Language processing in the occipital cortex of congenitally blind adults

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Humans are thought to have evolved brain regions in the left frontal and temporal cortex that are uniquely capable of language processing. However, congenitally blind individuals also activate the visual cortex in some verbal tasks. We provide evidence that this visual cortex activity in fact reflects language processing. We find that in congenitally blind individuals, the left visual cortex behaves similarly to classic language regions: (*i*) BOLD signal is higher during sentence comprehension than during linguistically degraded control conditions that are more difficult; (*ii*) BOLD signal is modulated by phonological information, lexical semantic information, and sentence-level combinatorial structure; and (*iii*) functional connectivity with language regions in the left prefrontal cortex and thalamus are increased relative to sighted individuals. We conclude that brain regions that are thought to have evolved for vision can take on language processing as a result of early experience. Innate microcircuit properties are not necessary for a brain region to become involved in language processing.

plasticity | language evolution

The capacity for language is a universal and uniquely human trait. Children acquire language across large variations in cultures and environments (1). Even without access to language, children create communication systems that share key features with natural languages. For example, deaf children raised without access to sign language develop home sign (2, 3). Conversely, blind children acquire normal language abilities, even though they have less perceptual access to the things people talk about than sighted children (4). Thus, the capacity to acquire language is consistent in the face of dramatic changes in the environment.

The neural substrates of language are also highly consistent across individuals and languages. During language processing, speakers of English, Mandarin, and sign languages activate a left-lateralized network of brain regions in the prefrontal, lateral temporal, and temporoparietal cortices (5, 6). Damage to these brain regions in adulthood leads to profound language deficits (7, 8).

The consistency in the neural substrates of language, along with the universal propensity of humans to acquire language, suggests that humans may have evolved a specific set of brain regions uniquely capable of language processing (for arguments for and against this proposal, see refs. 9–16).

However, there is one case where other brain regions can support language. Young children who suffer severe brain damage to the left-hemisphere language regions develop language abilities within the normal range (17, 18). Plasticity in this example is in some sense limited, because language processing appears to be supported by the right-hemisphere homologs of the left-hemisphere language regions (19). These right-hemisphere regions may be capable of supporting language because they are similar, in neural architecture, to the left-hemisphere regions that evolved for language (20).

A more challenging example of language-relevant plasticity may occur as a result of early blindness. In addition to classic language regions, individuals who have been blind from birth activate visual cortices during verbal tasks, such as Braille reading and verb generation (21–24). This occipital activity occurs in secondary and early visual areas, including the pericalcarine cortex (the anatomical location of the primary visual cortex V1) (25, 26). Disruption of occipital regions in congenitally blind individuals, by transcranial magnetic stimulation (TMS) or lesions, impairs Braille reading and verb generation (27–30). Furthermore, congenitally blind individuals with more visual cortex activity may have better verbal long-term memory (26). It is therefore possible that occipital brain regions that did not evolve for language can participate in language processing as a result of changes in early experience.

Still, it is not yet known whether the visual cortex really contributes to language processing in blind individuals. Occipital brain regions might instead contribute to sensory processing of verbal stimuli, e.g., responding to phonological properties of speech (31) or tactile properties of Braille (21, 29). Alternatively, because most previous studies have compared complex language tasks to simpler control tasks, the occipital cortex may support domain-general aspects of task performance: working memory, executive functions, or long-term verbal memory, rather than language processing per se (26, 32). The first goal of the present study was therefore to determine whether occipital cortices respond to language, once memory and other task-related demands are controlled.

A further unanswered question is whether occipital areas in blind individuals are sensitive to the same kinds of linguistic information as classic language regions. Do occipital areas respond to anything that sounds like speech, or, like classic language regions, respond more to rich linguistic stimuli (e.g., sentences) than degraded but speech-like stimuli (e.g., lists of nonwords)? The more similar the occipital response is to that of the classic language regions, the more likely this response reflects similar cognitive processes. We therefore asked whether occipital areas respond to phonological information (i.e., speech perception), lexical information (i.e., understanding individual words and morphemes), and sentence-level combinatorial information (i.e., combining words into phrases and sentences—syntax, and constructing complex meanings out of smaller meaning units)?

