Spoken language comprehension activates the primary visual cortex

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Abstract

Current accounts of neural plasticity emphasize the role of connectivity and conserved function in determining a neural tissue's functional role even after atypical early experiences. However, in apparent conflict with this view, studies of congenitally blind individuals have also suggested that language activates primary visual cortex, with no evidence of major changes in anatomical connectivity that could explain this apparent drastic functional change in what is typically a low-level visual area. To reconcile what appears to be unprecedented functional reorganization in V1 with known accounts of plasticity limitations, we tested whether primary visual cortex also responds to spoken language in sighted individuals. We found that primary visual cortex was activated by comprehensible speech as compared to a reversed speech control task, in a left-lateralized and focal manner, in sighted individuals. Importantly, left V1 activation was also significant and comparable for abstract and concrete words, precluding a visual imagery account of such activation. Together these findings suggest that primary visual cortex responds to verbal information in the typically developed brain, potentially to predict visual input. This capability might be the basis for the strong V1 language activation observed in people born blind, re-affirming the notion that plasticity is guided by pre-existing connectivity and abilities in the intact brain.

Introduction

For two decades it has been known that the visual cortex of people born blind could be activated by non-visual inputs, including sound and touch (Bedny, 2017; Bridge and Watkins, 2019; Cecchetti et al., 2016; Fine and Park, 2018; Heimler et al., 2015; Heimler et al., 2014; Ptito et al., 2012; Renier et al., 2014; Sadato et al., 1996). Most functional neuroimaging studies investigating sensory plasticity in the blind have shown that visual association cortex regions perform the same operations (e.g., recognition of objects, script, or motion direction) on input from other sensory modalities (e.g., touch, audition) as they otherwise would on visual input (Bi et al., 2016; Cecchetti et al., 2016; Heimler et al., 2015; Peelen and Downing, 2017; Renier et al., 2014; Ricciardi et al., 2014). These non-visual capacities of the blind are thought to be supported by the typical multisensory connectivity found also in sighted people (Heimler et al., 2015).

However, unlike association regions, the primary visual cortex of people born blind has also been shown to respond to tasks quite remote from visual processing, such as language comprehension and production (Abboud et al., 2019; Bedny et al., 2011a; Burton et al., 2003; Burton et al., 2002b; Dietrich et al., 2013; Lane et al., 2015; Röder et al., 2002). Although evidence for language activation is compelling, persuasive evidence for a mechanism by which such extreme functional reorganization might occur has not been provided to date: for example, beyond deterioration of the visual pathways (Noppeney et al., 2005; Shimony et al., 2006; Shu et al., 2009; Yu et al., 2007), no drastic differences in anatomical connectivity of the visual cortex were found between congenitally blind people and sighted controls. Importantly, most recent research suggests that brain organization is strongly determined by innate constraints on anatomical connectivity (Hannagan et al., 2015;

Heimler et al., 2015; Mahon and Caramazza, 2011; Saygin et al., 2016). This view implies that functional reorganization needs to build on, and is limited by, pre-existing capacities and connections of the available tissue, even in cases of sensory deprivation since birth (Striem-Amit et al., 2018a).

How can findings of language processing in primary visual cortex in the congenitally blind be reconciled with such a view? If the hypothesis of pre-existing anatomical connectivity and its constraints is correct, then to accord with language processing in primary visual cortex in the blind, there must also be language processing in primary visual cortex in sighted people. Evidence pointing in this direction can be found in the observation of V1 activation in several neuroimaging studies of language (e.g., Bookheimer et al., 1998; Gaillard et al., 2003; Kovelman et al., 2012; Wolmetz et al., 2010). However, these activations could potentially be driven by visual stimulation or imagery evoked by the language stimuli, and they are not discussed in depth in these studies.

To test directly whether language processing engages the primary visual cortex in sighted people, we investigated neural activation in a robust auditory sentence comprehension task, as compared with a low-level control (backward speech, not comprehensible), in 20 neurologically healthy sighted young adults. We also examined and controlled for visual imagery by testing responses in an independent second cohort to auditorily presented abstract words, which are hard to visualize. If language indeed activates primary visual cortex during sentence processing in a typically-developed cohort, such activation may be the basis for the more extreme, previously unaccounted for, plasticity in blindness. This finding would re-affirm the role of pre-existing connectivity and abilities in the intact brain in underlying brain plasticity. Alternatively, the absence of such activation would emphasize the inordinate nature of neural reorganization in blindness.

Results

To determine whether spoken sentence comprehension activates the visual cortex in the typically developed brain, we compared BOLD activation during blocks of forward versus reverse speech in 20 neurologically healthy sighted young adults (Experiment 1). Playing spoken sentences in reverse renders them incomprehensible while controlling for low-level auditory stimulation, which makes this contrast widely used for studying sentence comprehension (e.g., Ahmad et al., 2003; Gaillard et al., 2007a; Moore-Parks et al., 2010; Peña et al., 2003; Perani et al., 1996). Participants fixated at screen center throughout the experiment to control for visual stimulation.

In contrasting forward and reverse speech, a typical left-lateralized fronto-temporal network emerged (**Fig. 1A**), as identified by numerous neuroimaging studies (for reviews, see Price, 2012; Vigneau et al., 2006); the primary auditory cortex is not significantly activated by this contrast as the conditions are matched in low-level auditory information (see similarly Seydell-Greenwald et al., 2020). Importantly, the primary visual cortex was significantly more strongly activated by forward than by reverse speech (**Fig. 1A**). This preference was confirmed by extracting percent signal change from a retinotopically-defined ROI comprising left primary visual cortex (paired t-test, $t(19)=4.02$, $p=0.0004$, one-tailed, significant in testing against a Bonferroni-adjusted alpha level of 0.05/5 statistical comparisons for Experiment 1 dataset=0.01; **Fig. 1B**; see activation time-course in **Fig. S1A**). Importantly, the forward > reverse speech preference observed in V1 is left lateralized (**Fig. 1A**), suggesting that language processing in V1 matches the laterality of the rest of the language network. When sampling retinotopically-defined V1 as a whole, left V1 comprehension was indeed stronger than that in right V1, although the difference did not reach statistical significance after multiple comparison correction (**Fig. 1C;** paired t-test, $t(19)=1.98$, $p=0.031$ uncorrected). Moreover, activation seemed to be restrictedly localized to the primary visual cortex in the whole-brain activation map (**Fig. 1A**). Indeed, an ROI in retinotopically defined V2 showed

