OPINION ARTICLE

Life experience and the asymmetry of the human auditory system: clinical and auditory science laboratory implications [version 1; peer review: 1 approved, 1 approved with reservations]

Dale Hewitt

NHS England, Redditch, B97 9PT, UK

V1 First published: 29 May 2018, 7:675
<https://doi.org/10.12688/f1000research.14982.1>
Latest published: 29 May 2018, 7:675
<https://doi.org/10.12688/f1000research.14982.1>

Abstract

It is now almost 60 years since Doreen Kimura first described the asymmetries of the human auditory system (HAS). It is 30 years since Kenneth Hugdahl, and almost 15 years since David Poeppel, did the same. Our knowledge of these asymmetries is now considerable and detailed.

Here we review some of the literature concerning what is known about the asymmetry of the HAS, and use it to construct a simple model of how the central and peripheral components work together. The model details some of the asymmetry, the life-experience-dependant maturation of this asymmetry throughout the first two decades, possible reasons for the population variance in speech-in-noise perception, the central role of the corpus callosum, the involvement of the efferent auditory pathways, and the corticofugal control of the peripheral auditory system.

Although our knowledge of HAS asymmetry remains incomplete, this should not prevent the introduction of required changes to the current practices of audiologists and auditory science researchers, practices which fail to recognize the existence of any asymmetry in the HAS. The model described here suggests a clear need for: "asymmetry sensitive" hearing test tools that provide normative data for the lifespan, closer childhood and aging-adult hearing monitoring, and the development of a range of auditory training modules. Notably, the model suggests that without such tools our HAS asymmetry knowledge will remain incomplete. The status quo is a preoccupation with understanding hearing through knowledge of the peripheral hearing system, no answers for those with a "normal audiogram" but with an obvious difficulty hearing speech-in-noise, limited success cochlear implant rehabilitation, and missed opportunities to successfully intervene with childhood hearing/speech/language development problems.

Open Peer Review

Approval Status

	1	2
version 1
29 May 2018	view	view
1. Vasiliki Iliadou , Aristotle University of Thessaloniki, Thessaloniki, Greece		
2. Stefan Bleeck , University of Southampton, Southampton, UK		

Any reports and responses or comments on the article can be found at the end of the article.

Keywords

Audiological rehabilitation, auditory plasticity, auditory training, childhood development, dichotic listening test, hidden hearing loss, right ear advantage, speech-in-noise recognition

Corresponding author: Dale Hewitt (daleyhewitt2@gmail.com)

Author roles: Hewitt D: Conceptualization, Data Curation, Formal Analysis, Writing – Original Draft Preparation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: The author(s) declared that no grants were involved in supporting this work.

Copyright: © 2018 Hewitt D. This is an open access article distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: Hewitt D. **Life experience and the asymmetry of the human auditory system: clinical and auditory science laboratory implications [version 1; peer review: 1 approved, 1 approved with reservations]** F1000Research 2018, 7:675 <https://doi.org/10.12688/f1000research.14982.1>

First published: 29 May 2018, 7:675 <https://doi.org/10.12688/f1000research.14982.1>

Introduction

The progress of audiological rehabilitation and auditory science research remains compromised by the continuing preoccupation with understanding hearing through knowledge of the peripheral hearing system [Hewitt, 2018; Musiek *et al.*, 2017]. Only when the depth of our knowledge of the central auditory system matches that of the peripheral auditory system, and audiological practice is informed by the integration of this knowledge, can we expect to properly rehabilitate those with hearing problems.

Here we review some of the literature concerning the asymmetry of the human auditory system and use it to construct a model of how the central and peripheral components work together. The model uses the Doreen Kimura “structural model” of dichotic listening as its foundation [see Kimura, 1961; Kimura, 2011], and is augmented by the findings of the auditory scientists who have continued the work she began nearly 60 years ago.

The Doreen Kimura “structural model” of dichotic listening

There are ascending auditory pathways that connect both ears to both the left and right Auditory Cortices (ACs) (Figure 1). However, as Doreen Kimura discovered [Kimura, 1961; Kimura, 1967; Kimura, 2011], the primary connections are the crossed pathways. Normal hearing involves the right ear feeding sounds to the left AC and the left ear feeding sounds to the right AC.

