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Review article

# Listening with one hemisphere: A review of auditory processing among individuals after hemispheric surgery

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ABSTRACT

The human auditory system consists of both peripheral and central components, both of which play a role but contribute distinctly to overall auditory functioning and can be differentially impacted by pathophysiologic states. Hemispheric surgery (HS), a procedure used for the treatment of drug-resistant epilepsy, involves complete disconnection of the auditory cortex in the operative hemisphere, leaving hearing acuity (peripheral function) intact but having heavy implications for auditory processing (central function). The literature describing pre- and post-operative auditory processing abilities of individuals who have undergone HS is sparse, but the research available provides evidence that several central auditory processes including auditory spatial analysis and temporal processing may be impacted. Deficits noted in standardized testing within the clinical or research environment have concrete functional impacts that may be currently under-appreciated and could lead to under-utilization of appropriate therapeutic strategies and accommodations. This review describes the profile of central auditory processing abilities in patients who have undergone HS by synthesizing available literature and incorporating research in other clinical populations to help fill critical gaps in our understanding of how cerebral disconnection impacts the central auditory system.

## 1. Introduction

The human auditory system consists of two distinct components, the peripheral and the central auditory systems. These two portions of the auditory system function jointly but involve different structures and make unique contributions to the physiological and neural processes underlying hearing and auditory processing. The peripheral auditory system consists of the outer, middle and inner ear and is responsible for hearing in its earliest perceptual phases; that is, transmitting sound from the environment to the cochlea via mechanical energy. Damage or disruption to the functioning of these structures from infections, aging, or noise exposure can impede transmission of auditory information and result in hearing loss. On the other hand, the central auditory nervous system (CANS) consists of the nerves and pathways that course from the auditory nerve to the auditory cortex in the temporal lobe. The CANS is responsible for auditory processing, a complex neural process that integrates and interprets the temporal, spectral, and spatial information from an acoustic signal. Fine-tuned processing of this information is required for recognizing crucial sounds in the environment like a car horn and the direction the sound is coming from. Central auditory processing also allows us to focus attention on a particular sound despite competition from other sounds, and to understand speech in a noisy environment. Normal functioning of the CANS is critical to a variety of everyday functions, and it is not difficult to imagine the detrimental impact that deficits in auditory processing may have on safety, social interaction, and academic and occupational success. Damage or disruption to the CANS can result from focal neurological lesions like stroke and auditory processing deficits are well-documented in these individuals (Bamiou et al., 2006; Elias et al., 2014; Jafari et al., 2016; Koohi et al., 2020).

Despite its clear importance to everyday functioning, auditory processing has been decidedly under-investigated in individuals who have undergone hemispheric surgery (HS), involving the complete resection or disconnection of a cerebral hemisphere for the treatment of drug-

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resistant epilepsy. This procedure is associated with seizure freedom rates from 50 to 90% (Moosa et al., 2013; Schramm et al., 2012; Weil et al., 2021), improving quality of life (Griffiths et al., 2007; Ozanne et al., 2016; Schramm et al., 2012), and preventing further deleterious effects of seizures on neurodevelopmental and neurocognitive outcomes (Gavrilovic et al., 2019; Moosa et al., 2013b; Samargia and Kimberley, 2009); however, resection or disconnection of a cerebral hemisphere has inevitable sensorimotor consequences. Deficits in the visual and motor domains are well-described following HS (Devlin et al., 2003; Jonas et al., 2004; Moosa et al., 2013b), and attention has also been directed to linguistic and cognitive outcomes (Curtiss et al., 2001; Puka et al., 2021; Pulsifer et al., 2004), but studies of auditory processing remain relatively underrepresented in this population. Given the drastic anatomic impact of HS, it is likely that auditory processing is affected. Inconsistent documentation of auditory processing abilities in this population may lead to underestimation of its prevalence and underappreciation of its functional impact.

In this review, we discuss the anatomic impact of HS on the auditory system, synthesize existing literature describing central auditory processing abilities in individuals who have undergone HS, and describe the significance of potential deficits on day-to-day functioning in social, academic, and occupational settings. Throughout the manuscript we carefully integrate investigations of auditory processing in temporal lobe epilepsy (TLE), stroke, and corpus callosotomy (CC) to fill gaps in the HS literature and provide further support for the likelihood of auditory processing deficits in the HS population. We additionally highlight the challenges associated with assessment of auditory processing in individuals who have undergone HS and, in acknowledgement of these barriers, attempt to contextualize the findings of prior research in terms of their functional manifestations. In doing so, we aim to provide suggestions for both formal assessment and subjective observation of suspected auditory processing deficits. We conclude by discussing accommodations and modifications that can be made to compensate for auditory processing deficits and minimize their impact on overall neurocognitive functioning. The overarching goal of this review is to serve as a resource establishing the likelihood of auditory processing deficits, and their functional impacts, in individuals who have undergone HS, thereby promoting closer surveillance and further investigation of auditory processing in this population.

## 2. Challenges and limitations in assessment of auditory processing in HS

A major theme of this review is the scarcity of research contributing to our knowledge of auditory processing after HS. Given gaps in the literature specifically related to this population, we additionally incorporate findings from other epilepsy and epilepsy surgery populations throughout this review (Table 1). While these populations differ in key ways from patients who undergo HS, the results of these studies nonetheless contribute to our understanding of how focal lesion to or partial disruption of the CANS impacts auditory processing. The paucity of research on auditory processing in patients who undergo HS is not

**Table 1**
Summary table of included studies, patient populations, and characteristics.

| Study | Year | Patients, n | Surgical Procedure, n | Age at Surgery, y Mean (Range) | Age at Study, y Mean (Range) |
|---|---|---|---|---|---|
| Amaral et al. | 2014 | 13 | NA, epilepsy study | NA | 11.6 (9.6–14.1) |
| Aravindkumar et al. | 2012 | 26 | NA, epilepsy study | NA | 28.4 (UNK) |
| Báez-Martin et al. | 2014 | 27 | TL | 33.9 (UNK) | 35.9 (UNK) |
| Bamiou et al. | 2006 | 8 | NA, lesion study | NA | 63 (36–79) |
| Baran et al. | 1986 | 8 | Anterior callosotomy, 8 | UNK (20–41) | UNK (20–41) |
| Bellmann et al. | 2001 | 2 | Hemispherectomy | 33 (32–34) | 35 (34–36) |
| Bellmann et al. | 2001b | 4 | NA, lesion study | NA | 54.5 (40–64) |
| Boatman et al. | 2003 | 2 | Hemidecorticectomy | 9 | 10.5 (10–11) |
| Boatman et al. | 2006 | 11 | TL | 31.1 (17–43) | 31.1 (17–43) |
| Bougeard & Fischer | 2002 | 14 | TL | 36.6 (26–52) | 36.6 (26–52) |
| Collard et al. | 1986 | 30 | TL | 23.2 (11.8–30) | 23.2 (11.8–30) |
| Corballis & Ogden | 1988 | 5 | Commissurotomy, 3<br>Hemispherectomy, 2 | 18 (13–30) | 40.4 (34–54) |
| Curry | 1968 | 1 | Hemispherectomy | 8 | 21 |
| De Bode et al. | 2007 | 14 | Hemispherectomy/otomy | 6.42 (1.5–12) | 12.5 (10–22) |
| Efron et al. | 1977 | 3 | Commissurotomy | UNK | 25.3 (11–42) |
| Efron et al. | 1985 | 22 | TL | UNK | 30.3 (19–44) |
| Freeman & Boatman | 2007 | 1 | Hemispherectomy | 7 | 8 |
| Han et al. | 2015 | 22 | TL | 40.4 | 40.4 (16–62) |
| Hausmann et al. | 2005 | 6 | Hemispherectomy, 3 | 6.0 (0.92–9) | 41.3 (36–45) |
| | | | Callosotomy, 2 | 28 (26–30) | 42 (40–44) |
| | | | NA, lesion, 1 | NA | 37 |
| Hurley et al. | 2011 | 1 | Hemispherotomy | 9 | 10 |
| Jafari et al. | 2016 | 45 | NA, lesion study | NA | 52.3 (36–68) |
| Lavasani et al. | 2016 | 25 | NA, epilepsy study | NA | 31.1 (20–50) |
| Lessard et al. | 1999 | 3 | Hemispherectomy | 10.7 (8–16) | 23.3 (16–35) |
| Lessard et al. | 2000 | 3 | Hemispherectomy | 10.7 (8–16) | 23.3 (16–35) |
| Liasis et al. | 2003 | 17 | Hemispherectomy | 9.9 (0.4–15.4) | 14.2 (6.8–19.5) |
| Martin & Trauner | 2019 | 21 | NA, lesion study | NA | UNK (6–16) |
| Meneguello et al. | 2006 | 8 | NA, epilepsy study | NA | 36.4 (22–51) |
| Musiek et al. | 1985 | 1 | Two-stage callosotomy | 22 | 22 |
| Nagle et al. | 2013 | 1 | TL | 18 | 18–20[b] |
| Nebes & Nashold | 1980 | 3 | Hemispherectomy | 9.3 (6–15) | 20.3 (14–30) |
| Netley | 1972 | 12 | Hemispherectomy | 10.6 (UNK) | 14.4 (UNK) |
| Poirier et al. | 1994 | 3 | Hemispherectomy | 10.7 (8–16) | 21.3 (14–33) |
| Tong et al. | 2009 | 6 | Hemispherectomy | 11.5 (7–21) | 29.3 (25–38) |
| Wale & Geffen | 1986 | 1 | Hemispherectomy, 1 | 7, 9[b] | 24 |
| Wester et al. | 1991 | 1 | Hemispherectomy | 14 | 18 |
| Yao et al. | 2013 | 8 | Hemispherectomy | 11.6 (7–21) | 32.1(27–40) |
| Zatorre et al. | 1995 | 6 | Hemispherectomy | 18.6 (13–25) | 27 (18–41) |

NA = not applicable; TL = temporal lobectomy; UNK = unknown.
[b]Single patient at different timepoints.

without good reason. There are several factors that present challenges to assessment of auditory processing abilities in this population, which we review to provide an understanding of the complexities of this research question.

One of the largest barriers to pre-operative and immediate post-operative assessment of auditory processing in pediatric patients is the age at surgery. Many children who undergo HS develop seizures shortly after birth and prompt surgical intervention before the first year of life. Most tests of auditory processing are only appropriate for children roughly 7 years of age or older (Chermak et al., 2017). This not only limits pre-operative assessments but also means that a child who undergoes HS, for example, at the age of 4 months may not be assessed for auditory processing deficits for years following surgery. This effect can be appreciated in Table 1, demonstrating that many studies published on individuals who underwent HS in childhood report findings years to decades following surgical intervention and are rarely conducted pre-operatively. This makes it difficult to interpret to what degree observed abilities are the product of HS itself versus other variables such as pre-existing deficits, functional reorganization, or development of compensatory strategies.

