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Laterality and unilateral deafness: Patients with congenital right ear deafness do not develop atypical language dominance

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ABSTRACT

Auditory speech perception, speech production and reading lateralize to the left hemisphere in the majority of healthy right-handers. In this study, we investigated to what extent sensory input underlies the side of language dominance. We measured the lateralization of the three core subprocesses of language in patients who had profound hearing loss in the right ear from birth and in matched control subjects. They took part in a semantic decision listening task involving speech and sound stimuli (auditory perception), a word generation task (speech production) and a passive reading task (reading). The results show that a lack of sensory auditory input on the right side, which is strongly connected to the contralateral left hemisphere, does not lead to atypical lateralization of speech perception. Speech production and reading were also typically left lateralized in all but one patient, contradicting previous small scale studies. Other factors such as genetic constraints presumably overrule the role of sensory input in the development of (a)typical language lateralization.

1. Introduction

Language is well-known to be lateralized in humans. Numerous studies have reported a dominance of the left hemisphere for speech production, auditory perception, and reading (see Price, 2012 for a review). These three core subprocesses of language are the focus of the current study.

Speech production mainly activates the left middle and inferior frontal gyrus (IFG) or the so-called Broca's area including the pars opercularis and pars triangularis. Activity extends to other areas such as the cerebellum for the fast temporal organization of speech, the ventral premotor area for articulatory planning, pre- and post-central motor regions associated with mouth movements, the superior temporal gyri (STG)/sulci (STS) and planum temporale involved in auditory feedback.

Perception of speech relative to non-speech has been related to the left anterior and posterior STG/STS (aSTS/pSTS) surrounding the transverse gyrus of Heschl, to the left IFG and premotor areas for articulatory recoding and the attentional ventral supramarginal gyrus. When semantic comprehension is involved, the activity in the aSTS and pSTS is more widespread, in addition to for example the angular gyri for narrative comprehension. The pathway that auditory stimuli follow from the ear to the human cortex is complex due to parallel and crossed fiber tracts, but more nerve fibers lead to contralateral than ipsilateral brain areas. The left auditory cortices have been found to be specialized in fast temporally changing stimuli such as in speech, whereas the right homolog areas are found to be dominantly involved in tonal information processing (Firszt et al., 2006).

Finally, reading has been related to the left ventral occipito-temporal (vOT) region therefore called the visual word form area (Cohen et al., 2000). The exact nature of the region is still under debate, but the anterior part has been related to phonological and lexico-semantic processes of reading, whereas the posterior part is more responsible for visual features (Seghier and Price, 2011). Reading requires bilateral visual input. Due to the partial crossing of optic fibers, left/right visual field information is initially projected to the right (RH)/left (LH) hemisphere respectively. The information is however thought to be early reunited in the dominant LH before reading proper starts (Van der Haegen and Brysbaert, 2011).

The origins of hemispheric specialization have been attributed to several influences such as genetic, evolutionary, developmental

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and environmental factors (Bishop, 2013; Hervé et al., 2013). Pinel et al. (2014) compared the correlations between monozygotic and dizygotic twins in vOT lateralization during word reading, and found evidence for a partial genetic influence. Genetic influences are often associated with anatomical asymmetries, such as a deeper RH than LH pit in the STS found in both young infants and adults (Leroy et al., 2015). Greve et al. (2013) found significant differences in the surface area of the STG and vOT when comparing left-handers with LH and RH speech dominance. In Vingerhoets et al. (2013), correlations between the side and degree of praxis and speech lateralization pointed to a common evolutionary origin. Finally, (developing) higher-order cognitive functions can influence each other's asymmetry. For example, learning how to read leads to a LH lateralization in the occipitotemporal cortex which in turn may force face lateralization to be dominantly processed in the homolog area in the RH (Cantlon et al., 2011; Behrmann and Plaut, 2015). In adults, lateralization indices correlate between reading and speech production (Van der Haegen et al., 2012) and between reading and speech comprehension (Pinel et al., 2014). The purpose of this study is to test another possible environmental influence on the lateralization of speech production, reading and speech comprehension, namely sensory deprivation and more specifically a lack of sensory auditory input in congenital unilateral deaf patients.

Previous studies already described neural adaptions in sensory deprived subjects. The usual finding is that patients with unilateral hearing loss show more activity in the ipsilateral hemisphere upon hearing stimuli in the intact ear, suggesting some type of plasticity in brain functioning (e.g. (Burton et al., 2012) who presented noise-like random spectrogram sounds to left or right ear unilateral deaf patients who had developed profound hearing loss after birth, most often diagnosed after language development. Subjects performed an fMRI odd-ball task in which they had to press a button when hearing a deviant stimulus). In normally hearing participants, the contralateral hemisphere is stimulated more than the ipsilateral when auditory stimuli are presented unilaterally, in line with the typical dominance of crossed projections over uncrossed. In patients with unilateral hearing loss, however, the ipsilateral projections seem to gain importance. The difference is not always found, however (e.g., in an EEG study by Hine et al. (2008), with tone and noise stimuli while subjects watched a silent movie), raising questions about the magnitude and practical importance of the finding. Jensen et al. (1989) in addition proposed the right-ear advantage hypothesis, according to which unilateral left ear deafness would have less detrimental effects on cognitive performance than unilateral right ear deafness, because in the former case the contralateral connections to the language dominant hemisphere are still intact. Their conclusion was based on better recognition of interrupted speech in background noise for left ear compared to right ear hearing impaired children.

