

Neural Effects of Childhood Language Deprivation on Picture Processing: Insights from Adolescent First-Language Learners

Tristan S. Davenport (trdavenp@ucsd.edu)

Department of Linguistics, UC San Diego, 9500 Gilman Drive
San Diego, CA 92093 USA

Naja Ferjan Ramirez (naja@uw.edu)

Institute for Learning and Brain Sciences, University of Washington, Box 357988
Seattle, WA 98195-7988 USA

Matthew K. Leonard (LeonardM@neurosurg.ucsf.edu)

Department of Neurological Surgery, UC San Francisco, 675 Nelson Rising Lane
San Francisco, CA 94158 USA

Rachel Mayberry (rmayberry@ucsd.edu) *

Department of Linguistics, UC San Diego, 9500 Gilman Drive
San Diego, CA 92093 USA

Eric Halgren (ehalgren@ucsd.edu) *

Multimodal Imaging Laboratory, UC San Diego, 9500 Gilman Drive
San Diego, CA 92093 USA

* These authors contributed equally to this manuscript

Abstract

The developmental relationship between linguistic semantic processing and non-linguistic semantic processing (interpreting pictures) is investigated in a longitudinal neuroimaging study of two deaf individuals who did not begin acquiring their first language until the age of 14. 1-2 years after they began learning language, the two case studies performed a picture-sign priming task. Magnetoencephalography was localized to the cortical surface, showing that picture processing was initially bilateral or focused in the canonical left hemisphere language network, while single sign processing was initially focused in the right hemisphere. After 15 months of additional language experience, the neural responses to both pictures and single signs reversed in lateralization, becoming more similar to those observed in a control group of native signers. The results shed new light on the interdependence between linguistic and non-linguistic semantics in cognitive development, as well as the neural underpinnings of semantic processing.

Keywords: linguistics; neuroscience; cognitive development; language acquisition; semantics; experimental research with children; neuro-imaging; case studies; sign language.

Introduction

Exposure to language during early childhood is essential for fluent linguistic skill later in life. It is difficult to study exactly how early language input influences both behavioral and neural linguistic outcomes, primarily because early language deprivation is extremely uncommon among hearing children, who are exposed to language even before birth (Moon & Fifer, 2000). Likewise, some deaf children

(termed “deaf native signers”) grow up among deaf, signing adults and begin to acquire a sign language beginning shortly after birth. However, many other deaf children grow up without access to sign languages, typically because they are born in a community without sign language users and their parents are unable to access social services for deaf children. Such individuals, termed “late learners” here, may not begin to acquire language until they enter school, and in rare cases, not until adolescence. Individuals who began to acquire their first language, American Sign Language (ASL), in late childhood show deficits plateau in their adult language processing skills and their ultimate language proficiency. The effects of late first language acquisition are quantitatively stronger than those of late second language acquisition. Late first language acquisition is particularly

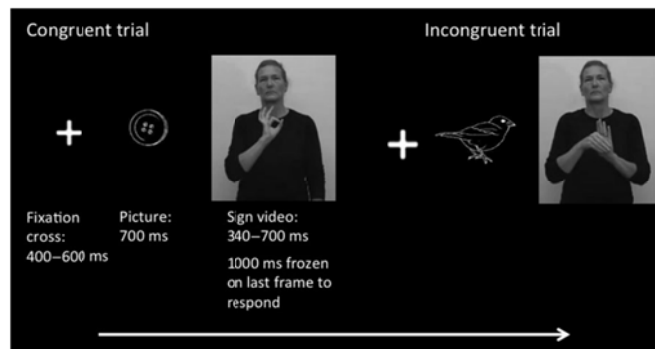


Figure 1: Schematic diagram of task design. Each picture and sign appeared in both the congruent and incongruent conditions.

deleterious when no formal language has been available until late childhood or the early teenage years (Mayberry, 1993; Mayberry, Lock & Kazmi, 2002; Ferjan Ramirez, Lieberman & Mayberry, 2013).

It is unknown why late first language acquisition creates such serious deficits in language learning. One possibility is that areas of the brain that are normally specialized for language use early in life – mainly structures in the left perisylvian cortex – become specialized for non-linguistic processes in children deprived of early language input, but who still interact with their environment through visual and tactile means. This possibility raises the question of how the adolescent brain adapts to language, and what happens to these areas that were previously specialized for non-linguistic processes. To understand the neural mechanisms involved in late learners’ linguistic and non-linguistic semantic processing abilities, our group has conducted a longitudinal imaging study on a unique pair of extreme cases of childhood language deprivation. “Carlos” and “Shawna” are two deaf teenagers who did not begin to acquire their first language, ASL, until roughly the age of 14 when they were placed in a group home for the deaf.