A second factor that has limited assessment of auditory processing in this population is the presence of other neurocognitive disorders. Individuals who undergo HS often present pre- and post-operatively with impairments in cognitive functioning (Bajer et al., 2020; Puka et al., 2021; van Schooneveld et al., 2016) and expressive/receptive language (De Bode and Curtiss, 2000; Harford et al., 2023), which may complicate assessment of auditory processing skills and/or confound results. While cognitive disorders are not necessarily the root of central auditory processing deficits, they frequently co-occur and may even be associated with one another (Chermak et al., 2017; Tomlin et al., 2015). Though assessments of auditory functioning exist that require no response (e.g., auditory brainstem responses, auditory evoked potentials) or simple responses (e.g., pointing to the source of a sound), many other assessments require complex verbal responses and place a high cognitive load on working memory and attention. Given the high prevalence of cognitive disorders in this population, many "standard" auditory processing assessments may not be feasible.

A final consideration in understanding the state of available literature and interpreting its results is the diversity of the population being studied. Individuals who undergo HS share a history of high seizure burden and, of course, have the surgical procedure itself in common, but present with a variety of underlying diagnoses. These include 1) congenital etiologies such (e.g., hemimegalencephaly) that produce diffuse pathology throughout the entire cerebral hemisphere, 2) acquired etiologies such as middle cerebral artery stroke that cause widespread damage to the temporal, parietal, and sometimes frontal lobes of the brain, and 3) progressive etiologies like Rasmussen's encephalitis which causes diffuse inflammation in a cerebral hemisphere but is generally preceded by typical development. Differences in etiology are associated with a wide range of both pre- and post-operative developmental levels and cognitive functioning (Jonas et al., 2004; Moosa et al., 2013b; Pulsifer et al., 2004; van Schooneveld et al., 2016). Though we expect that HS itself impacts auditory processing by nature of its anatomic disruption to auditory pathways, interpretation of results should take into consideration the possibility that etiology also contributes to findings.

## 3. Surgery and anatomic impact on the central auditory nervous system

Hemispheric surgery techniques have changed considerably from their origins in the 20th century to currently used approaches. The first documented HS was performed by Walter Dandy (1928) for invasive glioma. Its earliest applications for seizure control were published by KG McKenzie (1938) in a single patient with epilepsy and by Rowland Krynauw (1950) for infantile hemiplegia. These initial approaches involved complete removal of a cerebral hemisphere, or what is now commonly referred to as "anatomic hemispherectomy." Rasmussen (1983) provided the first technical description of a "subtotal hemispherectomy" involving complete functional disconnection of the cerebral hemispheres without complete anatomical resection. Modifications of this technique have been published by several groups over the years to develop a surgical approach that is less invasive and associated with fewer complications, while still achieving acceptable seizure control (Cook et al., 2004; Delalande et al., 2007; Schramm et al., 2001; Villemure and Mascott, 1995). Techniques such as these that involve complete functional disconnection paired with smaller cortical resections are often referred to as "hemispherotomy."

Regardless of the surgical approach, HS invariably has an anatomic impact on the human auditory pathway (Fig. 1). In the case of anatomical hemispherectomy the entire cerebral hemisphere is resected and several functional hemispherotomy techniques involve selective resection of tissue in the affected hemisphere including the auditory cortex and mesial temporal structures (i.e., the amygdala and hippocampus) (Fig. 1B). Even techniques that spare the auditory cortex structurally involve complete disconnection of the temporal lobe from the insular cortex, mesial temporal structures, and subcortical structures including the thalamus (Fig. 1C). Roughly 70% of fibers in the auditory pathway decussate at the level of the brainstem, resulting in dominance of this crossed pathway in transmission of information to the contralateral auditory cortex (Mangold and M Das, 2023; Paiement et al., 2008). As will be discussed in the following sections, performance on auditory processing tasks is thus predictably worse when stimuli are presented on the side contralateral to surgery. However, HS impacts both contra- and ipsilateral input by disrupting the pathway at the level between the medial geniculate body and the auditory cortex. Across techniques hemispheric surgery also involves complete corpus callosotomy (severing of the genu, body, and splenium), thereby interrupting interhemispheric transmission of auditory information. While the anterior commissure (AC), another interhemispheric pathway, is not typically disconnected, support for a major role of the AC in the transfer of auditory information remains tepid (Bamiou et al., 2007).

## 4. Impact of hemispheric surgery on auditory processing

When discussing the functional impact of HS on the auditory system, it is important to return to the distinction between peripheral and central components of the auditory system. The peripheral auditory structures are not directly involved in the HS surgical techniques; therefore, the unilateral resection or disconnection of the auditory cortex in HS is not expected to impact hearing at the level of the peripheral auditory system. As such, studies have found that pure tone auditory thresholds are typically symmetric and within normal limits bilaterally following HS (Boatman et al., 2003; Curry, 1968; De Bode et al., 2007; Hausmann et al., 2005; Hurley et al., 2011; Lessard et al., 1999, 2000; Liasis et al., 2003; Poirier et al., 1994; Wester et al., 1991; Yao et al., 2013). It is possible that a person selected for HS may present with a pre-existing hearing loss, which could impact assessment of auditory processing (American Academy of Audiology, 2010); however, these cases extend beyond the consideration of the impact of the surgical procedure itself. The central auditory system, however, is directly impacted by HS at a structural level, introducing the possibility that its function may be disrupted as well. The following sections review existing research on auditory processing abilities in individuals who have undergone HS, organized according to discrete domains assessed in the literature (see Table 2). We draw on studies conducted with other populations to strengthen evidence of the impact of both epilepsy and structural lesions on the functioning of the central auditory system. We contextualize abnormal assessment findings in each of these domains according to their functional manifestation and impact.

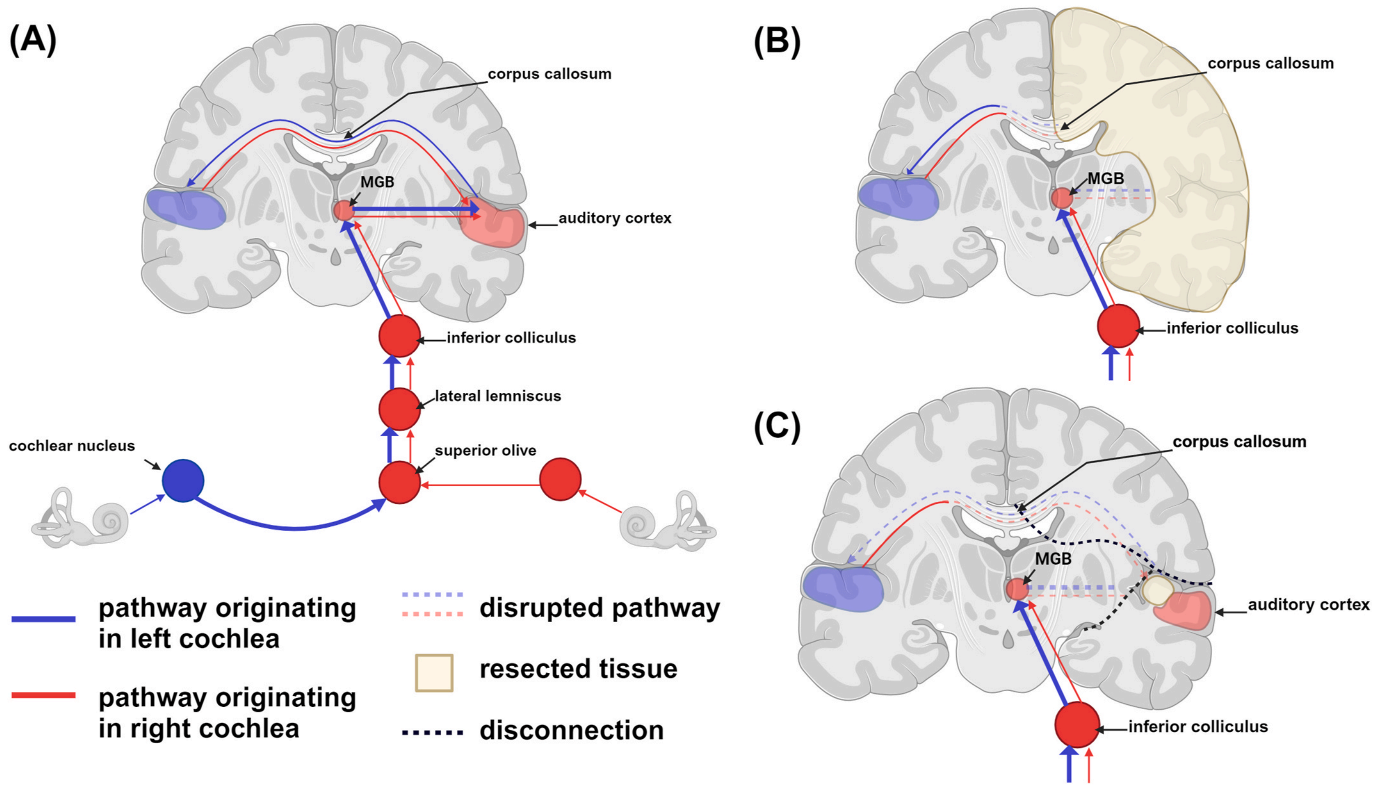


**Fig. 1.** The ascending auditory pathway depicting dominant contralateral (blue) and ipsilateral (red) input to the right auditory cortex (A) in it's typical organization. (B) Right anatomical hemispherectomy involving resection of the right hemisphere (yellow) including the mesial temporal lobe, and severance of the interhemispheric pathway to the auditory cortex. (C) A functional disconnection technique resulting in subtotal resection of the right auditory cortex but disruption of ipsi -and contralateral ascending pathways between the medical geniculate body (MGB) and cortex, and interhemispheric pathways.

### 4.1. Auditory brainstem responses (ABRs)

Portions of the CANS are anatomically preserved during HS including the auditory nerve and the pathways that ascend through a series of nuclei organized in the brainstem. Electrophysiological assessments such as auditory brainstem response (ABR) measure the activity in these lower-level central pathways and are reflective of hearing sensitivity as a function of the central auditory nervous system. In other words, though ABR tests central auditory structures, it tests earlier levels of auditory processing rather than central auditory processing *per se*. The few studies that have investigated ABRs in HS patients have found responses elicited bilaterally (Yao et al., 2013) that typically fall within normal limits (Boatman et al., 2003; Hurley et al., 2011). ABR testing was documented as normal both pre- and post-operatively in the study by Boatman et al. (2003). One notable exception to this pattern comes from Yao et al. (2013), who found significantly increased latencies for Waves III and V in ABR testing of patients 10 years post-anatomical hemispherectomy versus healthy controls. Increased latency was only found for stimulation of the ear contralateral to surgery. The authors suggest that these findings may be explained by long-term degeneration of contralateral auditory pathways following HS. Notably, assessments of ABRs in other studies were conducted at only 1–2 years post-surgically. While hemispheric surgery itself does not impact the auditory system at the level of the brainstem, reorganization and degeneration of pathways as suggested by Yao et al. (2013) may nonetheless occur in the long-term and impact ABR measurements. Future neuroimaging and electrophysiological studies that assess auditory pathways beyond 1–2 years post-HS may be helpful in determining if surgery is associated with long-term changes in the central auditory system at the subcortical level.