Two factors are likely to have an effect on the laterality findings in patients with sensory deficits. First, it can be expected that the effects will be larger in patients with *congenital deprivation* than in patients who acquired sensory deprivation later in life. For instance, Gordon et al. (2013) argued that congenitally deaf children better get bilateral cochlear implants, because a unilateral implant may cause permanent reorganization of the brain. They presented evidence from an EEG study measuring cortical activity during tone listening that unilateral implants may overactivate the contralateral hemisphere due to the lack of inhibition from the deaf ear. So, whereas later acquired unilateral deafness seems to result in strengthening the ipsilateral pathway (Burton et al., 2012), congenital unilateral deafness may lead to overexcitation of the contralateral pathway. The second factor that is likely to have an effect is the degree of hearing loss. One can optimize the clarity of the findings about lateralization in patients with sensory deprivation by limiting the study to participants with *profound unilateral hearing loss* (at least with respect to speech-related stimuli, so that no verbal input enters the brain via the affected ear).

One study followed the above two criteria (Adorni et al., 2013). An additional appeal of the study was that it investigated language lateralization rather than responses to low-level auditory stimuli. Reading lateralization was examined in a 31-year old female patient, RA, who was congenitally deaf in the right ear. She performed a letter detection task while event-related potentials were recorded. By comparing the N170 to words and non-orthographic control stimuli, Adorni et al. (2013) concluded that the visual word form area in this patient was situated in the right hemisphere, and not in the left hemisphere as seen in all the control participants tested with the same paradigm. Whereas the normalized hemispheric difference lateralization index based on the amplitudes of temporal occipital electrodes was $+0.33$ for the control participants, it was -0.47 for RA. Adorni et al. ventured that the atypically lateralized vOT might be due to the fact that auditory word processing in the patient is also lateralized to the right hemisphere, as a result of the congenital lack of input from the right ear. However, the authors did not test the laterality of auditory word recognition in RA and one should be careful not to draw strong conclusions on the basis of a single case study. Finding a higher chance of developing an atypical dominance for speech production, reading and auditory perception in a larger sample without input from the right ear would question a strong genetic origin of language dominance and would also provide further evidence for the warning that the complete absence of input from one ear may increase the strength of the contralateral pathway of the other ear (Gordon et al., 2013).

To investigate the issue properly, we searched for a reasonably large group of persons with profound, congenital, unilateral hearing loss in the right ear, and compared them to a control group. We also tested all three main language functions: speech production, speech perception, and word reading. Finally, we used paradigms that have shown a robust left hemispheric dominance in previous studies. These were a word generation task for speech production (Van der Haegen et al., 2011), an auditory semantic decision task to evaluate speech perception (Thierry et al., 2003), and a passive reading task to test reading lateralization (Cohen et al., 2002). We used fMRI paradigms to give us detailed spatial information.

2. Method

2.1. Participants

Participants' inclusion criteria were the presence of a congenital profound unilateral right-sided hearing impairment, and age between 18–70 y. Exclusion criteria were any significant neurological or psychiatric disorder, the presence of left-sided hearing impairment, and contraindications for fMRI testing. Seven patients were willing to take part in the study. This size is sufficient to test the strong claim made by Adorni et al. (2013) and also to find clinically meaningful increases in the probability of atypical brain dominance. The prevalence of newborns with congenital unilateral hearing loss is estimated to be 2–4 per 1000 in the US (White, 2004). Since 1998 standard, universal, neonatal hearing screening has been implemented in Flanders. Demographic data and etiology of the patients' deafness can be found in Table 1. Seven control participants matched on sex, age and education level (i.e. having a degree in higher education or not) were added for comparison purpose.

For each participant we assessed their lateral preferences index for handedness (Edinburgh Handedness Inventory), footedness and eyedness (Oldfield, 1971). Indices were calculated as (RH − LH/RH + LH)*100. All participants were right-handed, reducing the a priori chances of right hemisphere language dominance to less than 5% per participant (Knecht et al., 2000; Loring et al., 1990). In addition, performance of handedness was measured by a finger tapping task, in which participants had to press a button as many times as possible within 10 s. Five blocks were tested for each hand, starting with the index finger of their dominant hand. They were asked