Of particular interest is whether the occipital cortex in congenitally blind individuals is sensitive to sentence-level combinatorial structure. A key feature of human language is that elementary linguistic units (words and morphemes) combine into higher-level structures, such as phrases and sentences. It has been suggested that language regions, such as Broca's area, have evolved to be uniquely suited for such combinatorial processing (12, 33, 34). Finding that occipital areas in early blind individuals are capable of combinatorial language processing would suggest that such processing does not require intrinsic biological prop-

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erties of classic language regions. However, almost all prior studies of language in congenitally blind individuals have used single words. Suggestive evidence comes from one study that found an increase in occipital activity with increased grammatical complexity (35), but in that study the grammatically complex condition was also more difficult and led to greater activity in all examined brain regions and all groups. We therefore sought to establish whether the occipital areas of congenitally blind individuals are specifically sensitive to combinatorial linguistic processing.

In two experiments, we compared occipital activity during sentence comprehension to various linguistically degraded control conditions, in sighted and congenitally blind adults. Both experiments pitted task difficulty against linguistic richness. In experiment 1, participants performed a sentence comprehension task and a difficult auditory perceptual task. In experiment 2, participants performed a working memory task on sentences and four control conditions: word lists, jabberwocky sentences (sentences with grammatical structure, but with all of the content words, such as nouns, verbs, and adjectives, replaced with nonsense words, such as *florp*), lists of nonwords, and backward speech (for similar design, see ref. 36). All of the control conditions were less linguistically rich than sentences, but posed higher domain-general working-memory demands (Fig. S1).

We reasoned that if occipital regions in the blind are truly involved in language processing, the response in these regions should (*i*) be higher for linguistic than nonlinguistic stimuli (e.g., backward speech) even when the nonlinguistic stimuli are more difficult; (*ii*) distinguish among conditions that differ in linguistic complexity (e.g., jabberwocky vs. nonword lists); and (*iii*) show response profiles, across conditions, similar to the response of classic language regions.

To foreshadow the key results, both experiments provide evidence that regions of the left occipital cortex in congenitally blind adults are involved in high-level language processing. Therefore, to investigate how language information might reach neural circuits that evolved for visual perception, we measured resting-state correlations between occipital brain regions and the rest of the brain, in blind and sighted individuals.

Results

Behavioral Results. In both experiments the most linguistically rich condition (i.e., sentences) was also the easiest. In experiment 1, participants were more accurate on stories (82%, SD = 17%) than backward speech [54%, SD = 12%, t(35) = 7.6, P < 0.001]. Response time (RT) was not different across conditions [story 4.2 s, SD = 0.3; backward speech 4.3 s, SD = 0.4, t(35) < 2, P > 0.1].

In experiment 2, participants were most accurate in the sentence condition (82%, SD = 12%), followed by the jabberwocky (J), word list (W), and backward speech (B) conditions (J mean 80%, SD = 12%; W mean 80%, SD = 11%, B mean 76%, SD = 9%) and least accurate in the nonword list (NW) condition [NW 72%, SD = 11%; F(4, 100) = 30.84, P < 0.0001]. Both groups were fastest to respond to the sentences (S) and jabberwocky conditions (S = 1,460 ms, SD = 255; J = 1,423 ms, SD = 268) and slower for the word list, nonword list, and backward speech conditions [W = 1,580 ms, SD = 278, N = 1,615 ms, SD = 265, B = 1,629 ms, SD = 320; F(4, 100) = 17.10, P < 0.0001]. The effects of group and group × condition interactions were not reliable in either experiment (P > 0.1).

fMRI Results. In both experiments, we observed a larger difference between sentences and backward speech in the left pericalcarine cortex of congenitally blind individuals than sighted individuals [pericalcarine ROI: group × condition interaction experiment 1 F(1, 21) = 9.86, P = 0.005, experiment 2 F(4, 78) = 5.27, P = 0.001; Fig. 1]. Whole-brain analyses revealed that this group × condition interaction was present in the left pericalcarine cortex

[Brodmann's Area (BA)17/18/19] as well as the other left (and to a lesser extent right) occipital areas, including the left lateral middle occipital gyrus BA18/19 and the left occipital pole (Fig. S2 and Table S1; see *SI Results* for within-group analyses). Thus, in two experiments, the left occipital cortex responded more to sentences than to a harder perceptual task. This language response was distinct, neuroanatomically, from a response to sound: unlike sentences, nonlanguage sounds (backward speech > rest) produced bilateral activity in a different subset of the occipital cortex (Fig. S3).