Investigations into the neural underpinnings of language in these two adolescent deaf late learners were conducted using a picture-sign priming task (Ferjan Ramirez et al., 2013a; 2014). In two experiments, 15 months apart, participants viewed line drawings of objects followed by matching or mismatching ASL signs (Fig. 1) while magnetoencephalographic (MEG) brain responses were recorded. The experimental task was designed to evoke the N400m response, the MEG index of the N400 (Kutas & Hillyard, 1980; Kutas & Federmeier, 2011; Halgren et al., 2002). The N400 is an electrophysiological response that is reliably evoked by a meaningful stimulus, is measurable at the scalp, and is attenuated by supportive contextual factors such as semantic overlap with recent stimuli, predictability, and repetition. The dependent variable was therefore the difference in the N400m magnitude between the congruent and incongruent ASL signs.

Figure 2 summarizes the results of that study for the two adolescent late learners, Carlos and Shawna, described above. At Visit 1, Carlos’ and Shawna’s N400m effects of sign congruency were primarily lateralized to the right hemisphere (RH) and included large areas of cortex outside of the canonical left hemisphere (LH) perisylvian language network. At Visit 2, after 15 months of additional language experience, their neural activation patterns were substantially different. Neural responses to ASL signs were focused in bilateral (Carlos) and left hemisphere (LH) perisylvian cortex (Shawna). Compared to the pattern of neural activity observed at Visit 1, the neural responses at Visit 2 were substantially more similar to those observed in a control group of 12 deaf native ASL signers who performed the same task.

These results demonstrate that early language deprivation has profound impacts on the neural processing of linguistic input, and that continued exposure to language, even later in life, changes these representations. However, it is surprising

that the neural correlates of single sign processing can be relatively similar to those of deaf native signers following so little language exposure, while behavioral linguistic skills remain so far outside the normal range. To understand this disconnect, we examined the effects of late language acquisition on a non-linguistic aspect of the semantic system, the interpretation of meaningful pictures. The experimental design included two presentations of each picture prime, allowing us to measure a picture repetition (novel-repeated) effect on the N400m.

These neural responses allow us to investigate whether late acquisition of language affects the semantic processing of non-linguistic stimuli, namely pictures. We considered two hypotheses. First, it is possible that the linguistic and non-linguistic aspects of the semantic system develop in relative isolation from one another. If this is the case, then non-linguistic semantic processing would follow a similar developmental trajectory regardless of the presence or absence of linguistic input. We would also expect Carlos’s and Shawna’s brain responses to pictures to look similar to those of the deaf native signing controls, and to be unaffected by additional language experience between Visits 1 and 2. Alternatively, it is possible that the development of the linguistic and image-based semantic systems is coupled, and that the cortical localization of one system depends to some degree on the activity of the other. This hypothesis predicts that Carlos’ and Shawna’s responses to pictures would change from Visit 1 to Visit 2, resembling those of the deaf native signers more closely in Visit 2.

Methods

Participants

The study focused on two right-handed adolescent late learners (Carlos and Shawna) whose language input was delayed until adolescence. For a full description of Shawna’s and Carlos’s backgrounds, see Ferjan Ramirez et al. (2013a). In brief, they began to acquire their first language, ASL, at the age of 14 in the full immersion environment of a group home for deaf children. Despite their lack of language exposure and schooling prior to their

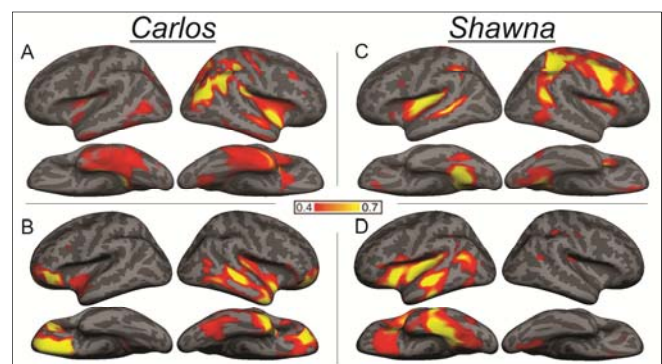


Figure 2: Anatomically constrained MEG (aMEG) maps of the sign congruence effect 300-350 ms after sign onset in the two case studies.