somewhat decreased language selectivity as compared to V1 (paired t-test, t(19)=2.05, p=0.027, uncorrected, does not exceed the threshold for multiple comparisons correction), suggesting that early visual cortex selectivity for language is at least mildly stronger in primary than secondary visual cortex. To test whether the observed V1 activations might reflect increased attention to the comprehensible speech stimuli, we also extracted signal change data from a superior parietal ROI in the dorsal attention network (Spreng et al., 2013). No significant signal differences were observed in this parietal ROI between forward and reverse speech blocks (t(19)= -0.787, p=0.44 uncorrected), making top-down attention effects an unlikely explanation for the V1 language activations.

Could these findings stem from visual imagery, due to the concrete content of the spoken sentences? Although visual imagery is unlikely to explain left-lateralized, focal activation in early visual cortex, we additionally investigated if V1 would show differential activation for abstract (less imaginable) and concrete (easily imaginable) spoken words. Just as for spoken sentence comprehension (Experiment 1 above), activation for blocks of abstract words in a separate group of sighted adults (Experiment 2; see also Striem-Amit et al., 2018b) included, in addition to vast activation of the temporal lobe and inferior frontal cortex, also significant localized activation in the calcarine sulcus, predominantly in the left hemisphere (**Fig. 2A**). Again, no significant activation was observed in the dorsal

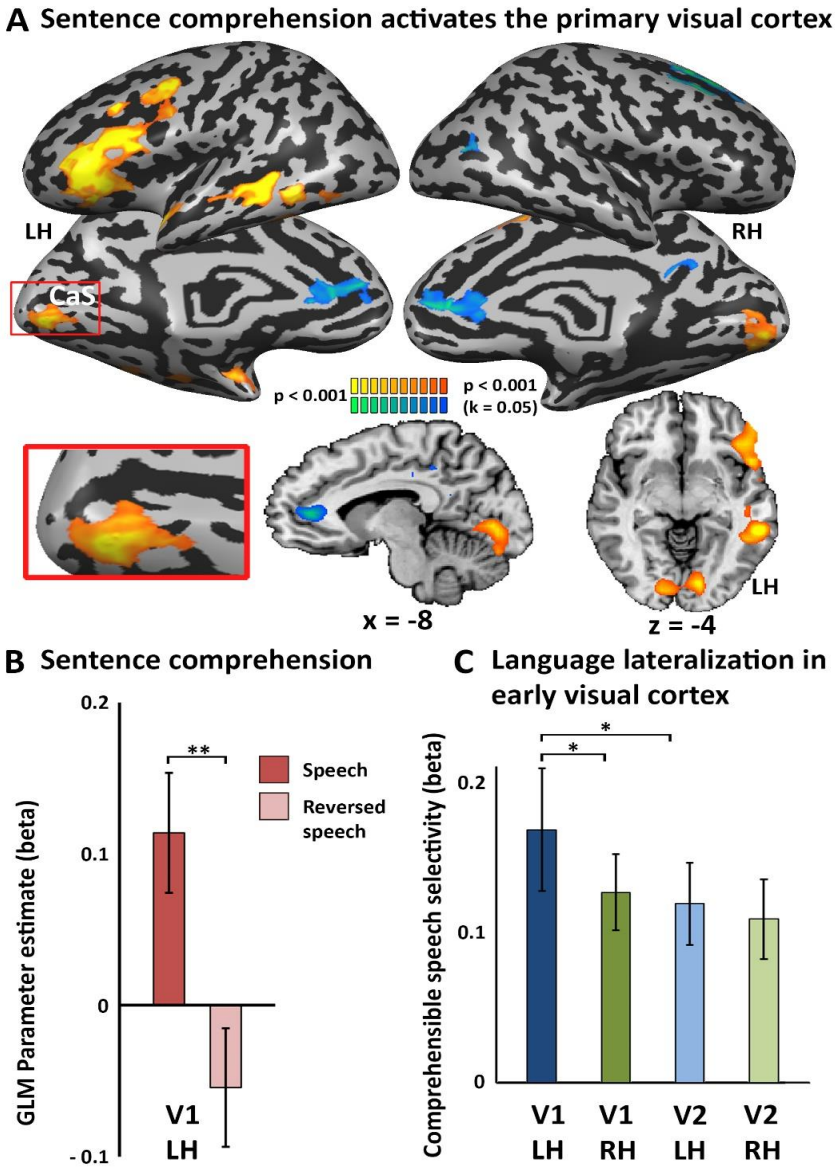

Figure 1: Left primary visual cortex is engaged in spoken language comprehension

A. A contrast of comprehensible vs. reversed spoken sentences is shown on brain slices and inflated cortical hemispheres. In addition to the left-lateralized fronto-parieto-temporal language network, significant activation is found in the primary visual cortex. CaS – Calcarine Sulcus.

B. GLM parameter estimates (betas) were sampled in the left retinotopically-defined primary visual cortex, showing significant selectivity for comprehensible vs. reversed speech. Error bars denote standard error of the mean, **p<0.005 uncorrected, significant with multiple comparisons correction at p<0.05.

