, the connectivity between blind individuals' visual cortex and non-sensory-deprived cortex was significantly lower, possibly to suppress interference from internal sensations on brain activity. Wang et al. (2014) compared differences in intra-network and inter-network connectivity between congenitally blind and sighted participants. They found that compared with sighted participants, congenitally blind participants had stronger internal network connectivity in both the salience network (SN network, including bilateral ventrolateral prefrontal cortex, anterior insula, and dorsal cingulate cortex) and the occipital cortex. Moreover, congenitally blind participants also had stronger network connectivity between the SN network and frontoparietal network, and between the frontoparietal network and occipital cortex. However, blind individuals' occipital cortex had weaker connectivity with sensorimotor networks. The researchers believe that early visual experience deprivation causes large-scale reorganization of functional networks in congenitally blind individuals' brains, and these enhanced intra-network and inter-network connections may improve their ability to identify stimuli, initiate executive functions, and top-down attention control, which are important for congenitally blind individuals to adapt to their environment. Additionally, Pelland et al. (2017) found that blind individuals' cognitive states affect their functional connectivity characteristics, with early-blind participants showing higher occipito-temporal activity correlation during tasks than at rest, while sighted participants showed the opposite pattern.

In short, the above research shows that visual experience deprivation causes some neuroplastic changes in blind individuals' brain structure and function, mainly manifested in: blind individuals have better speech representation than sighted individuals at the brainstem level; blind individuals' right occipital cortex participates in speech processing; blind individuals' left occipital cortex participates in various speech processing tasks, and the activation degree of occipital cortex may be mainly related to semantic processing. Their VWFA also participates in various speech processing tasks; blind individuals' left temporal cortex represents lexical knowledge they cannot directly perceive (such as color words). Additionally, the connectivity strength between blind individuals' visual cortex and prefrontal language functional areas is stronger than in sighted individuals.

Future research can expand explorations of cognitive processing mechanisms and neurophysiological bases for blind individuals of different language-cultural backgrounds, age groups, and different types of vocabulary recognition, and deepen research on the cognitive neural mechanisms of different levels (phonology, semantics, orthography) of auditory word processing in blind individuals.

4 Research Outlook

Sighted individuals' language acquisition and use are full of various visual cues, such as movements of lips and jaws during articulation, facial expressions, and body movements during conversation. These visual cues play important roles in individuals' language acquisition and development. However, blind individuals lack these vivid visual information inputs during language acquisition and rely more heavily and actively on auditory channels to obtain information about their surroundings. Visual experience deprivation causes a series of neuroplastic changes in blind individuals during environmental adaptation. Reviewing previous research, we find that blind individuals show certain auditory compensatory advantages in auditory word recognition. However, due to the lack of visual images and information, blind individuals' semantic representation and processing of some visually-related words are weaker than those of sighted individuals. Additionally, visual experience deprivation causes some neuroplastic changes in the neurophysiological mechanisms of blind individuals'auditory word processing. Auditory word recognition ability is important for blind individuals' speech comprehension. Currently, research and discussion on blind individuals' auditory word recognition are not systematic enough, with many confusions remaining that deserve more researchers' attention and exploration. Specifically, this study believes that research on the influence of visual experience deprivation on blind individuals' auditory word recognition can be further deepened from the following aspects.

First, research on blind individuals' auditory word recognition should classify and discuss words based on their visual relevance. For example, words can be divided into non-visually-related words (such as kindness, wisdom), weak visually-related words (such as water cup, computer), and strong visually-related words (such as color words, light words). Individuals' experience top-down influences the auditory word recognition process. Blind and sighted individuals have vastly different visual experiences, and these differences in visual experience not only affect the semantic representation, understanding, and processing of words with different degrees of visual relevance but may also have top-down effects on phonological-level processing of auditory words. Classifying and discussing words based on visual relevance can help us more clearly explore the complex influence mechanisms of visual experience deprivation on blind individuals' auditory word recognition and more deeply understand the relationship between sensation and cognition and the connection between matter and consciousness.