We then asked whether the occipital cortex is sensitive to the same kinds of linguistic information as classic language regions. To establish a reference for a language-sensitive response profile, we first examined the response of classic language regions of sighted adults. Four representative classic language ROIs were defined in sighted individuals based on the sentences/backward speech contrast: left inferior frontal gyrus [LIFG (−49 28 0), n = 16], left middle frontal gyrus [LMFG (−47 16 35), n = 14], left middle temporal gyrus [LMTG (−58 −40 −2), n = 15], and left angular gyrus [LAng (−48 −60 26), n = 14] (for analysis of language ROIs in blind adults, see *SI Results*). These regions were chosen as representative language ROIs because they are among the most well-studied language regions and most reliably associated with language processing across neuroimaging and neuropsychological studies (37, 38). Half the data were used to define ROIs and the other half to test for effects of condition (*Materials and Methods*). Across these classic language regions, we observed a main effect of combinatorial sentence structure [S + J > W + N, F(1, 199) = 24.59, P < 0.0001], a main effect of lexical information [S + W > J + N, F(1, 199) = 23.88, P < 0.0001], and a structure × lexical information interaction [F(1, 199) = 4.00, P < 0.05]. This profile was the same across all four regions (ROI × condition interaction, P > 0.3). Phonological information alone did not affect activity in these language regions [2 × 4 ANOVA: nonword lists > backward speech F(1, 83) = 0.41, P = 0.52] (Fig. 2). Blind adults and sighted adults showed a similar profile of activation in classic language regions we examined, including the LIFG, LMFG, LMTG, and LAng (*SI Results*, Figs. S4 and S5, and Table S2). A similar response profile was observed whether we used individual-subject ROIs or extracted from group ROIs based on the sentence/backward speech contrast from experiment 1 (*SI Results* and Fig. S5).

We then tested whether occipital regions in congenitally blind individuals showed a similar response profile to that of the classic language regions. In congenitally blind adults, three functional ROIs that responded more to sentences than backward speech were defined in the left occipital cortices: (*i*) a medial occipital region (LMO) near the calcarine suclus (−6 −83 −1; n = 7), a left posterior occipital (LPO) ROI near the occipital pole (−12 −96 12; n = 8), and a lateral occipital area (LLO) (−36 −90 −1; n = 8) on the border of lateral BA18/19. All of these regions
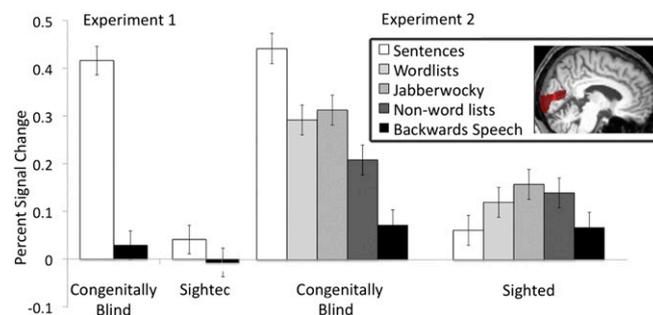

Fig. 1. Percent signal change in the left pericalcarine cortex for experiments 1 and 2.
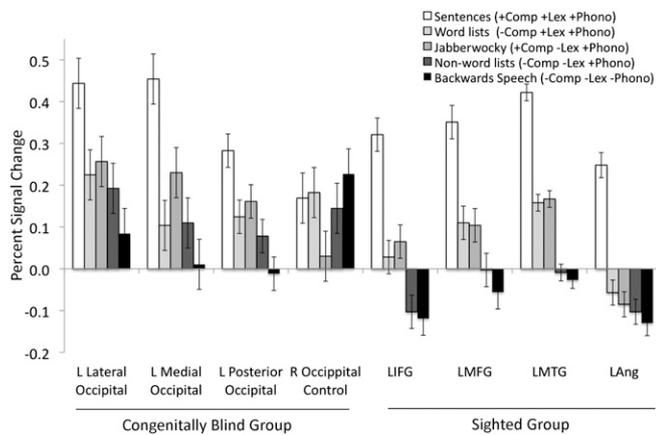
Fig. 2. Percent signal change in the left occipital ROIs of the congenitally blind group and classic language regions of the sighted group.