placement in the group home, they both had otherwise healthy upbringings, free of the abuse and social isolation typical in hearing late learners (Curtiss, 1976). At the time of their placement in the group home for their deaf, Shawna communicated through demonstration and limited use of non-linguistic gestures. Carlos knew a small number of ASL signs. Neither Carlos nor Shawna have ever been observed to use any signs indicative of a homesign system, though it is unknown whether they used a homesign system with their family members in the past. Additionally, the ASL-fluent social workers who have worked with Carlos and Shawna report that they have no knowledge of any conventional spoken language, that they are illiterate, and that they were unable to lipread.

At the time of Visit 1, Carlos and Shawna had lived in full ASL immersion for 1 year in Shawna's case and 2 years in Carlos's case. At this time, their vocabulary was assessed against the MacArthur-Bates Communicative Development Inventory for ASL. Their vocabulary was similar in composition to that of a typically developing deaf 2 year-old (i.e., with a preponderance of nouns and few verbs and function words), although somewhat larger in terms of the overall number of signs. Visit 2 was 15 months later.

In addition to Shawna and Carlos, 12 deaf native ASL signers (6 male, age 17-36) with no neuropsychological impairment participated in the study. These individuals were right-handed, profoundly deaf, and acquired ASL as the main language of communication beginning at birth from their deaf parents. Due to the difficulty of finding native signing participants who meet the criteria for MEG and MRI scanning, it was not possible to match the late learners and the native signers on factors such as age.

Materials

The task stimuli were a set of ASL signs that Shawna and Carlos knew well at Visit 1 (Ferjan Ramirez et al., 2013), as well as a set of matching line drawings to use as primes. Carlos, Shawna, and all control participants performed a semantic decision task intended to elicit an event-related brain response known as the N400 (Kutas & Hillyard, 1980; 1984; Kutas & Federmeier, 2011) or N400m in MEG (Halgren et al., 2002). While we recorded MEG, participants saw a line drawing of an object for 700 ms, followed by a sign (mean length: 515.3 ms; length range: 340–700 ms) that either matched (congruent; e.g., “cat-cat”) or mismatched (incongruent; e.g., “cat-ball”) the picture in meaning (Fig. 1). To measure accuracy and maintain attention, participants pressed a button when the word matched the picture; response hand was counterbalanced across blocks within participants.

Native signers saw 6 blocks of 102 trials each. Shawna and Carlos each saw 5 blocks of 102 trials due to vocabulary size and equipment malfunction, respectively (Ferjan Ramirez et al. 2013a). Prior to testing, Carlos and Shawna participated in a separate acclimation session during which they were familiarized with the MEG and MRI scanners and practiced the task. Before scanning began, all participants performed a practice run in the scanner. The practice run

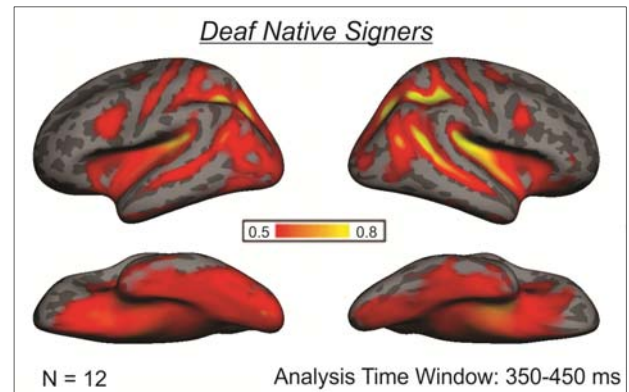


Figure 3: Average normalized aMEG responses to meaningful pictures in 12 deaf native signers. Red and yellow areas represent areas where picture repetition modulated neural activity between 350 and 450 ms.

implemented a separate set of stimuli that was not part of the experimental stimuli. All controls and both cases understood the task quickly. No participant required repetitions of the practice block.