C. Selectivity for comprehensible speech (the beta difference between forward and reversed speech) is higher in the left V1 than in right V1, showing lateralization for language, and compared with V2. Error bars denote standard error of the mean, *p<0.05 uncorrected.

attention network ROI (Spreng et al., 2013; t(13)= -1.065, p= 0.31), and activation for abstract words observed in left V1 was stronger than that in right V1 (**Fig. 2C**; paired t-test, t(13)=2.77, p=0.016 uncorrected, significant in testing against a Bonferroni-adjusted alpha level of 0.05/3 for Experiment 2 dataset=0.017; see also activation time-course in **Fig. S1C**). Importantly, activation in the retinotopically defined left V1 did not differ between abstract words and concrete words (object names; **Fig. 2B**; t(13)=0.48, p=0.65 uncorrected), even though the latter were significantly more imaginable according to behavioral ratings (t(9)=1074, p<0.001 uncorrected, significant with correction for multiple comparisons). In addition, an experiment where words of concrete and abstract concepts were presented in an event-related design (Experiment 3) allowed us to test whether LH V1 activation correlated with imaginability of and attentional arousal evoked by the spoken words of a variety of imaginable and abstract concept types (Striem-Amit et al., 2018b). No correlation was found between left V1 activation and imaginability ratings ($r^2(54)=0.003$, p=0.69 uncorrected) or arousal ratings of these words ($r^2(54)=0.01$, p=0.45, uncorrected). Together, these findings suggest that semantic content activation of left V1 does not result from imagery or attention confounds, but rather reflects responses to language comprehension.

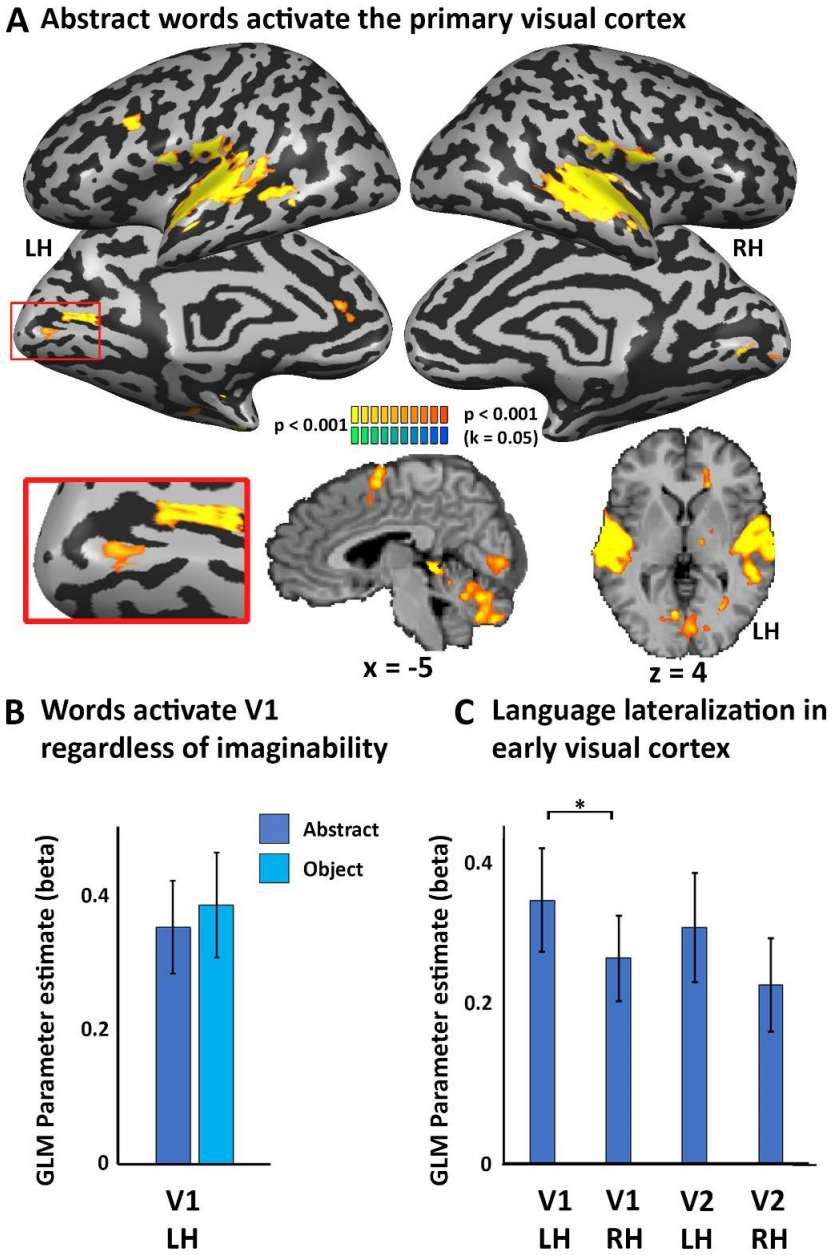

Figure 2: Left primary visual cortex spoken language activation is found for abstract, unimaginable words

A. Activation for spoken abstract words is shown on brain slices and inflated cortical hemispheres. In addition to the auditory cortex and inferior frontal cortex, significant activation is found in the primary visual cortex, despite the inability to visually imagine abstract concepts. CaS – Calcarine Sulcus.

B. GLM parameter estimates (betas) were sampled in the left retinotopically-defined primary visual cortex, showing significant activation for spoken words, which does not differ between abstract and concrete words.

C. Activation for abstract words is significantly higher in the left V1 than in right V1, showing lateralization for language. Error bars denote standard error of the mean, *p<0.01 uncorrected, significant with multiple comparisons correction at p<0.05.