Fig. 3. Greater activity for +combinatorial stimuli in red (sentences + jabberwocky > word lists + nonword lists), greater activity for +lexical stimuli in blue (sentences + word lists > jabberwocky + nonword lists). Effects are displayed by group, thresholded at $P < 0.05$, corrected. For a list of brain regions, see Table S3.

responded similarly to classic language regions of sighted individuals, showing a main effect of combinatorial structure [$F(1, 74) = 18.66$, $P < 0.0001$], a main effect of lexical semantic information [$F(1, 74) = 6.90$, $P = 0.01$], and a marginal combinatorial structure × lexical information interaction [$F(1, 74) = 3.84$, $P = 0.05$]. We also observed a small but reliable effect of phonology: more activity for pronounceable nonwords than for backward speech [$F(1, 32) = 4.48$, $P = 0.04$; Fig. 2]. The anatomically defined pericalcarine cortex was also sensitive to combinatorial structure and lexical semantic information (*SI Results*).

Whole-brain analyses confirmed sensitivity to combinatorial sentence structure and lexical information in the left-lateralized pericalcarine and extracalcarine occipital areas of congenitally blind participants (Fig. 3 and Table S3).

This language-sensitive response was present only in a left-lateralized subset of the occipital cortex: a control right occipital ROI that responded to sound did not respond differentially to linguistic stimuli [$F(4, 32) = 1.16$, $P = 0.34$] (*Materials and Methods*).

Altered Functional Connectivity in Language-Sensitive Occipital Regions. We next used resting-state functional connectivity analyses to explore how linguistic information might reach occipital cortices in congenitally blind adults. We found that in congenitally blind individuals, the language-sensitive left medial and lateral occipital areas had reduced resting-state correlations with the right retinotopic and secondary visual areas, as well as the auditory cortex and other sensory motor cortices (Fig. 4 and Table S4).

Crucially, correlations were increased between the left lateral occipital ROI and the inferior frontal sulcus, inferior frontal gyrus, and middle frontal gyrus (BA46/45, BA8). Both the left medial and the left lateral occipital ROIs also had increased connectivity with the left thalamus: ventral lateral and medial dorsal nuclei. These thalamic nuclei are anatomically connected with the prefrontal cortex and have been implicated in higher cognitive
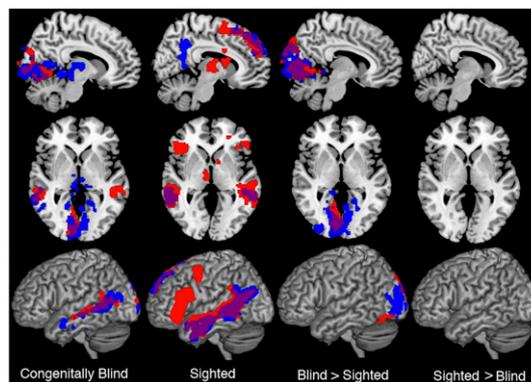
functions, including language (39, 40). These frontal and thalamic regions also responded to language in our sighted participants (sentences > backward speech, both experiments 1 and 2).

Discussion

We find that in congenitally blind adults, the left occipital cortex is active during sentence comprehension, even when the control tasks are more difficult and memory-intensive. Similar to classic language regions, the occipital cortex is sensitive to combinatorial structure (sentence-level syntax/compositional semantics), lexical semantic information, and in some regions to phonological information. Changes in the response profile of the occipital cortex were accompanied by increased resting-state correlations with the prefrontal and thalamic regions that are involved in language processing (for discussion of the thalamic nuclei involved in language, see ref. 40). Together, these data suggest that the left occipital cortices of congenitally blind individuals participate in language processing.

Possible Contributions of Occipital Cortex to Verbal Tasks. Based on the present findings, we conclude that the left-lateralized occipital activity during verbal tasks reflects language processing (25, 35, 41). However, prior studies have shown that regions of the occipital cortex in blind individuals also contribute to multiple nonverbal tasks, such as tactile discrimination and sound localization (42, 43). We hypothesize that distinct occipital regions support linguistic and nonlinguistic functions. The response to language is strongly left lateralized. By contrast, responses during nonverbal tasks are bilateral or right lateralized (44, 45). Consistent with this idea, we found neuroanatomically distinct patterns of response to backward speech and language in the occipital cortex. We therefore suggest that a left-lateralized subset of the occipital cortex is involved in language.
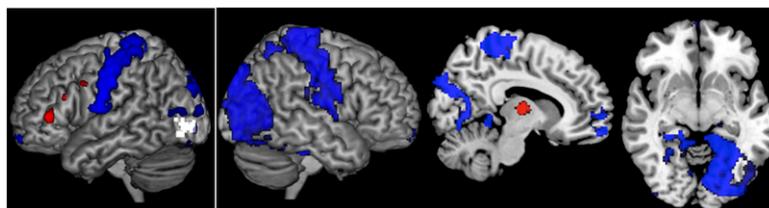