Procedure

MEG was recorded in a magnetically shielded room (IMEDCO-AG, Switzerland), with the head in a Neuromag Vectorview dewar containing 102 magnetometers and 204 planar gradiometers (Elekta AB, Helsinki, Finland). Data were collected at a continuous sampling rate of 1000 Hz with minimal filtering (0.1–200 Hz). The positions of 4 nonmagnetic coils affixed to the subjects' heads were digitized along with the main fiducial points such as the nose, nasion, and preauricular points for subsequent coregistration with high-resolution MRI images. Structural MRI was acquired on the same day after MEG, and participants were allowed to rest in the MRI scanner.

Analysis

The data were analyzed using a multimodal imaging approach, anatomically constrained MEG (aMEG), that constrains the MEG activity to the cortical surface as determined by high-resolution structural MRI (Dale et al. 2000). This noise-normalized linear inverse technique has been used extensively across a variety of paradigms, particularly language tasks that benefit from a distributed source analysis (Marinkovic et al. 2003), and has been validated by intracranial recordings (McDonald et al. 2010). The data acquisition methods are described in more detail by Ferjan Ramirez and colleagues (2013a; 2014). In brief, the cortical surface was reconstructed from a T1-weighted structural MRI, and MEG activity at each vertex on this surface model was estimated every 4 ms, and the F-distributed noise sensitivity at each location was estimated using the average prestimulus baseline from -190 to -20 ms. This activity is plotted on the cortical surface on a normalized scale represented as a fraction of the peak aMEG value. aMEG of the N400m effect was produced by subtracting repeated from novel trials.

The data were inspected for bad channels (channels with excessive noise, no signal, or unexplained artifacts), which were excluded from further analyses. Additionally, trials with large (>3000 fT/cm) transients were rejected. Blink artifacts were removed using independent components analysis (Delorme and Makeig 2004).

Individual subject aMEG movies were constructed from the averaged data in the trial epoch for each condition using only data from the gradiometers; these data were combined across subjects by taking the mean activity at each vertex on the cortical surface and by plotting it on a template brain at each latency in the normalized units described above.

Results

We examined the aMEG results at the group level (deaf native signers) and at the individual level (Shawna and Carlos) from 350 to 450 ms after the presentation of the picture, a time window during which pictures are known to elicit N400 effects (Kutas & Federmeier, 2011).

For the deaf native controls, it was hypothesized that the effect of picture repetition would be largest in bilateral perisylvian cortex, in keeping with prior work showing a larger RH role for processing meaningful pictures compared to words (Liljestrom et al., 2009; Chee et al., 2000). Indeed, the picture repetition N400m effect in deaf native signers was localized to several bilateral cortical areas, including the superior temporal sulcus, the planum temporale, and the intraparietal sulcus. In all of these areas, the effect was larger in RH (Fig. 3).

For the cases, Carlos and Shawna, we considered two hypotheses, discussed previously in the Introduction. The first hypothesis was that if the development of the linguistic and non-linguistic aspects of the semantic system were largely uncoupled, then aMEG maps of the picture repetition effect would look similar to those of the deaf native signing control participants, and would not change appreciably as participants became more experienced in communicating with language. The second hypothesis posited interdependence in development between the linguistic and non-linguistic semantic processing systems. This hypothesis predicts an atypical cortical distribution of picture processing in the two cases, as well as a change in that distribution between Visit 1 and Visit 2.

The cases' neural responses to pictures support the second hypothesis. Figure 4 shows that for both Carlos and Shawna, the N400 effect of picture repetition increased in RH and decreased in LH from Visit 1 (panels A and D) to Visit 2 (panels B and E). Carlos's picture N400m effect was localized to bilateral temporal cortex at Visit 1 (Figure 4A) and to RH temporal cortex at Visit 2 (Figure 4B). Shawna's picture repetition effect was larger in LH at Visit 1 (Figure 4D), and by Visit 2, the lateralization of this effect had reversed and now covered much of perisylvian and parietal cortex in RH (Figure 4E). Together, these results suggest that in both case studies, neural responses to pictures underwent a LH-to-RH shift over time. This is in contrast to sign processing, where both cases showed increased LH activity with increased linguistic experience (Figure 2).