Discussion

The primary visual cortex is widely thought to be a low-level sensory station devoted to the processing of simple visual features (Grill-Spector and Malach, 2004; Hubel and Wiesel, 1962, 1968; Wandell et al., 2007a). However, although still controversial, some recent evidence indicates that it may also receive signals related to higher level non-visual representations, specifically non-visual imagery (Vetter et al., 2014) and working memory (Lawrence et al., 2018). Such atypical activations resemble those observed in the primary visual cortex of people born blind for high-level cognitive functions (Abboud and Cohen, 2019; Abboud et al., 2019; Amedi et al., 2004; Amedi et al., 2003; Bedny, 2017; Bedny et al., 2011a; Burton, 2003; Burton et al., 2003; Burton et al., 2002b; Dietrich et al., 2013; Hamilton et al., 2000; Hull and Mason, 1995; Lane et al., 2015; Ofan and Zohary, 2006; Raz et al., 2005; Röder et al., 2000; Röder et al., 2002; Sadato et al., 1998; Sadato et al., 1996; Vetter et al., 2020) and may provide a possible precursor for such reorganization in the typically developed brain. However, the blind visual cortex has also been implicated in language (Abboud and Cohen, 2019; Abboud et al., 2019; Amedi et al., 2004; Bedny, 2017; Burton, 2003; Ofan and Zohary, 2006; Sadato et al., 1996; Vetter et al., 2020), which has not previously been proposed to meaningfully engage the primary visual cortex in sighted. Here we report activation for spoken sentences in V1 of typically developed individuals, which shows selectivity towards comprehensible speech (**Fig. 1A,B**). Moreover, this activation is left-lateralized (**Fig. 1A,C**), just like the frontotemporal activation typically associated with language tasks, and also like the V1 language activation in blindness (Bedny et al., 2011a; Burton, 2003; Burton et al., 2002b; Ofan and Zohary, 2006). It also seems to be confined to the primary visual cortex, rather than emerging by feedback cortico-cortical connectivity from visual language areas via higher retinotopic cortical stations (e.g. V2; **Fig. 1C**). Similar findings are observed for spoken abstract words in a separate sighted cohort (**Fig. 2**). Together these findings indicate that left-lateralized primary visual cortex responds to semantic information in typically developed sighted adults. These findings have importance for several key issues regarding the multisensory properties of primary visual cortex, the developmental origins of reorganization in the blind brain, and the nature of brain plasticity itself.

First we must address whether these findings could stem from more trivial confounds such as visual imagery or increased attention to speech. Early visual cortex activation during language tasks has been observed in functional neuroimaging studies contrasting speech with silence or non-speech stimuli (Binder et al., 2004; Bookheimer et al., 1998; Gaillard et al., 2003; Holle et al., 2010; Kovelman et al., 2012; Rämä et al., 2012; Wolmetz et al., 2010; Zekveld et al., 2006). However, this activation is usually either not discussed or ascribed to top-down attention effects or to visual imagery (Cate et al., 2009; Klein et al., 2000; O'Leary et al., 1997; Shaywitz et al., 2001). Similarly, meta-analyses on the neurosynth (Yarkoni et al., 2011) and neuroquery (Dockès et al., 2020) platforms reveal converging activation in left early visual cortex for studies on “language” (**Fig. S2**); some of the same confounds may apply there as well. As we will discuss next, neither attention nor imagery explanations readily apply to our findings. When attention to sounds activates V1, it serves a role in spatial attention orientation (Azevedo et al., 2015; Cate et al., 2009) and stems from direct connectivity between primary auditory cortices and primarily *peripheral* retinotopic locations of V1 (Borra and Rockland, 2011; Falchier et al., 2002; Falchier et al., 2001; Rockland and Ojima, 2003; Rockland and Van Hoesen, 1994). The activation pattern in comparing forward and reversed speech in our study, in contrast, was not peripherally localized (**Fig. 1A, Fig 2A, Fig. S1B**; ANOVA for an eccentricity effect in left V1 $F(2,143)=0.01$, $p=0.99$), nor did it engage the typical attention network (even when explicitly sampled; Spreng et al., 2013). Instead, the activation was left-lateralized and was accompanied only by activation of the typical left-lateralized language network, e.g. superior/middle temporal gyrus and inferior frontal gyrus. Further, activation in left V1 was not correlated with the arousal ratings of the heard words in Experiment 3, making attention an unlikely cause for the activation we

observed. Similarly, it does not appear to stem from visual imagery. Visual imagery may activate and its content can be decoded from the primary visual cortex (Chen et al., 1998; Cichy et al., 2012; Klein et al., 2000; Kosslyn et al., 1999; Kosslyn et al., 1995; Ragni et al., 2020; Senden et al., 2019; Slotnick et al., 2005). However, imagery responses are stronger in association rather than primary cortex (Lee et al., 2012; Reddy et al., 2010) and are typically bilateral (Cichy et al., 2012; Lee et al., 2012; O'Craven and Kanwisher, 2000). Moreover, V1 involvement has been associated mostly with explicit imagery of high-resolution detail of images (Dijkstra et al., 2019; Klein et al., 2000; Kosslyn and Thompson, 2003). In contrast, our sentence comprehension task did not require explicit imagery or attention to visual detail, and activation was left lateralized and stronger in V1 than V2 (**Fig. 1A,C**). Moreover, we observed the same localized left-lateralized V1 activation in a whole-brain analysis for abstract words (**Fig. 2A,C**), the V1 response did not differ between abstract and concrete words (**Fig. 2B**), and V1 activation was not correlated with imaginability ratings. This pattern of results all but excludes visual imagery as an explanation for the observed V1 activations.

If these V1 language activations are not due merely to attention or imagery, how does linguistic information reach V1 and what role does it play? Primary sensory cortices receive information from multiple cortical and subcortical stations. Specifically, beyond thalamic LGN and pulvinar projections, primary visual cortex receives input from auditory cortices, parietal cortex and other regions including frontal cortex in primates and other mammals (Batardiere et al., 1998; Clavagnier et al., 2004; Falchier et al., 2002; Falchier et al., 2001; Felleman and Van Essen, 1991; Hall and Lomber, 2008; Henschke et al., 2014; Majka et al., 2019; Muckli and Petro, 2013; Pennartz et al., 2019; Rockland and Van Hoesen, 1994). These feedback pathways (Muckli et al., 2015; Pennartz et al., 2019) allow for multisensory integration even in V1 (Ghazanfar and Schroeder, 2006; Murray et al., 2016; Rohe and Noppeney, 2016), along with integration of reward value information (Roth et al., 2020; Stănişor et al., 2013). Theoretically, these cross-modal and higher-level inputs to V1 play a role in predictive coding, whereby predictions of future states and inputs allows for efficient coding and adapting to the everchanging environment (Muckli and Petro, 2013; Pennartz et al., 2019). How language comprehension fits into this framework is uncertain. Language input into V1 may allow integrating contextual information that enables visual cortex to anticipate coming events (Battistoni et al., 2017; Pennartz et al., 2019; Petro et al., 2017). Alternatively, it may play a simpler role in alerting spatial or overall attention, without conveying specific content. It may even be epiphenomenal altogether; our data do not speak directly to these alternative explanations, which will need to be addressed in future work. Importantly, accounts of predictive use of speech information would have to reconcile the level of representation of incoming high-level inputs with the spatial and low-level nature of V1, such that these types of information can be integrated in a meaningful way. Regarding the pathways allowing language to reach V1, the relative confinement of the response we observed to V1 suggests that the typical visual hierarchy (V1->V2-> inferior temporal cortex or vice versa etc.) may not play a role in generating these responses. Similarly, we observed no visual thalamic activation for language selectivity, suggesting that other cortico-cortical pathways may underlie these effects.