Fig. 4. Changes in resting-state correlations from the lateral occipital region (LLO) in the congenitally blind relative to the sighted group. Blue represents decreased correlations, and red represents increased correlations. The LLO seed region is shown in white. For a list of brain regions, see Table S4.

An alternative but related account suggests that the left occipital cortex of blind adults is involved in long-term verbal memory consolidation, perhaps similar to the function of the hippocampus (26, 32). In light of the present data, we consider this possibility unlikely. Unlike the left occipital regions and classic language regions, the medial temporal lobe was not sensitive to linguistic information in our study (*SI Results*). Instead, the left occipital areas may improve verbal memory by supporting encoding and retrieval of linguistic information, similar to the contribution of the prefrontal cortex (46).

Several pieces of evidence suggest that, in blind people, the left occipital regions may serve a similar function to the left prefrontal cortex (LPFC) within language. In the present study, we observed similar functional profiles and increased functional connectivity between the left occipital regions and LPFC regions. Prior work has also shown that TMS to the LPFC and TMS to left occipital areas cause similar impairments during verb generation (in sighted and early blind groups, respectively) (28). Therefore, like the LPFC, occipital areas may support selection and manipulation of linguistic representations in working memory (47, 48). Alternatively, the left occipital cortex might combine linguistic units into structured wholes (49) or support recursive structure building during sentence processing (12, 33, 50). Furthermore, just as there are distinct functions with the prefrontal cortex, so there may be distinct parts of the occipital cortex that support different high-level cognitive or linguistic functions. A crucial outstanding question for future research is how this altered neural distribution of language affects linguistic behavior. An interesting possibility is that additional neural circuitry devoted to language leads to improvements in some aspects of language processing (26).

General Implications for Cross-Modal Plasticity. We find that typical functions of classic language regions, possibly including those of the LPFC, can be subserved by the occipital cortex. Our findings speak to the striking range of cognitive functions that a brain region can support in humans. Occipital cortices support basic vision in sighted adults and contribute to language in congenitally blind individuals. Such a transfer of function is even more dramatic than a change from spatial discrimination in vision to spatial discrimination in touch and sound (42, 51, 52), because the transfer is cross-domain as well as cross-modal, and the novel function is highly abstract.

Many outstanding questions remain regarding the mechanisms of plasticity in the occipital cortex. Cross-modal plasticity has often been assumed to arise through strengthening of existing bottom-up sensory connections from sensory brain regions (e.g., connections from the auditory thalamus or the primary auditory cortex to the occipital cortex). Evidence for this kind of plasticity comes from animal studies of surgical rewiring. In ferrets, cross-modal innervation from the retina to the auditory pathway reorganizes the auditory cortex and renders it capable of supporting visual behavior (51, 52). Thus, sensory thalamic input during development can reorganize cortical function. However, whether there are naturally occurring auditory-thalamic or primary auditory-cortex projections to the visual cortex in humans is not known. In nonhuman primates, there are very few projections from early auditory to early visual cortices, and cross-modal bottom-up input from thalamic relays has not been shown (53, 54). Even if such bottom-up connections exist in humans, they may be insufficient to alter the function of the occipital cortex in the manner observed in rewiring studies with animals. Unlike congenital blindness, surgical rewiring massively changes the modality of input to the cortex at a very early stage of development (much earlier than human birth).

An alternative possibility is that plasticity in blind adults is driven by top-down feedback from higher-order polymodal and amodal cortices. The resting-state correlations in our data suggest that language information may reach the occipital cortex in part via nonsensory top-down feedback from the frontal lobe. We found higher resting-state correlations between the left occipital areas of blind adults and language regions in the frontal lobe and thalamus, but not with primary auditory regions or the auditory thalamic nucleus. An interesting possibility is that in blind humans, auditory and tactile sensory information may reach the occipital cortices through top-down feedback as well (55).