### 4.2. Auditory spatial analysis

Sound localization and lateralization refer to a listener's ability to analyze determine interaural differences in time and intensity cues to determine the source of an auditory stimulus either in the external sound field (localization) or when simulated and presented through headphones (lateralization). In addition to explicitly identifying the origin of a sound, auditory spatial cues also allow listeners to "pick out" or discriminate individual sounds in auditory scene analysis (Bregman, 1994; also referred to as "sound object segregation" Thiran and Clarke, 2003). These abilities are primarily subserved by the dominant contralateral pathways which transmit sound from one ear to the opposite auditory cortex; however, the ability to detect discrete interaural differences depends on the joint function of both ipsilateral and contralateral pathways.

Sound localization and lateralization in individuals who have undergone HS are worse than healthy controls, particularly when stimuli are presented in the hemifield contralateral to the operative hemisphere (Bellmann et al., 2001; Hausmann et al., 2005; Lessard et al., 1999, 2000; Poirier et al., 1994; Zatorre et al., 1995). The ability to accurately identify sound sources is impacted across a variety of auditory stimulus categories including environmental sounds (Bellmann et al., 2001a), pure tones (Hausmann et al., 2005), clicks (Zatorre et al., 1995), and noise (Lessard et al., 1999, 2000; Poirier et al., 1994). While individuals who have undergone HS may retain some localization ability by effectively utilizing monaural cues, accuracy tends to decrease with increased task complexity such as assessing auditory motion and making fine-tuned analyses about sound source (Lessard et al., 1999, 2000; Poirier et al., 1994; Zatorre et al., 1995). Findings of impaired localization abilities were observed in one study of patients decades following their procedure in childhood (Hausmann et al., 2005), indicating that these deficits may persist rather than resolve over time. Furthermore,

**Table 2**
Summary of existing auditory processing findings in hemispheric surgery and functional impacts.

| Domain | Key Findings | Citations | Potential Functional Impact of Deficit |
|---|---|---|---|
| Auditory Agnosia | No prior investigations | | Difficulty recognizing, naming, and differentiating sounds |
| Auditory Brainstem Responses | Typically within normal limits | Boatman et al. (2003)<br>Hurley et al. (2011)<br>Yao et al. (2013) | |
| Auditory Closure | Speech recognition in quiet within normal limits<br>Speech recognition in noise, multispeaker babble, or in context of a filter is impaired | Boatman et al. (2003)<br>Hurley et al. (2011) | Difficulty understanding speech in noisy environments<br>Difficulty "filling in" information when speech is not clear<br>Difficulty processing and following directions<br>Tendency to become distracted in noisy environments |
| Auditory Neglect | No prior investigations | | Inattention to sounds coming from the hemifield contralateral to surgery<br>Misidentification of sounds as coming from the opposite side of their true origin (i.e., alloacusis). |
| Dichotic Listening | Performance is worse in ear contralateral to surgery; responses may be extinct<br>Performance may be impaired in ipsilateral ear | Boatman et al. (2003)<br>Corballis and Ogden (1988)<br>Curry (1968) De Bode et al., 2007<br>Freeman and Boatman (2007)<br>Hurley et al. (2011)<br>Nebes and Nashold (1980)<br>Netley (1972)<br>Wale and Geffen (1986)<br>Wester et al. (1991) | Establishing pre-operative ear dominance can assist in documenting language laterality<br>Comparing pre- to post-operative performance can assist in documenting reorganization |
| Hearing (Peripheral) | Pure tone thresholds typically within normal limits<br>Pre-existing HL may be evident in some patients | Boatman et al. (2003)<br>Curry (1968)<br>De Bode et al., 2007<br>Hausmann et al. (2005)<br>Hurley et al. (2011)<br>Lessard et al. (1999), 2000<br>Liasis et al. (2003)<br>Poirier et al. (1994)<br>Wester et al. (1991)<br>Yao et al. (2013) | Pre-existing HL may complicate assessment of auditory processing<br>Pre-existing HL has its own considerations[a] |
| Hyperacusis | No prior investigations | | Difficulty tolerating environments with moderate-to-high noise levels<br>Increased sensitivity to sound in general, or to particular sounds |
| Spatial Analysis | Impaired sound localization and lateralization, especially on side contralateral to surgery<br>Increased difficulty with analyzing moving vs static sound sources | Bellmann et al. (2001)<br>Hausmann et al., 2005<br>Lessard et al. (1999)<br>Lessard et al. (2000)<br>Poirier et al. (1994)<br>Zatorre et al. (1995) | Difficulty finding the source of a sound<br>Difficulty identifying from which direction a sound originated<br>Difficulty tracking a moving sound<br>Difficulty isolating one specific sound out of many in an environment with competing noise |
| Temporal Processing | Performance within normal limits on frequency pattern, duration pattern, and gap detection tasks[±] | Boatman et al. (2003)<br>Hurley et al. (2011) | Impaired phonological processing<br>Difficulty with speech perception<br>Difficulty with language comprehension<br>May be correlated with impaired reading performance |

HL = hearing loss.
[a] These considerations are critical but go beyond the scope of this review.

there is evidence that perceptual and attentional vision deficits may impact processing of auditory spatial cues (Kerkhoff et al., 1999). Homonymous hemianopia is a consequence of HS, therefore the impact of surgery on the visual system alone may produce auditory localization impairments. That said, there is variability at an individual level in terms of the degree of impairment observed. Milder impairment may be associated with more typical fMRI activation patterns within and in extended auditory networks (Bellmann et al., 2001a) and could represent the development of compensatory strategies or functional reorganization of pathways (Lessard et al., 1999, 2000; Poirier et al., 1994; Zatorre et al., 1995).

The ways in which impairments in analyzing auditory spatial cues may manifest in day-to-day functioning have concrete implications for personal well-being as well as social and academic functioning. Findings of impaired sound localization are not merely significant in the context of research results but are noticeable and have been self-reported in everyday activities after stroke (Bamiou et al., 2012; Koohi et al., 2017). Research has suggested that processing of sound source and motion may be especially difficult in dynamic auditory environments with competing sound sources. Translating these findings outside the controlled research environment, ineffective use or processing of auditory spatial cues may result in impaired ability to identify approaching traffic as a pedestrian or to find a parent calling to them at a busy playground. Prior evidence demonstrating decreased localization ability with presentation of sounds in extreme lateral hemifields and on the side contralateral to the disconnected hemisphere suggests that individuals who undergo HS may have increased success in social, academic, or occupational settings when conversation partners or other crucial sources of sound are positioned more centrally. Identification and consideration of potential impairments in sound localization is therefore helpful in determining simple environmental modifications that may compensate for this impairment and increase participation in a variety of contexts.

### 4.3. Dichotic listening

Dichotic listening is a task employed in experiments to study laterality within the auditory system, specifically in speech processing. In these tasks, participants are simultaneously presented with different auditory stimuli in each ear and are asked to report back one or both stimuli (see Supplementary Table 1 for description of stimuli and paradigms used across studies). For most listeners, the left hemisphere specialization for language combined with dominance of the contralateral auditory pathway leads to a right ear advantage for speech stimuli (Della Penna et al., 2007; Kimura, 1961, 1967) and a left ear advantage for non-speech stimuli (Bamiou et al., 2007). This does not imply that listeners cannot complete dichotic speech perception via the left ear and associated auditory pathways, but rather that interhemispheric transfer of auditory information via commissural fibers to the language dominant hemisphere is crucial. The structural disturbance of HS on both dominant contralateral and interhemispheric auditory pathways clearly presents the possibility that dichotic listening performance will be impacted.

As with sound localization, dichotic listening performance in patients who have undergone HS is worse for stimuli presented to the ear contralateral to the operated hemisphere (Corballis and Ogden, 1988; Hurley et al., 2011; Nebes and Nashold, 1980; Netley, 1972), often with near extinction of responses (Boatman et al., 2003; Curry, 1968; De Bode et al., 2007; Freeman and Boatman, 2007; Wale and Geffen, 1986; Wester et al., 1991). Studies that have compared patient participants to neurotypical control subjects have found varying degrees of impairment even in the ear contralateral to the remaining hemisphere. De Bode et al., 2007 found that performance was significantly worse than expectations for children, while other studies have found highly accurate (>95%) performance (Corballis and Ogden, 1988; Nebes and Nashold, 1980). Interhemispheric communication appears to be important specifically for dichotic speech perception; therefore, dichotic presentation of environmental sounds or pure tones may not reveal a deficit (Efron et al., 1977). This differential impairment for speech versus non-speech stimuli was observed in a study of a right hemispherectomized subject by Curry (1968) but was contradicted in a study by Freeman and Boatman (2007), who identified extinction of contralateral dichotic listening responses for both speech and environmental sounds. Variability in results may be associated with etiology, age at seizure onset, or which hemisphere is affected though no single variable has been identified as correlating with overall performance on dichotic listening tasks (Corballis and Ogden, 1988; De Bode et al., 2007; Netley, 1972).

Though dichotic listening is, in and of itself, a research method that doesn't have a direct practical correlate, it is nonetheless useful in illustrating the impact of HS on the auditory system and determining language lateralization. Comparison of dichotic listening results in HS patients versus other patient populations with lesion or pathology of the CANS reveals key differences that may better our understanding of auditory functioning and language network organization in this population. Studies in patients who have undergone temporal lobectomy indicate that dichotic listening performance may be impaired relative to healthy controls, but that there is little change pre-to post-resection of the temporal lobe (Collard et al., 1986; Han et al., 2016). These findings argue for the possibility that individuals with epilepsy impacting the temporal lobe, as is the case with the diffuse epileptic activity evident in patients who undergo HS, may present with abnormalities in auditory processing even prior to any surgical intervention (Meneguello et al., 2006). However, the lack of change pre-to post-resection change versus the post-operative deterioration noted in HS patients (Boatman et al., 2003) underscores the fact that HS may further impair already abnormal auditory processing abilities. Dichotic listening performance also highlights the importance of interhemispheric auditory pathways, namely the corpus callosum which is the largest set of fibers connecting the two cerebral hemispheres and is thought to play a critical role in the transmission of auditory information (see Musiek and Weihing, 2011; Bamiou et al., 2007 for a review). Severance of this pathway, completed in both corpus callosotomy and HS, eliminates the pathway for auditory information presented to the left ear to cross from the right hemisphere back to the language-dominant left hemisphere. Patients who have undergone complete corpus callosotomy demonstrate a predictable amplification of the left ear deficit and right ear advantage for dichotic speech perception (Corballis and Ogden, 1988; Efron et al., 1977; Musiek et al., 1985). In contrast, the ear advantage demonstrated by HS patients depends on the hemisphere operated on and may point to atypical organization of language networks in this population. Establishing laterality of the language network is relevant when considering the anticipated impact of HS on language outcomes if resection or disconnection is completed on the language-dominant hemisphere.