Although their role is unclear, the activation patterns observed here suggest an involvement of primary visual cortex in language in a left-lateralized manner in sighted individuals and resemble the findings in people born blind. In people born blind, association visual cortices seem to retain their selectivity towards the same types of information typically processed through vision (e.g. script in the visual word-form area (Reich et al., 2011; Striem-Amit et al., 2012), motion processing in hMT+ (Jiang et al., 2016; Poirier et al., 2006; Ptito et al., 2009; Saenz et al., 2008), and complex visual categories in the ventral visual cortex (Amedi et al., 2007; Bola et al., 2020; He et al., 2013; Mattioni et al., 2020; Peelen et al., 2013; Peelen and Downing, 2017; Pietrini et al., 2004; Ratan Murty et al., 2020; Striem-Amit and Amedi, 2014; van den Hurk et al., 2017). These functions are thought

to arise based on existing multisensory processes in and input to these areas, allowing for minimal changes in functional properties (Crollen et al., 2019) even with a change to the dominant input modality (Bi et al., 2016; Heimler et al., 2015; Kupers and Ptito, 2013; Ricciardi et al., 2013). This retention of function in higher visual areas of people born blind contrasts sharply with the apparent dramatic change in the function of their earlier retinotopic visual cortices, including V1, which are activated by high-level cognitive tasks such as language, verbal memory and executive function (Abboud and Cohen, 2019; Amedi et al., 2003; Bedny et al., 2011a; Burton et al., 2003; Burton et al., 2002b; Dietrich et al., 2013; Hamilton et al., 2000; Hull and Mason, 1995; Lane et al., 2015; Ofan and Zohary, 2006; Röder et al., 2000; Röder et al., 2002; Sadato et al., 1998) that do not resemble the original low-level functions of these regions. The fact that stimulating primary visual cortex affects Braille reading (Cohen et al., 1997) and verb generation in the blind (Amedi et al., 2004) suggests that this activation may indeed contribute to language processing.

How does early visual cortex come to process language in the early blind? Even though years have elapsed since the discovery of these atypical activations, with additional evidence suggesting increased functional connectivity between early visual cortex and the inferior frontal lobe in the blind (Burton et al., 2014; Liu et al., 2007; Qin et al., 2014; Striem-Amit et al., 2015; Wang et al., 2013; Yu et al., 2008), a clear mechanism for such remarkable reorganization has not been uncovered. Broadly, with the exception of language-related activation in the congenitally blind visual cortex, cortical plasticity in humans seems to be constrained to relatively small-scale and topographically limited changes in function, even in extreme cases of sensory or motor deprivation from birth (e.g., Striem-Amit et al., 2018a). Differences in anatomical connectivity of the visual cortex between congenitally blind people and sighted controls appear to be limited in scope, mostly to the deterioration of the visual pathways in the blind (Noppeney et al., 2005; Shimony et al., 2006; Shu et al., 2009; Yu et al., 2007). Evidently, even in congenital blindness, functional and anatomical connectivity develop largely typically, allowing topographic connectivity for retinotopic areas (Bock et al., 2015; Bock et al., 2013; Striem-Amit et al., 2015) and domain- or category-based connectivity for association cortices (e.g., reviewed in Heimler et al., 2015). This typical connectivity stems from the fact that large-scale anatomical connectivity, including that of the visual cortex, is largely formed at birth (Arcaro and Livingstone, 2017; Barone et al., 1996; Burkhalter et al., 1993; Coogan and Van Essen, 1996; Horton and Hocking, 1996; Takahashi et al., 2012). Connectivity is principally driven by evolutionarily-constrained genetic cascades that direct brain development (Gomez et al., 2018; Krubitzer and Prescott, 2018) even prior to the onset of visual experience. Therefore, the effects of visual deprivation on anatomical connectivity are limited, and may be restricted to changes in connection weights or synaptic pruning (Innocenti and Price, 2005). Even mechanisms such as decreased pruning of otherwise transient projections (Dehay et al., 1984; Innocenti et al., 1988; Innocenti and Clarke, 1984; Kennedy et al., 1989; Rockland and Van Hoesen, 1994) underlying anatomical rewiring and increased cross-modal connectivity in animal models of blindness (Henschke et al., 2017; Karlen et al., 2006; Magrou et al., 2017; Nicolelis et al., 1991) have not been reported in humans.

An alternative way in which reorganization could occur is the unmasking of existing connections that are not dominant in the presence of sight (Pascual-Leone and Hamilton, 2001). While this proposal does not require massive change in anatomical structure, it assumes that such functions, or at least their predecessor connectivity, exist in the sighted brain. Our findings support this account by demonstrating that primary visual cortex receives language-related information even in sighted people. In early blindness, this normally non-dominant input may become dominant, potentially allowing V1 to functionally contribute to language processing to a much larger extent than it does when its dominant input is visual. Importantly, this explanation of V1 language activation in the early blind does not require pluripotency of visual cortex in the sense of massive

changes in function that allow it to perform higher-cognitive functions instead of low-level visual processing (Bedny, 2017). Rather, our data suggest a more conservative explanation of V1's language recruitment in blindness: little reorganization of V1 structure or function is required to support language recruitment of deprived cortex because it also recruits non-deprived cortex, albeit to a lower extent.