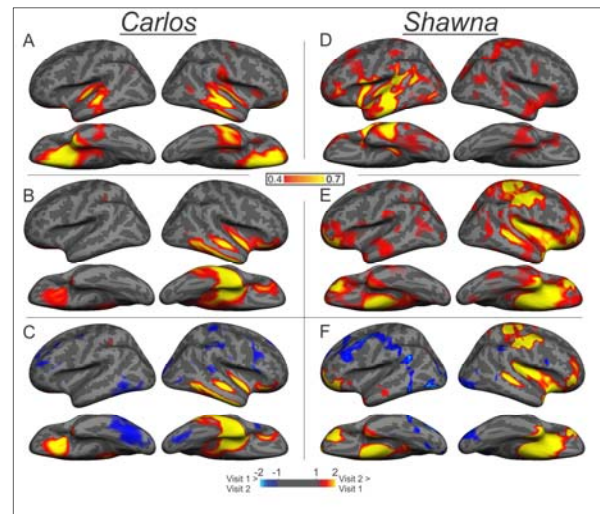


Figure 4: aMEG maps of the picture repetition effect in Carlos (A, B & C) and Shawna (D, E & F).

To quantify the changes from Visit 1 to Visit 2 at each vertex on the cortical surface, we converted the aMEG values of the difference between conditions (novel vs. repeated pictures) to z-scores separately at Visit 1 and Visit 2 (Fig. 4, panels C & F). These z-score maps show the brain areas where semantic modulation in Carlos and Shawna is greater in Visit 1 compared with Visit 2 (shown in blue and cyan) and areas where semantic modulation is greater in Visit 2 compared with Visit 1 (shown in yellow and red) in normalized units. Both subjects showed increased activity at Visit 2 greater than 2 standard deviations in the RH anterior and superior temporal cortices. In addition, Shawna showed increased activity of at least 2 standard deviations in similar RH parietal areas (Figure 4F) as is normal in the native deaf signer group (Figure 3). Areas with activity at least 1 standard deviation greater at Visit 1 than at Visit 2 were mostly confined to the left hemisphere.

Discussion

We examined semantic processing of non-linguistic visual stimuli in two individuals who were deprived of language until adolescence. In the context of previous work examining linguistic processing in the same individuals (Ferjan Ramirez et al., 2013a; 2014), the present study provides novel insights into the relationship between language experience in early life and the neural architecture of the semantic system, in both its linguistic and non-linguistic aspects. Carlos and Shawna became immersed in an ASL-signing community around age 14. Until that time, they had little or no language input, but they had interacted with meaningful objects in non-linguistic ways. Previous studies with other late L1 learners of sign language have shown that delayed L1 acquisition is associated with lifelong low language proficiency, as well as anomalous patterns of language processing in the brain (Newport 1990; Mayberry 1993; Mayberry et al. 2011; Emmorey et al. 1995; Ferjan Ramirez et al., 2014). The present study asks how this early language deprivation affects other aspects of

semantic processing, namely the processing of meaningful pictures, and how that processing changes when formal language becomes available in adolescence.

At Visit 1, aMEG recordings of Carlos and Shawna indicated that their neural processing of pictures was atypical. They both displayed a greater LH focus than that observed in deaf native signers, and they also differed strikingly from one another. In particular, Carlos's activation was confined to the bilateral temporal and inferior prefrontal cortex, while Shawna's was strongly left-lateralized in the temporal lobe. (Fig. 4). Although a rich fMRI literature suggests that semantic processing is not localized to the left anterior temporal lobe (Binder et al., 2009), these results appear to be artifacts of signal dropout in the anterior temporal lobes caused by nearby sinuses. Later investigations with fMRI protocols specifically designed to detect anterior temporal activations have shown that semantic processing does indeed modulate left anterior temporal lobe (Binder et al., 2011).

We considered two hypotheses concerning longitudinal changes in these response patterns. The first hypothesis, predicated on the developmental independence of linguistic and image-based semantic systems, predicted that Carlos's and Shawna's neural responses to pictures would look similar to those of deaf native signers and would not change between Visit 1 and Visit 2. The second hypothesis posited interdependence of the two systems, predicting that as the cases experienced more language, their responses to both linguistic and non-linguistic material would become more like those of the deaf native signers at Visit 2 than at Visit 1.

Our results support the second hypothesis. In both Carlos's and Shawna's aMEG maps, the sign congruence effect became more left-lateralized and localized to the perisylvian cortex at Visit 2 (Fig. 2), and the picture repetition effect became more right-lateralized (Fig. 4). This suggests that the effect of additional language experience was not confined to linguistic processing, but also affected the processing of visual objects.