### 4.4. Auditory neglect

It may be questioned whether the basis of deficits observed in auditory spatial and dichotic listening tasks a perceptual consequence of structural disruption to the auditory pathways, or attentional in nature and indicative of auditory neglect. There are currently no published investigations of auditory neglect in the HS population, though hemispatial neglect has been documented as a rare finding in children who have undergone HS (Marsh et al., 2009). Hemispatial neglect has received more attention in the literature than auditory neglect though there is an argument for neglect being multisensory in nature (Gutschalk and Dykstra, 2015), meaning that neglect in visual, sensory, and auditory modalities may co-occur.

Some studies use dichotic listening and/or localization tasks as direct measures of auditory neglect. For example, Martin and Trauner (2019) used results of a localization task to suggest that children who experienced left hemisphere perinatal stroke may exhibit contralateral (right) auditory neglect while children who experienced right hemisphere perinatal stroke may exhibit an auditory neglect that is bilateral in nature. Bellmann et al., 2001b pointed out the limitations to interpreting results of these tasks as direct evidence of auditory neglect and attempted to dissociate structural/perceptual from attentional deficits by combining dichotic listening, auditory localization, and a "diotic" task, which resembles dichotic listening but presents both stimuli to both ears and simulates spatial cues through interaural time differences. Their studies revealed evidence of distinct behavioral manifestations of auditory neglect; spatial inattention in patients with subcortical lesions and deficient spatial representations in patients with cortical lesions (Bellmann et al., 2001b; Thiran and Clarke, 2003). Replication of these methods in individuals who have undergone HS may be informative in establishing the prevalence of auditory neglect in this population.

Typical behavioral assessments of sound localization and dichotic listening do not allow for identification of the basis of impairments, which could make detection of auditory neglect difficult. In the clinical or research environment, parsing out the difference between sound localization impairments and true auditory neglect likely requires the level of granularity employed in the Bellmann and Clarke studies. The functional manifestations of auditory neglect may present as an inability to detect a sound coming from the affected hemifield in environments with competing sound sources or as incorrectly localizing the source of a sound to the opposite side from which it was presented (i.e., alloacusis).

### 4.5. Temporal processing

Temporal processing refers to the ability to perceive and analyze auditory information over time (Shinn, 2003). It is frequently measured using established tests like the Duration Pattern Test (Musiek et al., 1990), Frequency/Pitch Pattern Test (Musiek and Pinheiro, 1987), and Gaps-in-Noise Test (Musiek et al., 2005) which require the listener to perceive, integrate, and make judgements about acoustic information over time.

The few studies that have specifically tested temporal processing in children who have undergone HS found performance within normal limits both pre-operatively (Boatman et al., 2003) and post-operatively (Boatman et al., 2003; Hurley et al., 2011), though these are studies of only 1 to 2 patients. Research conducted with other clinical populations has indicated that temporal processing abnormalities may be evident in individuals with temporal lobe epilepsy (Aravindkumar et al., 2012; Lavasani et al., 2016; Meneguello et al., 2006), middle cerebral artery and insular stroke (Bamiou et al., 2006; Efron et al., 1985), and agenesis of commissural fibers including the corpus callosum and anterior commissure (Bamiou et al., 2007b). While none of these findings can be directly generalized to HS patients, they provide some indication that pathology at various levels of the central auditory processing system potentially impacts the ability to reconcile complex, temporal information contained in auditory signals.

Speech processing is perhaps the most concrete functional correlate of temporal processing, as discrimination of the individual phonemes that comprise words requires this same type of rapid integration and analysis (Amaral et al., 2015). Some researchers have suggested that deficits in temporal processing may result in "abnormal encoding" and "unstable representations" of phonemes leading to difficulties with speech perception and language comprehension in general (Phillips, 1999; Wright et al., 1997).Additionally, several studies have found that performance on temporal processing measures is correlated with performance on phonological processing tasks (Amaral et al., 2015; Zaidan and Baran, 2013) and reading ability (Gokula et al., 2019; Lewandowska et al., 2013; Tomlin et al., 2015). The impact of HS on temporal processing specifically is therefore of critical consideration from a developmental standpoint for patients undergoing surgery in infancy or early childhood. Despite these significant implications for functional and academic outcomes, temporal processing remains largely under-represented in research with HS patients. Further investigation of temporal processing and associated deficits in patients selected for HS will need to further consider the potential role of hemispheric specialization and the cognitive demands placed on participants when interpreting results of assessments and, especially, in reconciling differences observed between specific measures.

### 4.6. Auditory closure/speech-in-noise

Of the many tests utilized in the typical battery for evaluating central auditory processing, perhaps the clearest illustration of the impact deficits in central auditory processing may have on quality of life comes from auditory closure and speech-in-noise (SIN) tasks. Auditory closure is the "ability to integrate auditory stimuli into a whole; i.e., completion of a word or words by filling in the parts omitted" (Nicolosi et al., 1989). Functionally, deficits in auditory closure present as the inability to "fill in the gaps" of a speech signal that is degraded, perceived in competition with noise, or otherwise partially lacking in comprehensibility. Speech in noise tasks tap auditory closure abilities, but with the crucial difference that the speech signal itself is clear whereas other auditory closure tasks may involve the use of filtered, incomplete, or otherwise degraded speech stimuli. A listener with impaired auditory closure may thus have trouble understanding speech in the presence of background noise or over a degraded phone connection.

Research with HS patients suggests that speech recognition and perception in quiet conditions is within normal limits (Boatman et al., 2003) but may be impaired or reduced in the context of background noise or when speech signals are distorted (Boatman et al., 2003; Hurley et al., 2011). It is thought that while the left hemisphere is typically the primary driver of language comprehension, the right hemisphere is instrumental to speech processing in noise (Boatman et al., 2006; Shtyrov et al., 1998). One hypothesis explaining the role of the right hemisphere in speech processing under adverse listening conditions comes from Boatman et al. (2003), who theorize that the language dominant hemisphere completes phonological closure while the non-dominant hemisphere suppresses extraneous noise. In agreement with this idea are findings from a study by Nagle et al. (2013), who documented impaired auditory closure ability in a left hemisphere language-dominant patient following right temporal lobectomy. This effect could be mediated by efferent projections via an inhibitory function performed by the medial olivocochlear (MOC) bundle system in the presence of a steady masker (Kumar and Vanaja, 2004; Muchnik et al., 2004). In a single case study of a patient who had undergone left functional hemispherectomy, Hurley et al. (2011) explicitly tested auditory efferent functioning. They found that, although accuracy with SIN intelligibility was low in the right ear (<50%), introduction of additional white noise in the contralateral (left) ear produced the typical pattern of enhanced performance. The overall better performance noted in this study as compared to the findings of Boatman et al. (2003) may be associated with differences in surgical technique and the extent to which an approach disrupts the auditory efferent system though this has yet to be formally investigated. Regardless of the exact mechanism responsible for dysfunction in auditory closure, it is reasonable to expect that the large-scale impact of HS on afferent and efferent auditory pathways will produce difficulties in this area.

Difficulty perceiving and processing speech in noise has an obvious potential impact on day-to-day functioning. Our everyday surroundings are full of overlapping auditory stimuli including the voices of other people, music, and the noises of vehicles, construction, electronics, and machinery. Nearly everyone has had the frustrating experience of trying to attend to and understand a conversation in a noisy restaurant. Individuals with central auditory processing impairments have increased difficulty filling in information in the auditory signal that is lost to noise or distortion. The behavioral manifestation of deficits in auditory closure may bear out as difficulty following verbal instructions or the tendency to become easily distracted in the classroom (De Wit et al., 2016). While these behavioral observations are not specific to auditory processing disorder and could be the result or combined effect of deficits in attention or cognition more generally, they should raise suspicion for evaluation of auditory processing impairments.

## 5. Functional reorganization

While the literature base examining auditory processing abilities in individuals who have undergone HS is already quite small, we are further limited in our interpretation of results by nature of the fact that most report only post-operative assessments. There are several factors that complicate the feasibility of pre-operative auditory assessment including but not limited to age, ability of participants to engage in traditional assessments, institutional referral practices, and the desire to perform surgery as soon as appropriate. HS inherently involves significant disruption to the central auditory system and undoubtedly impacts auditory processing. On the other hand, the human brain exhibits remarkable plasticity and can compensate for injury through functional pathway reorganization. It is therefore tempting to attribute impairments in auditory processing to the surgical procedure itself and preservation of skills to post-operative reorganization. In the absence of pre-operative behavioral assessment or functional neuroimaging, though, it is difficult to determine precisely how HS impacts auditory processing skills and the networks that subserve them.

Putative functional reorganization of neural pathways has been reported following HS and includes findings of decreased activation of the intact hemisphere to contralateral auditory stimulation (Paiement et al., 2008), as well as increased between (Kliemann et al., 2019) and within-network (Blauwblomme et al., 2019; Ivanova et al., 2017) connectivity in the intact hemisphere. However, there is precedent for the thought that brain networks may be atypically organized in patients with epilepsy (Goldmann and Golby, 2005). Several studies have suggested that continued epileptiform discharges have the potential to alter neural pathways (Amaral et al., 2015; Báez-Martín et al., 2014; Bougeard and Fischer, 2002; Han et al., 2016; Meneguello et al., 2006). Given the especially protracted nature of auditory cortex development

(Eggermont and Moore, 2012; Moore, 2002), it is possible that the disturbance produced by epileptiform activity, or the diffuse hemispheric pathology associated with referral for HS, may lead to atypical auditory system organization even prior to surgical intervention. Patients with non-congenital etiologies who experience rapid seizure onset later in development (e.g., Rasmussen's encephalitis) may provide evidence of verifiable functional reorganization following HS. Several functional MRI and diffusion tensor imaging (DTI) studies have documented atypical organization of auditory pathways and language lateralization in these patients (Hertz-Pannier et al., 2002; Loddenkemper et al., 2003; Meoded et al., 2016; Paiement et al., 2008). Presumed typical development prior to seizure onset, along with short duration between onset and surgical intervention make it less likely that the organization of neural pathways has been substantially altered prior to surgery. The time course of this potential reorganization and its impact on auditory processing over the post-operative period have yet to be determined.