Notably, our findings do not preclude additional reorganization in early onset blindness beyond unmasking. There is abundant evidence for increased activation of visual cortex for language tasks in early onset blindness as compared to sighted people (Abboud and Cohen, 2019; Bedny et al., 2011a; Burton, 2003; Burton et al., 2003; Burton et al., 2002b; Lane et al., 2015; Röder et al., 2002), suggesting a role for local reweighting and better utilization of inputs. Similarly, evidence for differences in the extent of recruitment depending on the timing of blindness onset also suggests that early-onset blindness involves more than unmasking, and that such additional processes are time-sensitive (Bedny et al., 2011b; Burton et al., 2003; Burton and McLaren, 2005; Burton et al., 2002a; Burton et al., 2002b; Cohen et al., 1999; Kanjlia et al., 2018). However, our results reveal a key piece of this puzzle by explaining how language information arrives in early visual cortex. The presence of language responses in the visual cortex of sighted people greatly decreases the requirement for large-scale structural or functional changes to account for this tissue's recruitment for language in blindness. Further, our evidence brings the inordinate plasticity for language in line with current views of connectivity-driven functional brain organization (Hannagan et al., 2015; Heimler et al., 2015; Mahon and Caramazza, 2011; Saygin et al., 2011; Saygin et al., 2016). Thus, we contribute to a unifying explanatory framework for findings in the primary and association cortices in the blind, based on extant non-visual functions of the visual cortex.

In summary, our findings show that the primary visual cortex is engaged in language processing in typically sighted individuals in a localized and left-lateralized manner. Importantly, these findings provide evidence that language-driven visual cortex activation in the blind can be explained without proposing drastic changes to cortical tissue connectivity or function. This suggests that human cortical plasticity is still limited by innate anatomical structures and functional characteristics, and is not unconstrained even following extreme changes in early experience.

Materials and methods

Participants:

Experiment 1: Participants were 20 young adults (5 men, ages 18 to 38, mean 21.8 years) with normal or corrected-to-normal vision and no history of neurological disorder from the Georgetown University community. All were native speakers of English and had not been fluent in any other language by the age of 12. All experimental protocols were approved by the institutional review board of Georgetown University Medical Center, in accordance with the Declaration of Helsinki. Participants provided informed consent and were compensated for their time.
Experiments 2, 3: Participants were 14 adults with normal or corrected-to-normal vision and no history of neurological disorder (8 men, ages 23 to 66, mean 43.85 years). All were native speakers of Mandarin Chinese. All experimental protocols were approved by the institutional review board of the Department of Psychology at Peking University, China, as well as by the institutional review board of Harvard University, in accordance with the Declaration of Helsinki. Participants provided informed consent and were compensated for their time.

Experimental Design:

Experiment 1: The fMRI language task used here was a modified version of an Auditory Description Decision Task used to determine language dominance prior to epilepsy surgery (Berl et al., 2014; Gaillard et al., 2007b). In the Forward Speech condition, participants heard short English sentences (e.g., "A big gray animal is an elephant") and pushed a button if they considered it a true statement. In the Reverse Speech condition, they heard the same sentences played in reverse (thus rendered incomprehensible) and pushed a button when they heard a soft beep inserted at the end of the utterance. The proportion of correct statements and reverse speech utterances with beeps was 50%. The task was designed to be easy; performance was nearly perfect (median performance at 100% for both tasks, mean 97.2±4.5% for sentence comprehension, mean 99.5±1.1% for beep detection). Each participant completed 2 fMRI runs of 5 min and 48 s duration, each containing 4 30-second blocks of each of 2 experimental conditions (Forward and Reversed Speech, 6 utterances per block) in counterbalanced order, with 12-s silent rest periods at the beginning and end of the run, as well as in between each of the 8 active blocks. Aside from a fixation cross that participants were asked to rest their eyes on throughout the scan, no visual stimulation was provided. The Forward>Reverse activation differences evoked by this task are highly robust and reproducible, making them suitable for localizing language-associated brain areas across development (Olulade et al., 2020) and even in cases of atypical functional organization, such as participants with a history of chronic epilepsy (Berl et al., 2014) or perinatal stroke (Newport et al., 2017). Imaging data were acquired on Georgetown's research-dedicated 3T Siemens Trio Tim scanner with a 12-channel birdcage head coil. Auditory stimuli were delivered via insert earphones (Sensimetrics S14) worn under ear defenders (Bilsom Thunder T1). Stimulus presentation and response collection (via a Cedrus fiber optics button box) were coordinated by E-Prime 2.0 software. Each of the 2 functional runs contained 100 functional (T2*-weighted) volumes covering the whole brain in 50 slices acquired in descending order and oriented parallel to the AC-PC plane (EPI parameters: TE = 30 ms, TR = 3000 ms, flip angle = 90°, matrix 64x64, slice thickness = 2.8 mm, distance factor = 7%, resulting in an effective voxel size of 3x3x3 mm^3). A high-resolution anatomical (T1-weighted) scan was acquired for co-registration (MPRAGE parameters: whole-brain coverage in 176 sagittal slices, TE = 3.5 ms, TR = 2530 ms, TI = 1100 ms, flip angle = 7°, matrix 256x256, voxel size = 1x1x1 mm^3).

Experiments 2, 3: The experiment included presentation of spoken words, each a two-character word in Mandarin Chinese, belonging to eight concept categories: abstract concepts (e.g. "freedom"), concrete everyday object names (e.g. "cup"), and six additional content categories which were not analyzed in the current manuscript (astral/weather phenomena - e.g. "rainbow", "rain"; scenes - "island", "beach"; and object features - colors and shapes, e.g. "red", "square"; see full detail in Striem-Amit et al., 2018b). Each category included 10 words whose imaginability and attentional arousal (as well as other measures not used here) were rated on a 7-point scale (Barca et al., 2002) by an independent sample of 45 sighted Chinese participants with similar levels of education. Concrete objects and abstract concepts differed significantly in imaginability (Welch t-test contrast, $p< 0.001$, but not in arousal $p=0.06$, uncorrected, after correction for multiple comparisons the difference in imaginability is significant; see full detail in Striem-Amit et al., 2018b). During Experiment 2, the participants kept their eyes closed and heard short lists of words in a block design paradigm (8 second blocks with 8 words each, baseline between blocks 8 seconds). Each run began with a 12 sec rest period. Each block contained words from one of the eight concept categories.