Second, during auditory word recognition, individuals match auditory input signals with orthography-phonology-semantics representations in the mental lexicon to recognize and understand target words. Auditory word recognition includes pre-lexical phonological processing and lexical-level semantic processing, with both bottom-up and top-down processing occurring simultaneously. Research on blind individuals' auditory word processing characteristics can conduct comprehensive and systematic studies from multiple levels such as phonemes, words, and semantic categories, as well as interaction mechanisms between different levels.

Specifically, at the phoneme level, on the one hand, blind individuals' more optimized phoneme perception abilities may be related to more basic speech perception abilities, such as speech category perception abilities. Future research can further explore the more basic processing mechanisms underlying blind individuals' phoneme perception advantages. On the other hand, blind individuals' good phoneme perception abilities may also have bottom-up effects on word-level phonological processing and semantic extraction, which awaits further in-depth research. At the lexical level, although researchers consistently find that blind participants judge auditory words faster than sighted participants, explanations for this phenomenon are controversial (Röder et al., 2003; Schild & Friedrich, 2018). Speech information includes both basic to complex phonological information such as duration, amplitude, pitch, phonemes, phonological units, syllables, and intonation, as well as various semantic-grammatical information such as word meaning, word frequency, word form, syntax, and linguistic context. These phonological and semantic cues in speech may all have certain influence on blind individuals' auditory word recognition, and the importance of these cues in auditory word recognition may also differ. These questions await further research. At the semantic category level, previous research has mostly used qualitative analysis or behavioral research paradigms to explore differences in semantic representation dimensions of visually-related words between blind and sighted individuals, with less exploration of differences in semantic processing and understanding degree. Future research can comprehensively use multiple research methods such as interviews, questionnaires, behavioral tests, and cognitive neuroscience techniques to explore blind individuals' semantic representation and processing characteristics of words with different visual relevance. Additionally, Frith (1998) proposed that individuals' reading and writing experiences affect their spoken language processing. Existing research has also confirmed that individuals' reading experience has top-down modulating effects on auditory word processing (Chéreau, Gaskell, & Dumay, 2007; Miller & Swick, 2003; Chen et al., 2016; Qu & Damian, 2017; Zou et al., 2012). Sighted individuals use a visually-dominated writing system for reading, while blind individuals use the touch-dominated Braille system for reading. Different reading experiences between blind and sighted individuals may lead to the formation of different lexical orthographic representations in their mental lexicons, thereby having different effects on their auditory word processing. For example, blind individuals may have automatic activation of Braille orthographic information during auditory word recognition. It is hoped that through comprehensive and in-depth research on blind individuals' auditory word recognition, processing models that reflect the characteristics of blind individuals' auditory word recognition can be proposed.

Third, the neurophysiological mechanisms of blind individuals' auditory word recognition need further expansion. For example, the functions and roles of blind individuals' left fronto-temporal language functional areas, occipital visual cortex, and VWFA in auditory word processing; similarities and differences in lateralization advantages of phoneme processing between blind and sighted individuals in tonal language contexts; differences between blind and sighted individuals' brain representation and processing of words with different visual relevance; and characteristics of brain processing pathways and networks for the entire process of lexical recognition from speech input to semantic understanding in blind individuals.

Finally, various cognitive abilities in adults are relatively stable, while children are in rapid growth and development stages, more influenced by the environment and with stronger plasticity. The influence of visual experience deprivation on blind individuals' auditory word recognition may show greater variability and higher complexity in child populations. For example, blind individuals' speech processing advantages may not be present from the beginning but may undergo a transformation process from disadvantage to compensatory advantage during childhood. Blind children lacking visual experience and with relatively weaker cognitive abilities may show more difficulties in word understanding and learning. Researchers can conduct more in-depth studies on blind children' s language acquisition and development. On the one hand, this can deepen our understanding of the relationship between sensory experience and language cognition at different developmental stages; on the other hand, it can also provide strong theoretical support for blind children' s language teaching.

It is hoped that more researchers will explore this field in the future, enabling humans to more deeply understand the influence of environment on individuals and its mechanisms. At the same time, it will also increase society' s understanding of special groups and provide them with more convenient learning, work, and living environments, contributing scientific strength to achieving common development for all society and all humanity.

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Note: Figure translations are in progress. See original paper for figures.