The possibility that HS patients with other epilepsy etiologies may demonstrate atypical auditory pathway development/organization preoperatively can be tentatively examined using the temporal lobe epilepsy literature. Temporal lobe epilepsy (TLE) is a focal form of epilepsy in which seizure foci are localized to temporal lobe structures, including the mesial structures in mesial temporal lobe epilepsy (MTLE). Though pathology and epileptogenic activity is not as diffuse compared to individuals selected for HS, TLE patients nonetheless have a history of epileptic activity involving auditory and auditory adjacent regions and demonstrate auditory processing deficits in dichotic listening (Bougeard and Fischer, 2002; Collard et al., 1986) and temporal processing (Aravindkumar et al., 2012; Lavasani et al., 2016; Meneguello et al., 2006). While some studies have suggested that patients who undergo anterior temporal lobectomy (ATL) do not experience significant decreases in baseline auditory processing deficits (Bougeard and Fischer, 2002; Han et al., 2016), others have found further impairment in auditory processing post-operatively (Báez-Martín et al., 2014; Collard et al., 1986). Comparison with HS is imperfect because ATL typically preserves primary auditory cortex and commissural fibers, though these findings support the idea that auditory pathways in epilepsy patients may be altered from the organization seen in neurotypical development and are not necessarily the consequence of surgical intervention.

The mechanisms that subserve aberrant development of neural pathways and/or functional reorganization following surgery, though relevant, are beyond the scope of this review. Importantly, patterns of connectivity are not necessarily indicative of or correlated with functional performance of the systems those pathways serve (Ivanova et al., 2017). Regardless of the timing or driving force, it is evident that atypical organization of neural pathways is a frequent finding in HS patients. The relatively protracted development of the auditory cortex and its circuitry has led some researchers to suggest that it is therefore more plastic and amenable to reorganization following insult (Chang and Kanold, 2021); this makes both abnormal development and functional reorganization plausible hypotheses. Given inconclusive answers to the atypical development versus reorganization debate, it may be prudent to consider accommodations and modifications related to auditory processing both pre- and post-operatively for children presenting with disease processes frequently targeted by HS.

## 6. Accommodations and environmental modifications

Current evidence suggests that individuals who undergo HS are likely to have impairments in central auditory processing. As discussed throughout this review, central auditory processing makes important contributions to speech comprehension, social participation, literacy, and academic achievement; therefore, HS patients may require accommodations in educational, vocational, or other social environments. Using the school environment as an example, a typical classroom may be chronically noisy enough to hinder the academic performance of children (Shield and Dockrell, 2008), to render some of the teacher's instructions incomprehensible to students (Skarlatos and Manatakis, 2003), and even to permanently damage the hearing of teaching staff (Eysel-Gosepath et al., 2012; Jiang, 1997; Novanta et al., 2020). Given documented difficulty with speech-in-noise recognition and auditory spatial analysis, these effects may be amplified for children with auditory processing deficits. Individualized accommodations mitigating the impact of auditory processing deficits may be critical to academic outcomes. In fact, studies reporting on academic attainment generally find that a large proportion of patients who undergo HS receive academic support services both pre- and postoperatively (Moosa et al., 2013b; Sherlock et al., 2022; van Schooneveld et al., 2016). Though no studies have investigated the effectiveness of specific intervention strategies for auditory processing in HS patients, accommodations and environmental modifications routinely used for individuals with impairments in central auditory processing including simplification of oral instructions, providing areas with reduced noise to complete work, and seating strategies may help to compensate for deficits and improve overall participation (Bellis and Anzalone, 2008). One of the most well-studied intervention techniques for deficits in central auditory processing is the use of frequency-modulated (FM) amplification systems. Both children and adults with auditory processing deficits have shown increased performance on speech-in-noise recognition when using personal FM systems (Johnston et al., 2009; Koohi et al., 2017). There has been preliminary evidence that these systems provide long-term benefit for speech-in-noise recognition (Koohi et al., 2017) and may be associated with improvements in academic performance and self-reported psychosocial measures when used consistently (Johnston et al., 2009).

## 7. Future considerations and conclusions

One of the only statements that can be applied to HS patients as a group is that no singular outcome can be anticipated for every patient. The primary takeaway from existing literature is that, despite undergoing the same surgical procedure, there is a wide spectrum of functioning and outcomes observed both pre- and postoperatively (Devlin et al., 2003; Harford et al., 2023; Jonas et al., 2004; Moosa et al., 2013b; Schramm et al., 2012; van Schooneveld et al., 2016). This observed variation may be dependent upon underlying etiology, duration of epilepsy, age at seizure onset, age at surgery, or a combination of these factors (Curtiss and De Bode, 1999; Devlin et al., 2003; Jonas et al., 2004; Pulsifer et al., 2004). Given the crucial role of interhemispheric communication and binaural integration in central auditory processing, it is reasonable to expect that all patients will experience impairment in this area following HS, though it is currently unknown how patient-specific variables may impact pre-operative auditory functioning and how baseline impairments may be exacerbated by surgery. Research conducted thus far has already demonstrated that variability in performance on auditory processing measures may be evident within a single study sample (Lessard et al., 2000). The degree of impairment documented may additionally vary depending on the specific area of central auditory processing assessed, the type of stimuli used (i.e., speech versus tones), and the cognitive demands of tasks. While existing research on auditory processing in HS patients is not extensive enough to allow the types of correlational analyses that have been performed in research on motor, cognitive, and linguistic outcomes, it stands to reason that similar variability may be expected in auditory abilities as well.

Throughout this review we have provided examples of the functional impact of central auditory processing deficits on areas such as literacy, academic achievement, and social participation. Many patients who undergo HS present with language, literacy, and cognitive deficits that may be independent of (or at least not the direct cause of) auditory processing deficits, though there is likely a complex interaction between all these domains. An important consideration is whether standardized assessments used to measure linguistic or academic performance or to determine qualification for support services, and the environments and manner in which they are administered, adequately account for contributions of auditory processing deficits. Despite the very clear detriment HS may pose to auditory processing, formal audiologic evaluation of central auditory processing does not appear to be standard practice for these patients. In the absence of recognition and documentation of these impairments, patients who undergo HS may not receive appropriate accommodations or interventions that could increase success in academic, social, and vocational contexts. Further research of central auditory processing following and, where possible, prior to HS is critical in establishing a need for the incorporation of audiologic services into common clinical practice. While we have highlighted the difficulties in assessment of auditory processing in this population, we feel strongly that it is needed to fully describe and address disability. There is currently no single, agreed upon battery of standardized tests used to diagnose auditory processing disorders in the United States (American Academy of Audiology, 2010), which presents its own issues but allows for some flexibility in the assessment process. Chermak et al. (2017) have argued for a more individualized approach in which tests are selected based on a combination of patient characteristics including age, specific auditory-related symptoms, and cognitive or linguistic comorbidities. In addition to these factors, teams considering assessment of auditory processing in children who are selected for HS should also consider response modality and any limitations it may introduce to accurate evaluation. For example, teams may consider whether responses are verbal or non-verbal, the linguistic complexity of required responses (e.g., sentences vs words), and whether hemiparesis or spasticity may impact the individual's ability to provide motor responses. For children who present with significant limitations in cognition and language, the evaluation team may also consider the use of questionnaires to assist in describing the functional and socioemotional impact of central auditory processing deficits. While questionnaires lack the specificity to formally diagnose deficits in auditory processing (Chermak et al., 2017), they provide additional information that helps to form a more holistic picture of auditory-related disability.

Perhaps the most resounding theme of this review is the paucity of research addressing auditory processing outcomes in this population. Available research is sparse, typically comprises small sample sizes, and has been conducted over the course of decades. Over this time, our understanding of central auditory processing has increased, standardized assessments have changed, and surgical techniques have evolved. The literature base in its current state has provided us with initial evidence that auditory processing abilities are indeed abnormal in patients who have undergone HS, but it is difficult to generalize across heterogenous methodology and patient samples. Our primary suggestion for future research is further investigation of central auditory processing abilities in patients following HS. We acknowledge the inherent difficulty of single centers procuring large sample sizes, though our hope is that more consistent research in this area will provide a clearer picture of the spectrum of auditory processing deficits observed within this clinical population. Identification of specific impairments in subdomains such as temporal processing, dichotic listening, auditory closure, and auditory spatial analysis may aid in the development of a standard test battery that assesses fine-grained central auditory processing skills. Furthermore, longitudinal prospective research with patients will better our understanding of how auditory processing impairments evolve over time and, importantly, provides us with the opportunity to evaluate functional reorganization within auditory pathways. We also call attention to areas that have yet to be addressed in the literature. Deficits such as auditory neglect (Bellmann et al., 2001b; Martin and Trauner, 2019; Thiran and Clarke, 2003) and auditory agnosia (Clarke et al., 2000, 2002) have been observed in populations with unilateral focal lesion to the temporal lobe but have yet to be explicitly documented in patients who have undergone HS. Future research may also consider the presence of hyperacusis, or increases sensitivity to sound, in this population. There are thus large knowledge gaps remaining in the literature pertaining to auditory processing in patients who undergo HS. Further consistent investigation addressing these questions will be instrumental in understanding how auditory processing is impacted by HS, how these impairments manifest behaviorally and physiologically, and ultimately will assist in formulating intervention strategies to help mitigate the functional impact of auditory processing deficits.

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## CRediT authorship contribution statement

**Emily E. Harford:** Writing – review & editing, Writing – original draft, Conceptualization. **Erin D. Smith:** Writing – review & editing, Writing – original draft, Conceptualization. **Lori L. Holt:** Writing – review & editing, Conceptualization. **Taylor J. Abel:** Writing – review & editing, Conceptualization.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2024.109019.

## Data availability

No data was used for the research described in the article.

## References

Amaral, M.I.R., Casali, R.L., Boscariol, M., Lunardi, L.L., Guerreiro, M.M., Colella-Santos, M.F., 2015. Temporal auditory processing and phonological awareness in children with benign epilepsy with centrotemporal spikes. BioMed Res. Int. 2015, e256340. https://doi.org/10.1155/2015/256340.

American Academy of Audiology, 2010. Diagnosis. Treatment and Management of Children and Adults with Central Auditory Processing Disorder. In: https://www.audiology.org/practice-guideline/clinical-practice-guidelines-diagnosis-treatment-and-management-of-children-and-adults-with-central-auditory-processing-disorder/.