As Carlos and Shawna gained additional language experience, the neural substrate of picture processing as revealed by aMEG became *less* similar to that of language processing, rather than more similar. As their linguistic knowledge developed, the neural substrates recruited to interpret pictures and ASL signs diverged. The reason for this shift in neural activation patterns remains unclear, particularly since Carlos and Shawna have not exhibited large changes in their linguistic performance. We have observed no evidence of the explosive growth in vocabulary and morphology that young children undergo, nor have their syntactic abilities have increased appreciably, either (Ferjan Ramirez et al., 2013; 2013a; 2014).

The observed shifts in neural activation patterns are presumably related to their additional language experience during the 15 months between Visits 1 and 2. These results suggest that in the absence of early input, the LH perisylvian structures that normally process language are instead utilized for the most reliably meaningful signal available to deaf individuals without language exposure, namely visual

images. This suggests that LH perisylvian networks are tuned, perhaps from birth, for extracting semantic information from input. However, as linguistic information becomes available, the LH perisylvian network gradually re-specialized to process language in preference to visual objects. This change indicates that regardless of an individual's experience, LH perisylvian cortex remains capable of adapting quite rapidly to a new, perhaps semantically richer, form of input.

This finding is consistent with recent investigations of changes in the brain due to learning to read late in life. Dehaene and colleagues (2010) conducted an fMRI study on illiterate and literate adults, including groups of literate adults who learned to read in adulthood ("ex-illiterate subjects") and others who learned to read in childhood ("literate subjects"). They found that illiterate subjects, and to a lesser extent ex-illiterates, showed larger responses to faces and smaller responses to written sentences in the LH visual word form area in basal occipito-temporal cortex. Likewise, literates showed greater specialization for faces in the RH homologue of the visual word form area, compared to illiterates and ex-illiterates. This result was interpreted to reflect a process of "cortical recycling," whereby a given cortical area or network can be trained by structured, interpretable input to take on a new function similar to its previous specialization. This process can cause conflict between the area's old function and its new function, prompting another brain areas with similar properties to become more specialized for the old function.

In the case of the semantic system for adolescent late learners like Shawna and Carlos, a similar type of cortical recycling appears to have occurred during the interval between Visits 1 and 2. In response to consistent language input, LH and RH perisylvian cortex gradually became more functionally specialized for language and visual object processing, respectively. This response is suggestive about the nature of the semantic system in ways that have previously been difficult to test experimentally. Our results suggest that the linguistic and non-linguistic aspects of the semantic system are partially but not completely dissociable. They are similar in that the same neural substrate, the LH perisylvian cortex, is able to process visual objects in the absence of language input; in addition, images in particular are processed bilaterally in deaf native signers, albeit with a RH bias (Fig. 3). However, linguistic and non-linguistic semantics must also be distinct because when both forms of input are present, their processing is biased to the LH and RH perisylvian regions, respectively.

One possibility that bears further investigation is that the LH perisylvian cortex specializes in extracting semantic information from the environment, using whatever type of stimulus is most reliably meaningful. If a new, richer mode of extracting meaning from the environment becomes available (e.g., by becoming immersed in a signed language for the first time), the new source of semantic information gradually "takes over" the LH perisylvian network. This hypothesis, although quite underspecified, is intended to capture the generalization that in early learners of signed

and spoken languages, the LH is typically specialized for language. In Carlos and Shawna, and perhaps in other adolescent late learners, LH perisylvian cortex is initially more responsive to meaningful pictures – a route to semantics that late learners have been using for their entire lives. Then, as they gain more language experience, this LH perisylvian network changes in function and becomes more sensitive to linguistic meaning and less sensitive to meaningful images. In tandem with that change, picture processing becomes more localized to perisylvian areas in the right hemisphere.

In summary, the present results suggest that the brain remains sensitive to different forms of semantic input throughout young adulthood, even if language acquisition is delayed until relatively late in life. However, the neural substrates of linguistic and nonlinguistic semantic processes may change with late-onset language experience. The two adolescent late learners described here displayed single-sign processing predominantly in RH initially, shifting primarily to LH after 15 months of additional language experience. Likewise, processing of meaningful pictures was initially bilateral or LH biased, and became strongly RH biased after 15 months of additional language experience. Whether this pattern of change is typical of late learners or idiosyncratic to these subjects remains an open question, requiring further research on late learners with different ages of language acquisition and different lengths of language exposure.

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