Language Processing in Occipital Cortex: Implications for Language Evolution. The current findings are most striking because multiple theories within evolutionary biology and psychology assume that humans have evolved specific brain regions uniquely capable of language (11, 33, 56). Occipital regions clearly did not evolve for language, and the microcircuitry of early visual areas in sighted adults is different from those of other cortical regions (57). Nevertheless, we find that in blind adults, these occipital regions participate in high-level linguistic functions, including sentence-level combinatorial processing. Two interpretations of these results are possible. One possibility is that, with altered experience, the occipital cortex can acquire the distinctive structural features necessary for language processing, over the course of a lifetime. If so, the structure of the left occipital regions of blind individuals should resemble, in critical respects, the structure of classic language regions (52). Alternatively, there may be no intrinsic structural features of a cortical region that are necessary for language; if so, any cortical region could process language, given the right inputs. These inputs themselves are determined by the long-range connectivity of a brain region, and by experience (e.g., the absence of vision and the presence of language input).

Our findings do not rule out the possibility that some language-relevant computations require specialized microcircuit properties that cannot be induced by experience. First, the left prefrontal and lateral temporal language regions of blind individuals were similar to those of sighted individuals. Therefore, large-scale changes to sensory experience do not appear to dramatically alter the function of these classic language areas. Second, our experiment identifies the presence of language processing in the occipital cortex, but does not show that every language-relevant computation can be carried out by the occipital cortex, or that these computations are performed in the same way by the occipital cortex as by classic language regions. For example, the capacity for building grammatical recursive structures has been put forward as a uniquely human adaptation for language (10) and may require the distinctive structural properties of Broca's area (12). Our experiments did not isolate recursive structure building from other computations involved in combinatorial syntax. In future work, it will be crucial to isolate distinct language-relevant computations, and to test which of these computations occipital areas can support.

Conclusions. In summary, we report a language-sensitive response profile in the occipital cortices of congenitally blind individuals. The occipital cortex was sensitive to combinatorial structure, lexical semantics, and, to a lesser extent, phonology. The response of occipital regions across conditions was similar to the response of classic language regions. Language sensitivity was restricted to a subset of the left occipital cortex. Some left occipital regions that responded to language also had increased functional connectivity with LPFC and thalamic regions typically involved in language processing. Based on these data, we conclude that the occipital cortices of congenitally blind individuals contribute to language. Our results therefore suggest that brain regions that did not evolve for language can nevertheless participate in language processing.

Materials and Methods

Participants. Twenty-two sighted (12 females, mean age 41 y, SD = 19), nine congenitally blind (five females, mean age 50 y, SD = 7), and one early blind individual took part in experiment 1. Seventeen sighted (eight females, mean age 45 y, SD = 13) and 11 congenitally blind adults (four females, mean age 44, SD = 13) participated in experiment 2. A 12th congenitally blind participant was not included in the analysis because he was unable to perform the experimental task.

All blind participants were blind since birth, except one individual in experiment 1, who lost vision before age 3 y. This participant's data were not different from that of the other blind individuals. All blind participants reported having, at most, faint light perception and had lost their vision due to pathology in or anterior to the optic chiasm. None of the participants had any known neurological disorders or had ever sustained head injury. Blind participants were matched to sighted individuals on age, and in experiment 2, also on level of education (Table S5). The study was approved by the institutional review board, and all participants gave written informed consent.

Procedure. In experiment 1, participants heard brief verbal passages (12 s) and answered true-or-false questions about them (6 s). In the control condition, participants heard segments of backward speech sounds and performed an auditory match to sample task. Blocks were separated by 12 s of rest.

Experiment 2 consisted of five conditions: sentences, word lists, jabberwocky, nonword lists, and backward speech. On each trial, participants heard a sentence, list of words, jabberwocky sentence, list of nonwords, or a backward speech segment (each exactly 7 s long, followed by 0.25 s of silence), followed by a tone (0.25 s) and a memory probe (word/nonword/fragment of backward speech). Participants were asked to decide (within 2.5 s) whether the probe appeared in the stimulus they just heard (each probe was between 0.29 s and 1.14 s long; Fig. S1). The probe always matched the stimulus in type (e.g., a word after a sentence and a nonword after a jabberwocky sentence). The probe came from the preceding stimulus on half of the trials. Trials were separated by 10 s of rest.