Aravindkumar, R., Shivashankar, N., Satishchandra, P., Sinha, S., Saini, J., Subbakrishna, D.K., 2012. Temporal resolution deficits in patients with refractory complex partial seizures and mesial temporal sclerosis (MTS). Epilepsy Behav. 24 (1), 126–130. https://doi.org/10.1016/j.yebeh.2012.03.004.

Báez-Martín, M.M., Morales-Chacón, L.M., García-Maeso, I., Estupiñán-Díaz, B., Lorigados-Pedre, L., García, M.E., Galvizu, R., Bender, J.E., Cabrera-Abreu, I., Pérez-Téllez, Y., Galán, L., 2014. Temporal lobe epilepsy surgery modulates the activity of auditory pathway. Epilepsy Res. 108 (4), 748–754. https://doi.org/10.1016/j.eplepsyres.2014.02.017.

Bajer, C., Hofer, W., Pieper, T., Kudernatsch, M., Holthausen, H., Staudt, M., 2020. Correlates of intellectual development before and after hemispherotomy: an analysis of 75 children and adolescents. Epileptic Disord. 22 (5), 571–581. https://doi.org/10.1684/epd.2020.1193.

Bamiou, D.-E., Free, S.L., Sisodiya, S.M., Chong, W.K., Musiek, F., Williamson, K.A., van Heyningen, V., Moore, A.T., Gadian, D., Luxon, L.M., 2007a. Auditory interhemispheric transfer deficits, hearing difficulties, and brain magnetic resonance imaging abnormalities in children with congenital aniridia due to PAX6 mutations. Arch. Pediatr. Adolesc. Med. 161 (5), 463–469. https://doi.org/10.1001/archpedi.161.5.463.

Bamiou, D.-E., Musiek, F.E., Stow, I., Stevens, J., Cipolotti, L., Brown, M.M., Luxon, L.M., 2006. Auditory temporal processing deficits in patients with insular stroke. Neurology 67 (4), 614–619. https://doi.org/10.1212/01.wnl.0000230197.40410.db.

Bamiou, D.-E., Sisodiya, S., Musiek, F.E., Luxon, L.M., 2007b. The role of the interhemispheric pathway in hearing. Brain Res. Rev. 56 (1), 170–182. https://doi.org/10.1016/j.brainresrev.2007.07.003.

Bamiou, D.-E., Werring, D., Cox, K., Stevens, J., Musiek, F.E., Brown, M.M., Luxon, L.M., 2012. Patient-reported auditory functions after stroke of the central auditory pathway. Stroke 43 (5), 1285–1289. https://doi.org/10.1161/STROKEAHA.111.644039.

Bellis, T.J., Anzalone, A.M., 2008. Intervention approaches for individuals with (central) auditory processing disorder. Contemporary Issues in Communication Science and Disorders 35, 143–153. https://doi.org/10.1044/cicsd_35_F_143 (Fall).
Bellmann, A., Clarke, S., Adriani, M., Maeder, P., Meuli, R., Fornari, E., Thiran, J.-P., Foletti, G., Villemure, J.-G., 2001a. Auditory localisation in patients with right hemispherectomy: performance and fMRI data. Neuroimage 13 (6, Suppl. ment), 861. https://doi.org/10.1016/S1053-8119(01)92203-7.
Bellmann, A., Meuli, R., Clarke, S., 2001b. Two types of auditory neglect. Brain 124 (4), 676–687. https://doi.org/10.1093/brain/124.4.676.
Blauwblomme, T., Demertzi, A., Tacchela, J.-M., Fillon, L., Bourgeois, M., Lositto, E., Eisermann, M., Marinazzo, D., Raimondo, F., Alcauter, S., Steen, F.V.D., Colenbier, N., Laureys, S., Dangouloff-Ros, V., Naccache, L., Boddaert, N., Nabbout, R., 2019. Functional Cortico-Subcortical Reorganization after Complete Hemispheric Disconnection for Intractable Epilepsy. bioRxiv, 707539. https://doi.org/10.1101/707539.
Boatman, D.F., Lesser, R.P., Crone, N.E., Krauss, G., Lenz, F.A., Miglioretti, D.L., 2006. Speech recognition impairments in patients with intractable right temporal lobe epilepsy. Epilepsia 47 (8), 1397–1401. https://doi.org/10.1111/j.1528-1167.2006.00562.x.
Boatman, D., Vining, E.P.G., Freeman, J., Carson, B., 2003. Auditory processing studied prospectively in two hemidecorticectomy patients. J. Child Neurol. 18 (3), 228–232.
Bougeard, R., Fischer, C., 2002. The role of the temporal pole in auditory processing. Epileptic Disord. 4 (1), 29–32.
Bregman, A.S., 1994. Auditory Scene Analysis: the Perceptual Organization of Sound. MIT Press.
Chang, M., Kanold, P.O., 2021. Development of auditory cortex circuits. Journal of the Association for Research in Otolaryngology 22 (3), 237–259. https://doi.org/10.1007/s10162-021-00794-3.
Chermak, G.D., Bamiou, D.-E., Vivian, Iliadou, V., Musiek, F.E., 2017. Practical guidelines to minimise language and cognitive confounds in the diagnosis of CAPD: a brief tutorial. Int. J. Audiol. 56 (7), 499–506. https://doi.org/10.1080/14992027.2017.1284351.
Clarke, S., Bellmann, A., Meuli, R.A., Assal, G., Steck, A.J., 2000. Auditory agnosia and auditory spatial deficits following left hemispheric lesions: evidence for distinct processing pathways. Neuropsychologia 38 (6), 797–807. https://doi.org/10.1016/S0028-3932(99)00141-4.
Clarke, S., Bellmann Thiran, A., Maeder, P., Adriani, M., Vernet, O., Regli, L., Cuisenaire, O., Thiran, J.-P., 2002. What and where in human audition: selective deficits following focal hemispheric lesions. Exp. Brain Res. 147 (1), 8–15. https://doi.org/10.1007/s00221-002-1203-9.
Collard, M.E., Lesser, R.P., Lüders, H., Dinner, D.S., Morris, H.H., Hahn, J.F., Rothner, A. D., 1986. Four dichotic speech tests before and after temporal lobectomy. Ear Hear. 7 (6), 363.
Cook, S.W., Nguyen, S.T., Hu, B., Yudovin, S., Shields, W.D., Vinters, H.V., Wiele, B. M. V. de, Harrison, R.E., Mathern, G.W., 2004. Cerebral hemispherectomy in pediatric patients with epilepsy: comparison of three techniques by pathological substrate in 115 patients. J. Neurosurg. Pediatr. 100 (2), 125–141. https://doi.org/10.3171/ped.2004.100.2.0125.
Corballis, M.C., Ogden, J.A., 1988. Dichotic listening in commissurotomized and hemispherectomized subjects. Neuropsychologia 26 (4), 565–573. https://doi.org/10.1016/0028-3932(88)90113-3.
Curry, F.K.W., 1968. A comparison of the performances of a right hemispherectomized subject and 25 normals on four dichotic listening tasks. Cortex 4 (2), 144–153. https://doi.org/10.1016/S0010-9452(68)80027-9.
Curtiss, S., De Bode, S., 1999. Age and etiology as predictors of language outcome following hemispherectomy. Dev. Neurosci. 21 (3–5), 174–181. https://doi.org/10.1159/000017396.
Curtiss, S., de Bode, S., Mathern, G.W., 2001. Spoken Language outcomes after hemispherectomy: factoring in etiology. Brain Lang. 79 (3), 379–396. https://doi.org/10.1006/brln.2001.2487.
Dandy, W.E., 1928. Removal of right cerebral hemisphere for certain tumors with hemiplegia. JAMA, J. Am. Med. Assoc. 90 (11), 823–825. https://doi.org/10.1001/jama.1928.02690380007003.
De Bode, S., Curtiss, S., 2000. Language after hemispherectomy. Brain Cognit. 43 (1–3), 135–138. https://doi.org/10.1006/brcg.1999.1134.
De Bode, S., Sininger, Y., Healy, E.W., Mathern, G.W., Zaidel, E., 2007. Dichotic listening after cerebral hemispherectomy: methodological and theoretical observations. Neuropsychologia 45 (11), 2461–2466. https://doi.org/10.1016/j.neuropsychologia.2007.03.026.
De Wit, E., Visser-Bochane, M.I., Steenbergen, B., Van Dijk, P., Van Der Schans, C.P., Luinge, M.R., 2016. Characteristics of auditory processing disorders: a systematic review. J. Speech Lang. Hear. Res. 59 (2), 384–413. https://doi.org/10.1044/2015_JSLHR-H-15-0118.