Experiment 3 was an item-level slow event-related design and was conducted at a different scanning session on the same participants. The stimuli were eight of the ten words of each category from Experiment 2, except for the concrete object names. During each of eight slow event-related runs, the participants heard each word once, in a random order, followed by a 5 second baseline period. In both Experiments 2 and 3 the participant's task was to detect and respond to semantic catch trials, a fruit name appearing within blocks or as individual events; these blocks/events were removed from further analysis, and runs with more than one missed catch event were excluded.

Imaging data were acquired using a Siemens Prisma 3-T scanner with a 20-channel phase-array head coil at the Imaging Center for MRI Research, Peking University. Functional imaging data for Experiment 2 were comprised of four functional runs, each containing 251 continuous whole-brain functional volumes. Functional imaging data for the single-item-level event-related Experiment 3 were comprised of eight functional runs, each containing 209 continuous whole-brain functional volumes. Data was acquired with a simultaneous multi-slice (SMS) sequence supplied by Siemens: slice planes scanned along the rectal gyrus, 64 slices, phase encoding direction from posterior to anterior; 2 mm thickness; 0.2mm gap; multi-band factor = 2; TR = 2000 ms; TE = 30 ms; FA = 90°; matrix size = 112 × 112; FOV = 224 × 224 mm; voxel size = 2 × 2 × 2 mm. T1-weighted anatomical images were acquired for coregistration using a 3D MPRAGE sequence: 192 sagittal slices; 1mm thickness; TR=2530 ms; TE=2.98 ms; inversion time=1100 ms; FA=7°; FOV=256 × 224 mm; voxel size=0.5 × 0.5 × 1 mm, interpolated; matrix size=512 × 448.

Data Analysis:

Preprocessing: Imaging data were analyzed using BrainVoyager (BVQX 3.6). Anatomical images were corrected for field inhomogeneities and transformed into Talairach space using 9-parameter affine transformation based on manually identified anatomical landmarks. Functional runs underwent slice time correction, removal of linear trends, and 3D motion correction to the first volume of each run using rigid-body transformation. The first two volumes of each run were discarded to allow for magnetization stabilization. Each run was coregistered with the native-space anatomical image of the same participant using 9-parameter gradient-based alignment, and subsequently warped into Talairach space using the same affine transformation used for warping the anatomical data.

Whole-brain group-level analysis: To create group-level activation maps (**Fig. 1A; 2A**), we smoothed the Talairach-warped functional data with a 3D Gaussian kernel of 8 mm FWHM and conducted a hierarchical random effects analysis (RFX GLM; Friston et al., 1999). Each experimental condition's predictor was modeled by convolving the boxcar predictor describing the condition's time-course with a standard hemodynamic response function (two gamma, peak at 5 s, undershoot peak at 15 s). In addition, the model included nuisance predictors to capture participant- and run-specific effects as well as motion-related effects (using the z-transformed motion estimates generated during preprocessing). During modeling, voxel time courses were normalized using percent signal change transformation and corrected for serial autocorrelations (AR2). Activation maps contrasting the beta values for the different conditions via voxel-wise t-tests were thresholded by applying a single-voxel threshold of $p < 0.001$ (uncorrected) and running BrainVoyager's Cluster-Level Statistical Threshold Estimator Plugin to determine a cluster-size threshold corresponding to $k < 0.05$.

Region-of-interest analyses: Regions-of-interest (ROIs) for the primary and secondary visual cortex (V1 and V2, respectively) were defined from an external localizer (Striem-Amit et al., 2015). The external retinotopy localizer was acquired in a separate group of 14 normally sighted participants using a standard phase-encoded retinotopic mapping protocol, with eccentricity and polar mapping of ring and wedge stimuli, respectively, to measure visual retinotopic mapping (Engel et al., 1994; Sereno et al., 1995; Wandell et al., 2007b; Wandell and Winawer, 2011), delivered during two separate experiments. The experimental detail can be found at Striem-Amit et al., 2015. Angle (polar) mapping was used to define the borders of V1 and V2 in both hemispheres, used as a ROI to sample activation for the language conditions in the early visual cortices (**Fig. 1B,C; 2B,C**). V1 was further divided to three portions largely representing foveal, middle and peripheral visual fields based on the eccentricity mapping. Beta values for each condition were sampled in individuals, and comparisons across conditions within the same ROI were computed with a two-tailed paired t-test. Comparisons across areas were computed based on the subtraction of beta values between direct and reversed speech for each individual, and

applying a one-tailed paired t-test between regions, under the prediction that language activation would be localized to the left V1, as seen in blindness (Bedny et al., 2011a; Burton, 2003; Burton et al., 2003; Burton et al., 2002b).

To assess the possibility of an attention confound in our findings, we also examined language activation in the dorsal attention network using a 4mm radius sphere centered around peak Talairach coordinates (x,y,z =38,-44,48; from Spreng et al., 2013) as an ROI. In addition, we explored correlations between imaginability and arousal behavioral ratings of the words presented in Experiment 3 and language activation in the left V1 ROI, across all 56 words used in the experiment. T-tests' p-values are corrected for multiple comparisons using a Bonferroni correction per experiment. Specifically, five statistical comparisons were conducted with Experiment 1: V1 forward>reverse speech, left vs right V1, Left V1 vs V2, dorsal attention network forward>reverse speech and the V1 eccentricity effect. Three statistical comparisons were conducted with Experiment 2: V1 abstract>concrete words, left vs right V1, dorsal attention network. Behavioral data correction for multiple comparisons is based on the number of comparisons made in the context of the whole experimental design behavioral testing; see full detail in Striem-Amit et al., 2018b.