Each item occurred in every condition across participants and in only one condition within a participant. The jabberwocky condition was created by removing content words from the sentences condition and replacing them with pronounceable nonsense words. The word list condition was created by replacing function words in the sentences condition with high-frequency, length-matched content words, and scrambling the word order. Nonword lists were created by replacing all words with length-matched pronounceable nonwords. This procedure ensured that conditions were matched in number of words/nonwords, word frequency (for the sentence and word list conditions), word/nonword length, and sentence structure (for the sentence and jabberwocky conditions, see Fig. S1 and SI Materials and Methods).

fMRI Data Acquisition and Analyses. MRI structural and functional data of the whole brain was collected on a 3 T Siemens scanner (SI Materials and Methods). Data analyses were performed using SPM2 (http://www.fil.ion.ucl.ac.uk/) and Matlab-based in-house software. Functional connectivity analyses were performed using CONN-fMRI Functional Connectivity SPM (http://web.mit.edu/swg/software.htm). Before modeling, data were realigned, smoothed with a 5-mm smoothing kernel, and normalized to a standard template in Montreal Neurological Institute (MNI) space.

In whole-brain analyses, a general linear model was used to analyze BOLD activity of each subject as a function of condition. Covariates of interest were convolved with a standard hemodynamic response function. Nuisance covariates included run effects, an intercept term, and global signal

and data high-pass filtered (one cycle/128 s). BOLD signal differences between conditions were evaluated through second-level, random-effects analysis thresholded at α < 0.05 (corrected) by performing Monte Carlo permutation tests on the data (cluster size threshold of 3) (58).

Pericalcarine ROIs were drawn around the calcarine sulcus of each congenitally blind and sighted participant. A 2 × 2 ANOVA was used to test for language-sensitive responses in pericalcarine cortex in the congenitally blind group relative to the sighted group (sentences/backward speech × blind/sighted).

Language-sensitive functional ROIs were created in individual congenitally blind and sighted participants based on sentences/backward speech contrast in odd-numbered runs, and analyses were conducted on data from even-numbered runs. A right occipital control ROI was also defined using the backwards/rest contrast.

ROIs were created at a threshold of P < 0.001, uncorrected with k = 10. If no regions were observed at this threshold, the threshold was lowered to P < 0.01. If no regions were observed at the lowered threshold, the subject was excluded from that analysis. For the classic language ROIs, there were no between-group differences in ROI size or peak t value. From each ROI, we extracted percent signal change (PSC) from the stimulus portion of the trial, accounting for the hemodynamic lag (seconds 6–12; SI Materials and Methods).

Individual-subject ROIs comprised the main analyses, as they have been found to be more sensitive than group ROIs (59). To confirm these results, we analyzed data from experiment 2 using group ROIs defined on the sentences/backward speech contrasts from experiment 1 (SI Materials and Methods).

We used ANOVAs to test for effects of sentence-level combinatorial structure (i.e., syntax/compositional semantics), lexical information, and phonological information (sentences: +combinatorial, +lexical; jabberwocky: +combinatorial, −lexical; word lists: −combinatorial, +lexical; nonword lists: −combinatorial, −lexical). A 2 × 2 × 4 ANOVA was used with the language ROIs of the sighted group, and a 2 × 2 × 3 ANOVA with the occipital ROIs of the blind group [combinatorial(±) × lexical(±) × ROI].

For resting-state functional connectivity analyses, we measured the correlations between low-frequency fluctuations in BOLD signal of three left occipital ROIs and the rest of the brain. ROIs were defined based on the group data for the sentences/backward speech contrast from experiment 2: LMO (−6 −74 −6), LLO (−42 −82 −2), and LPO (−10 −100 0). No increase or decrease in correlations was observed in the LPO ROI. Resting data were obtained from the rest blocks of a separate experiment (total 17.5 min) with 10 congenitally blind participants (SI Materials and Methods). Data were band-pass filtered (0.01–0.08), and nuisance covariates included fluctuations in BOLD signal from cerebrospinal fluid and white matter and their derivatives, as well as motion parameters (60). Connectivity analyses were FDR corrected at α < 0.05 at both the voxel and cluster levels (SI Materials and Methods).

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