Delalande, O., Bulteau, C., Dellatolas, G., Fohlen, M., Jalin, C., Buret, V., Viguier, D., Dorfmüller, G., Jambaqué, I., 2007. Vertical parasagittal hemispherotomy: surgical procedures and clinical long-term outcomes in a population of 83 children. Operative Neurosurgery 60 (2), 19. https://doi.org/10.1227/01.NEU.0000249246.48299.12.
Della Penna, S., Brancucci, A., Babiloni, C., Franciotti, R., Pizzella, V., Rossi, D., Torquati, K., Rossini, P.M., Romani, G.L., 2007. Lateralization of dichotic speech stimuli is based on specific auditory pathway interactions: neuromagnetic evidence. Cerebr. Cortex 17 (10), 2303–2311. https://doi.org/10.1093/cercor/bhl139.
Devlin, A.M., Cross, J.H., Harkness, W., Chong, W.K., Harding, B., Vargha-Khadem, F., Neville, B.G.R., 2003. Clinical outcomes of hemispherectomy for epilepsy in childhood and adolescence. Brain: J. Neurol. 126 (Pt 3), 556–566. https://doi.org/10.1093/brain/awg052.
Efron, R., Bogen, J.E., Yund, E.W., 1977. Perception of dichotic chords by normal and commisurotomized human subjects. Cortex 13 (2), 137–149. https://doi.org/10.1016/S0010-9452(77)80005-1.
Efron, R., Yund, E.W., Nichols, D., Efron, R., Yund, E.W., Nichols, D., Crandall, P.H., 1985. An ear asymmetry for gap detection following anterior temporal lobectomy. Neuropsychologia 23 (1), 43–50. https://doi.org/10.1016/0028-3932(85)90042-9.
Eggermont, J.J., Moore, J.K., 2012. Morphological and functional development of the auditory nervous system. In: Human Auditory Development. Springer, pp. 61–105.
Elias, K.M.I.F., Oliveira, C.C., Airoldi, M.J., Franco, K.M.D., Rodrigues, S., das, D., Ciasca, S.M., Moura-Ribeiro, M.V.L., 2014. Central auditory processing outcome after stroke in children. Arq. Neuro. Psiquiatr. 72, 680–686. https://doi.org/10.1590/0004-282X20140107.
Eysel-Gosepath, K., Daut, T., Pinger, A., Lehmacher, W., Erren, T., 2012. Effects of noise in primary schools on health facets in German teachers. Noise Health 14 (58), 129–134. https://doi.org/10.4103/1463-1741.97258.
Freeman, J., Boatman, D.F., 2007. Auditory verbal impairment in a child with Rasmussen encephalopathy and recurrent seizures. Dev. Med. Child Neurol. 49 (9), 717–718.
Gavrilovic, A., Toncev, G., Boskovic Matic, T., Vesic, K., Ilic Zivojinovic, J., Gavrilovic, J., 2019. Impact of epilepsy duration, seizure control and EEG abnormalities on cognitive impairment in drug-resistant epilepsy patients. Acta Neurol. Belg. 119 (3), 403–410. https://doi.org/10.1007/s13760-019-01090-x.
Gokula, R., Sharma, M., Cupples, L., Valderrama, J.T., 2019. Comorbidity of auditory processing, attention, and memory in children with word reading difficulties. Front. Psychol. 10. https://doi.org/10.3389/fpsyg.2019.02383.
Goldmann, R.E., Golby, A.J., 2005. Atypical language representation in epilepsy: implications for injury-induced reorganization of brain function. Epilepsy Behav. 6 (4), 473–487. https://doi.org/10.1016/j.yebeh.2005.03.012.
Griffiths, S.Y., Sherman, E.M.S., Slick, D.J., Eyrl, K., Connolly, M.B., Steinbok, P., 2007. Postsurgical health-related quality of life (HRQOL) in children following hemispherectomy for intractable epilepsy. Epilepsia 48 (3), 564–570. https://doi.org/10.1111/j.1528-1167.2006.00966.x.
Gutschalk, A., Dykstra, A.R., 2015. Chapter 31—auditory neglect and related disorders. In: Aminoff, M.J., Boller, F., Swaab, D.F. (Eds.), Handbook of Clinical Neurology, vol. 129. Elsevier, pp. 557–571. https://doi.org/10.1016/B978-0-444-62630-1.00031-7.
Han, S.-H., Lee, E.M., Choi, E.J., Ryu, H.U., Kang, J.K., Chung, J.W., 2016. Changes in central auditory processing in patients with mesial temporal lobe epilepsy after anterior temporal lobectomy with amygdalohippocampectomy. J. Clin. Neurol. 12 (2), 151–159. https://doi.org/10.3988/jcn.2016.12.2.151.
Harford, E., Houtrow, A., Al-Ramadhani, R., Sinha, A., Abel, T., 2023. Functional outcomes of pediatric hemispherotomy: impairment, activity, and medical service utilization. Epilepsy Behav. 140, 109099. https://doi.org/10.1016/j.yebeh.2023.109099.
Hausmann, M., Corballis, M.C., Fabri, M., Paggi, A., Lewald, J., 2005. Sound lateralization in subjects with callosotomy, callosal agenesis, or hemispherectomy. Cognit. Brain Res. 25 (2), 537–546. https://doi.org/10.1016/j.cogbrainres.2005.08.008.
Hertz-Pannier, L., Chiron, C., Jambaqué, I., Renaux-Kieffer, V., Moortele, P. V. de, Delalande, O., Fohlen, M., Brunelle, F., Bihan, D.L., 2002. Late plasticity for language in a child's non-dominant hemisphere: a pre- and post-surgery fMRI study. Brain 125 (2), 361–372. https://doi.org/10.1093/brain/awf020.
Hurley, A., Turner, R.G., Arriaga, E., Troyer, A., 2011. Auditory afferent and efferent assessment post functional hemisopherectomy: a case study. Journal of Educational Audiology 17, 81–93.
Ivanova, A., Zaidel, E., Salamon, N., Bookheimer, S., Uddin, L.Q., de Bode, S., 2017. Intrinsic functional organization of putative language networks in the brain following left cerebral hemispherectomy. Brain Struct. Funct. 222 (8), 3795–3805. https://doi.org/10.1007/s00429-017-1434-y.
Jafari, Z., Esmaili, M., Delbari, A., Mehrpour, M., Mohajerani, M.H., 2016. Auditory temporal processing deficits in chronic stroke: a comparison of brain damage lateralization effect. J. Stroke Cerebrovasc. Dis. 25 (6), 1403–1410. https://doi.org/10.1016/j.jstrokecerebrovasdis.2016.02.030.
Jiang, T., 1997. Acoustical Society of America—Can Noise Levels at School Gymnasia Cause Hearing Loss: A Case Study of a Physical Education Teacher.
Johnston, K.N., John, A.B., Kreisman, N.V., Hall III, J.W., Crandell, C.C., Johnston, K.N., John, A.B., Kreisman, N.V., Hall III, J.W., Crandell, C.C., 2009. Multiple benefits of personal FM system use by children with auditory processing disorder (APD). Int. J. Audiol. 48 (6), 371–383. https://doi.org/10.1080/14992020802687516.
Jonas, R., Nguyen, S., Hu, B., Asarnow, R.F., LoPresti, C., Curtiss, S., Bode, S. de, Yudovin, S., Shields, W.D., Vinters, H.V., Mathern, G.W., 2004. Cerebral hemispherectomy: hospital course, seizure, developmental, language, and motor outcomes. Neurology 62 (10), 1712–1721. https://doi.org/10.1212/01.WNL.0000127109.14569.C3.
Kerkhoff, G., Artinger, F., Ziegler, W., 1999. Contrasting spatial hearing deficits in hemianopia and spatial neglect. Neuroreport 10 (17), 3555.
Kimura, D., 1961. Cerebral dominance and the perception of verbal stimuli. Can. J. Psychol./Rev. Canad. Psychol. 15 (3), 166–171. https://doi.org/10.1037/h0083219.
Kimura, D., 1967. Functional asymmetry of the brain in dichotic listening. Cortex 3 (2), 163–178. https://doi.org/10.1016/S0010-9452(67)80010-8.
Kliemann, D., Adolphs, R., Tyszka, J.M., Fischl, B., Yeo, B.T.T., Nair, R., Dubois, J., Paul, L.K., 2019. Intrinsic functional connectivity of the brain in adults with a single cerebral hemisphere. Cell Rep. 29 (8), 2398–2407.e4. https://doi.org/10.1016/j.celrep.2019.10.067.
Koohi, N., Vickers, D.A., Lakshmanan, R., Chandrashekar, H., Werring, D.J., Warren, J. D., Bamiou, D.-E., 2020. Hearing characteristics of stroke patients: prevalence and