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Supplementary Material

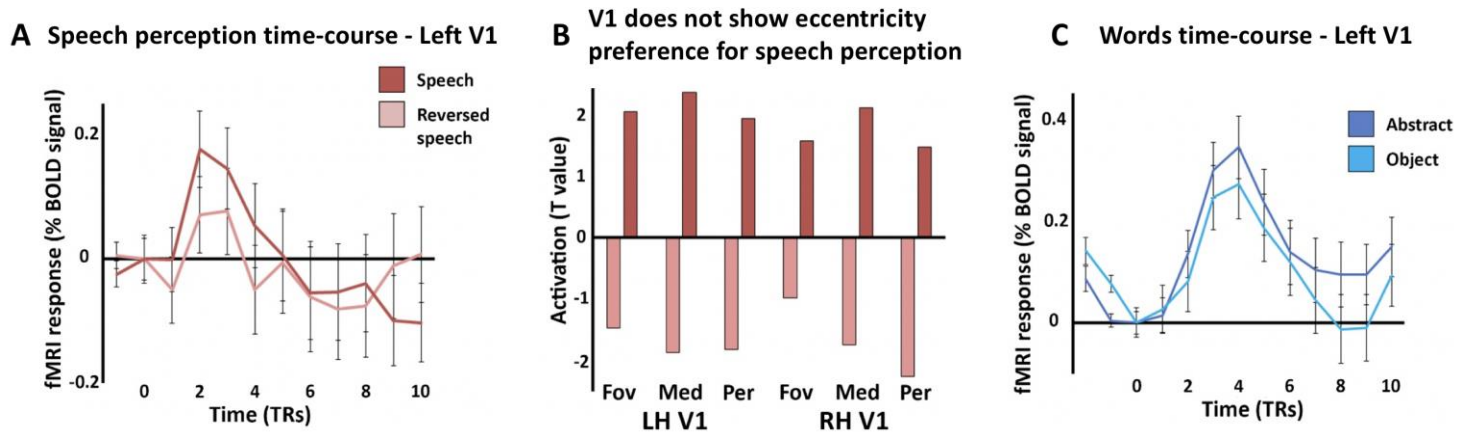

Figure S1: Activation for speech comprehension in primary visual cortex

- **A.** Time course of activation from Experiment 1 was sampled from retinotopic left V1, showing typical BOLD-shaped response in V1 for speech, which is higher for forward as compared to reversed speech.
- **B.** GLM parameter estimates (betas) were sampled in the left retinotopically-defined primary visual cortex divided based on eccentricity, showing that the activation for forward speech does not differ between foveal, middle and peripheral-representing V1 sections.
- **C.** Time course of activation from Experiment 2 was sampled from retinotopic left V1, showing typical BOLD-shaped response in V1 for abstract and concrete words.

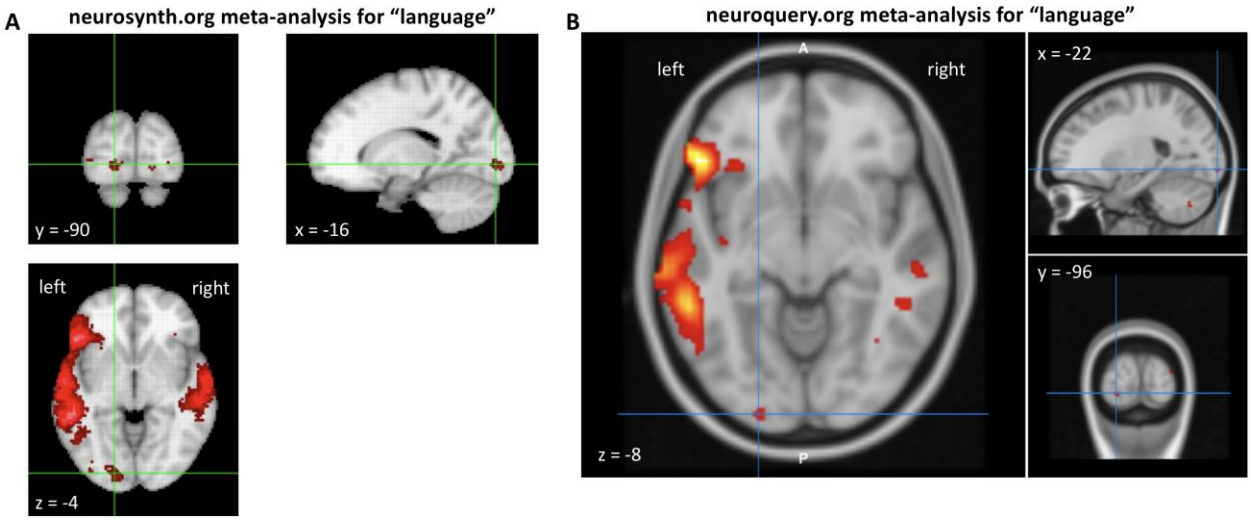

Figure S2: Left-lateralized early visual activation in "language" meta-analyses

- **A.** Screenshot of the results of a coordinate-based meta-analysis using the neurosynth.org platform (Yarkoni et al., 2011) showing a left early visual cluster. The map is based on the activation coordinates reported in 1101 functional neuroimaging studies based on a two-way ANOVA testing whether activation at the voxel occurs more consistently in studies mentioning the term "language" with high frequency in their full text than in studies that do not. The map is thresholded to limit the false discovery

rate to 1% (FDR<0.01). The left early visual cortex activation highlighted by the crosshairs is highly significant (z=4.4).

B. Screenshot of the predicted activation for “language” using the neuroquery.org platform (Dockès et al., 2020) showing a left early visual cluster. The map is derived using a reduced-rank linear regression model on the activation coordinates reported in a training corpus of 14,000 neuroimaging studies. The “language” map was automatically generated using Neuroquery and included mainly contribution from 73 neuroimaging studies associated with the term “language” and several additional studies on related terms such as “speech” or “comprehension”. The z-value at the voxel highlighted by the crosshairs is z=3.9.