characteristics of hearing impairment and auditory processing disorders in stroke patients. J. Am. Acad. Audiol. 28, 491–505. https://doi.org/10.3766/jaaa.15139.
Koohi, N., Vickers, D., Chandrashekar, H., Tsang, B., Werring, D., Bamiou, D.-E., 2017. Auditory rehabilitation after stroke: treatment of auditory processing disorders in stroke patients with personal frequency-modulated (FM) systems. Disabil. Rehabil. 39 (6), 586–593. https://doi.org/10.3109/09638288.2016.1152608.
Krynauw, R.A., 1950. Infantile hemiplegia treated by removing one cerebral hemisphere. J. Neurol. Neurosurg. Psychiatr. 13 (4), 243–267.
Kumar, U.A., Vanaja, C.S., 2004. Functioning of olivocochlear bundle and speech perception in noise. Ear Hear. 25 (2), 142. https://doi.org/10.1097/01.AUD.0000120363.56591.E6.
Lavasani, A.N., Mohammadkhani, G., Motamedi, M., Karimi, L.J., Jalaei, S., Shojaei, F.S., Danesh, A., Azimi, H., 2016. Auditory temporal processing in patients with temporal lobe epilepsy. Epilepsy Behav. 60, 81–85. https://doi.org/10.1016/j.yebeh.2016.04.017.
Lessard, N., Leporé, F., Poirier, P., Villemagne, J., Lassonde, M., 1999. Localization of moving sounds by hemispherectomized subjects. Behav. Brain Res. 104 (1), 37–49. https://doi.org/10.1016/S0166-4328(99)00048-0.
Lessard, N., Lepore, F., Poirier, P., Villemagne, J., Lassonde, M., 2000. Sound localization in hemispherectomized subjects: the contribution of crossed and uncrossed cortical afferents. Exp. Brain Res. 134 (3), 344–352. https://doi.org/10.1007/s002210000463.
Lewandowska, M., Ganc, M., Wlodarczyk, E., Senderski, A., McPherson, D.L., Bednarek, D., Skarzynski, H., 2013. Central auditory processes predict reading abilities of children with developmental dyslexia. J. Hear. Sci. 3 (2), 30–40. https://doi.org/10.17430/889538.
Liasis, A., Boyd, S., Rivera-Gaxiola, M., Towell, A., 2003. Speech and non-speech processing in hemispherectomised children: an event-related potential study. Cognit. Brain Res. 17 (3), 665–673. https://doi.org/10.1016/S0926-6410(03)00190-3.
Loddenkemper, T., Wyllie, E., Lardizabal, D., Stanford, L.D., Bingaman, W., 2003. Late language transfer in patients with Rasmussen encephalitis. Epilepsia 44 (6), 870–871.
Mangold, S.A., M Das, J., 2023. Neuroanatomy, cortical primary auditory area. In: StatPearls. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK554521/.
Marsh, E.B., Newhart, M., Kleinman, J.T., Heidler-Gary, J., Vining, E.P.G., Freeman, J.M., Kossoff, E.H., Hillis, A.E., 2009. Hemispherectomy sustained before adulthood does not cause persistent hemispatial neglect. Cortex; a Journal Devoted to the Study of the Nervous System and Behavior 45 (5), 677–685. https://doi.org/10.1016/j.cortex.2008.06.012.
Martin, K., Trauner, D.A., 2019. Auditory neglect in children following perinatal stroke. Behav. Brain Res. 359, 878–885. https://doi.org/10.1016/j.bbr.2018.06.026.
McKenzie, K., 1938. The present status of a patient who had the right cerebral hemisphere removed. JAMA 111, 168–183.
Meneguello, J., Leonhardt, F.D., Pereira, L.D., 2006. Auditory processing in patients with temporal lobe epilepsy. Brazilian Journal of Otorhinolaryngology 72 (4), 496–504. https://doi.org/10.1016/S1808-8694(15)30995-2.
Meoded, A., Faria, A.V., Hartman, A.L., Jallo, G.I., Mori, S., Johnston, M.V., Huisman, T.a.G.M., Poretti, A., 2016. Cerebral reorganization after hemispherectomy: a DTI study. Am. J. Neuroradiol. 37 (5), 924–931. https://doi.org/10.3174/ajnr.A4647.
Moore, J.K., 2002. Maturation of human auditory cortex: implications for speech perception. Ann. Otol. Rhinol. Laryngol. 111 (5_Suppl. l), 7–10.
Moosa, A.N.V., Gupta, A., Jehi, L., Marashly, A., Cosmo, G., Lachhwani, D., Wyllie, E., Kotagal, P., Bingaman, W., 2013a. Longitudinal seizure outcome and prognostic predictors after hemispherectomy in 170 children. Neurology 80 (3), 253–260. https://doi.org/10.1212/WNL.0b013e31827dead9.
Moosa, A.N.V., Jehi, L., Marashly, A., Cosmo, G., Lachhwani, D., Wyllie, E., Kotagal, P., Bingaman, W., Gupta, A., 2013b. Long-term functional outcomes and their predictors after hemispherectomy in 115 children. Epilepsia 54 (10), 1771–1779. https://doi.org/10.1111/epi.12342.
Muchnik, C., Ari-Even Roth, D., Othman-Jebara, R., Putter-Katz, H., Shabtai, E.L., Hildesheimer, M., 2004. Reduced medial olivocochlear bundle system function in children with auditory processing disorders. Audiol. Neurootol. 9 (2), 107–114. https://doi.org/10.1159/000076001.
Musiek, F.E., Baran, J.A., Pinheiro, M.L., 1990. Duration pattern recognition in normal subjects and patients with cerebral and cochlear lesions. Audiology 29 (6), 304–313. https://doi.org/10.3109/00206099009072861.
Musiek, F.E., Pinheiro, M.L., 1987. Frequency patterns in cochlear, brainstem, and cerebral lesions. Audiology 26 (2), 79–88. https://doi.org/10.3109/00206098709078409.
Musiek, F.E., Reeves, A.G., Baran, J.A., 1985. Release from central auditory competition in the split-brain patient. Neurology 35 (7), 983. https://doi.org/10.1212/WNL.35.7.983.
Musiek, F.E., Shinn, J.B., Jirsa, R., Bamiou, D.-E., Baran, J.A., Zaida, E., 2005. GIN (Gaps-In-Noise) test performance in subjects with confirmed central auditory nervous system involvement. Ear Hear. 26 (6), 608. https://doi.org/10.1097/01.aud.0000188069.80699.41.
Musiek, F.E., Weihing, J., 2011. Perspectives on dichotic listening and the corpus callosum. Brain Cognit. 76 (2), 225–232. https://doi.org/10.1016/j.bandc.2011.03.011.
Nagle, S., Musiek, F.E., Kossoff, E.H., Jallo, G., Boatman-Reich, D., 2013. Auditory processing following consecutive right temporal lobe resections: a prospective case study. J. Am. Acad. Audiol. 24 (7), 535–543. https://doi.org/10.3766/jaaa.24.7.2.
Nebes, R.D., Nashold, B.S., 1980. A comparison of dichotic and visuo-acoustic competition in hemispherectomized patients. Brain Lang. 9 (2), 246–254. https://doi.org/10.1016/0093-934X(80)90144-3.
Netley, C., 1972. Dichotic listening performance of hemispherectomized patients. Neuropsychologia 10 (2), 233–240. https://doi.org/10.1016/0028-3932(72)90065-6.
Nicolosi, L., Harryman, E., Kresheck, J., 1989. Terminology of Communication Disorders: Speech-Language-Hearing, third ed. Williams & Wilkins.
Novanta, G.G.R., Garavelli, S.L., Sampaio, A.L.L., 2020. Is the level of noise in a school environment be harmful to the hearing of teachers? Int. Arch. Otorhinolaryngol. 24 (4), e503–e507. https://doi.org/10.1055/s-0040-1702969.
Ozanne, A., Verdinelli, C., Olsson, I., H Graneheim, U., Malmgren, K., 2016. Parental experiences before and long-term after their children's hemispherotomy—a population-based qualitative study. Epilepsy Behav. 60, 11–16. https://doi.org/10.1016/j.yebeh.2016.04.025.
Paiement, P., Champoux, F., Bacon, B.A., Lassonde, M., Gagné, J.-P., Mensour, B., Leroux, J.-M., Lepore, F., 2008. Functional reorganization of the human auditory pathways following hemispherectomy: an fMRI demonstration. Neuropsychologia 46 (12), 2936–2942. https://doi.org/10.1016/j.neuropsychologia.2008.06.009.
Phillips, D.P., 1999. Auditory gap detection, perceptual channels, and temporal resolution in speech perception. J. Am. Acad. Audiol. 10 (6), 343–354. https://doi.org/10.1055/s-0042-1748505.
Poirier, P., Lassonde, M., Villemure, J.-G., Geoffroy, G., Lepore, F., 1994. Sound localization in hemispherectomized patients. Neuropsychologia 32 (5), 541–553. https://doi.org/10.1016/0028-3932(94)90143-0.
Puka, K., Jones, M., Mathern, G.W., 2021. Functional cognitive and language outcomes after cerebral hemispherectomy for hemimegalencephaly. Epilepsia 62 (12), 2932–2940. https://doi.org/10.1111/epi.17088.
Pulsifer, M.B., Brandt, J., Salorio, C.F., Vining, E.P.G., Carson, B.S., Freeman, J.M., 2004. The cognitive outcome of hemispherectomy in 71 children. Epilepsia 45 (3), 243–254. https://doi.org/10.1111/j.0013-9580.2004.15303.x.
Rasmussen, T., 1983. Hemispherectomy for seizures revisited. Can. J. Neurol. Sci. 10 (2), 71–78. https://doi.org/10.1017/S0317167100044668.
Samargia, S.A., Kimberley, T.J., 2009. Motor and cognitive outcomes in children after functional hemispherectomy. Pediatr. Phys. Ther. 21 (4), 356–361. https://doi.org/10.1097/PEP.0b013e3181bf710d.
Schramm, J., Kral, T., Clusmann, H., 2001. Transsylvian keyhole functional hemispherectomy. Neurosurgery 49 (4), 891–900. https://doi.org/10.1097/00006123-200110000-00021. ; discussion 900-901.
Schramm, J., Kuczaty, S., Sassen, R., Elger, C.E., von Lehe, M., 2012. Pediatric functional hemispherectomy: outcome in 92 patients. Acta Neurochir. 154 (11), 2017–2028. https://doi.org/10.1007/s00701-012-1481-3.
Sherlock, C., Madigan, C., Linehan, C., Keenan, L., Downes, M., 2022. Academic attainment following pediatric epilepsy surgery: a systematic review. Epilepsy Behav. 134, 108847. https://doi.org/10.1016/j.yebeh.2022.108847.
Shield, B.M., Dockrell, J.E., 2008. The effects of environmental and classroom noise on the academic attainments of primary school children. J. Acoust. Soc. Am. 123 (1), 133–144. https://doi.org/10.1121/1.2812596.
Shinn, J.B., 2003. Temporal processing: the basics. Hear. J. 56 (7), 52. https://doi.org/10.1097/01.HJ.0000292557.52409.67.
Shtyrov, Y., Kujala, T., Ahveninen, J., Tervaniemi, M., Alku, P., Ilmoniemi, R.J., Näätänen, R., 1998. Background acoustic noise and the hemispheric lateralization of speech processing in the human brain: magnetic mismatch negativity study. Neurosci. Lett. 251 (2), 141–144. https://doi.org/10.1016/S0304-3940(98)00529-1.
Skarlatos, D., Manatakis, M., 2003. Effects of classroom noise on students and teachers in Greece. Percept. Mot. Skills 96 (2), 539–544. https://doi.org/10.2466/pms.2003.96.2.539.
Thiran, A.B., Clarke, S., 2003. Preserved use of spatial cues for sound segregation in a case of spatial deafness. Neuropsychologia 41 (9), 1254–1261. https://doi.org/10.1016/S0028-3932(03)00014-9.
Tomlin, D., Dillon, H., Sharma, M., Rance, G., 2015. The impact of auditory processing and cognitive abilities in children. Ear Hear. 36 (5), 527. https://doi.org/10.1097/AUD.0000000000000172.
van Schooneveld, M.M.J., Braun, K.P.J., van Rijen, P.C., van Nieuwenhuizen, O., Jennekens-Schinkel, A., 2016. The spectrum of long-term cognitive and functional outcome after hemispherectomy in childhood. Eur. J. Paediatr. Neurol. 20 (3), 376–384. https://doi.org/10.1016/j.ejpn.2016.01.004.
Villemure, J.G., Mascott, C.R., 1995. Peri-insular hemispherotomy: surgical principles and anatomy. Neurosurgery 37 (5), 975–981. https://doi.org/10.1227/00006123-199511000-00018.
Wale, J., Geffen, G., 1986. Hemispheric specialization and attention: effects of complete and partial callosal section and hemispherectomy on dichotic monitoring. Neuropsychologia 24 (4), 483–496. https://doi.org/10.1016/0028-3932(86)90093-X.
Weil, A.G., Lewis, E.C., Ibrahim, G.M., Kola, O., Tseng, C.-H., Zhou, X., Lin, K.-M., Cai, L.-X., Liu, Q.-Z., Lin, J.-L., Zhou, W.-J., Mathern, G.W., 2021. Hemispherectomy Outcome Prediction Scale: Development and Validation of a Seizure Freedom Prediction Tool—Weil—2021. Epilepsia—Wiley Online Library. https://onlinelibrary.wiley.com/doi/full/10.1111/epi.16861.
Wester, K., Hugdahl, K., Asbjørnsen, A., 1991. Dichotic listening during forced-attention in a patient with left hemispherectomy. Percept. Mot. Skills 72 (1), 151–159. https://doi.org/10.2466/pms.1991.72.1.151.
Wright, B.A., Lombardino, L.J., King, W.M., Puranik, C.S., Leonard, C.M., Merzenich, M.M., 1997. Deficits in auditory temporal and spectral resolution in language-impaired children. Nature 387 (6629), 176–178. https://doi.org/10.1038/387176a0.
Yao, N., Qiao, H., Li, P., Liu, Y., Wu, L., Deng, X., Wang, Z., Chen, D., Tong, X., Liu, Y., Yang, C., Xu, Y., 2013. Ipsilateral and contralateral auditory brainstem response

reorganization in hemispherectomized patients. Neural Plast., e832473 https://doi.org/10.1155/2013/832473, 2013.

Zaidan, E., Baran, J.A., 2013. Gaps-in-noise (GIN©) test results in children with and without reading disabilities and phonological processing deficits. Int. J. Audiol. 52 (2), 113–123. https://doi.org/10.3109/14992027.2012.733421.

Zatorre, R.J., Ptito, A., Villemure, J.-G., 1995. Preserved auditory spatial localization following cerebral hemispherectomy. Brain 118 (4), 879–889. https://doi.org/10.1093/brain/118.4.879.