The Bergen dichotic listening test with consonant-vowel syllables

In her research, Doreen Kimura made extensive use of various dichotic listening (DL) tests. One of the most popular dichotic listening tests is the Bergen dichotic listening test with consonant-vowel (CV) syllables (DL-CV) [Hugdahl & Andersson, 1986; Hugdahl & Asbjørnsen, 2013]. Each running of the Bergen DL-CV test involves 30 presentations using headphones. Each presentation involves the simultaneous playing of two randomly chosen CV syllables—one to the right ear and one to the left ear. The test uses only six CV syllables—all of them stop consonants combined with the /a/ vowel: /ba/, /da/, /ga/, /pa/, /ta/, /ka/. There are three DL-CV test runs, of 30 presentations

each. The first run is the non-forced condition. This is then followed by the forced-right condition and then the forced-left condition. An option is to reverse the order of the forced conditions. Figure 2 includes the instructions given to test participants for the three different conditions.

For all three DL-CV test conditions, a correct report (%) is calculated for both the right ear and the left ear. Figure 3 shows the right and left ear scores that are typically found in DL-CV studies with normal hearing participants. It also includes the typical non-forced condition scores found for studies of participants who have had a callosotomy—a surgical procedure involving some level of cutting of the corpus callosum so as to limit the spread of epileptic activity between the two hemispheres of the brain [see Musiek & Weihing, 2011].

The results for studies involving individuals with normal hearing typically show higher non-forced condition scores for the right ear than for the left ear. This difference increases with the forced-right condition scores and decreases with the forced-left condition scores. This many repeated set of findings has become known as the “right-ear advantage (REA)”. However, we should be careful to be more specific and refer to these findings as showing a “REA for CV syllables” (REA-CV). Doreen Kimura conducted many different dichotic listening studies [Kimura, 2011] and as well finding a “REA for digits”, also found a “left-ear advantage (LEA) for melodies” and a “LEA for non-verbal sounds”. Following on from this work Ley & Bryden [1982] found a “LEA for the emotional tone of speech”. The REA-CV finding is therefore only one of many dichotic listening study findings which demonstrate the asymmetry of the two hemispheres of the human brain and auditory system. The REA-CV is a result of the right ear being “directly” connected by the crossed pathway to the left AC, and the left AC being more specialised at phoneme processing. As the left ear is only “indirectly” connected to the left auditory cortex (via the contralateral pathway, the right AC and the corpus callosum) then it is at a disadvantage with a dichotic test involving CV syllables [Kimura, 2011]. By contrast, the left ear has the advantage with a dichotic test involving emotionally intoned sentences. This is because of the “direct”

Figure 1. The Doreen Kimura “structural model” of dichotic listening. The right ear feeds sounds to the left auditory cortex (AC) and the left ear feeds sounds to the right AC using the crossed ascending pathways.

Figure 2. The Bergen dichotic listening test with consonant-vowel syllables. AC, auditory cortex.

Figure 3. The "right ear advantage for consonant-vowel syllables". Higher non-forced condition (NF) scores for the right ear than for the left ear. This difference increases with the forced-right condition (FR) scores and decreases with the forced-left condition (FL) scores. For those who have had a callostomy, the right ear has almost no competition from the left ear. (Data is contrived.)

connection of the left ear to the right AC by the crossed pathway, and the right AC being more specialised at prosody processing. We can refer to this as the LEA-emotion or LEA-prosody.

The corticofugal modulation of the asymmetrical auditory system

Taken on their own, the non-forced condition scores for the REA-CV and the LEA-prosody reflect bottom-up processing advantages. However, the forced condition results (Figure 3) show that top-down driven attention to one of the ears is able to

modulate the scores. In the case of attention to the right ear this equates to increasing the REA-CV, and in the case of attention to the left ear it equates to decreasing the REA-CV, and in some individuals even reversing the advantage altogether. [Westerhausen & Hugdahl \[2008\]](#) describe this as two components working together; one "in-built" and bottom-up that is stimulus driven, the other attention driven and top-down, that enables modulation of the "in-built" asymmetry. The Bergen DL-CV Test has been used by many different studies over many years. Kenneth Hugdahl and his team at Bergen University, Norway

developed the test, and have used it as a research tool for over 30 years [Hugdahl *et al.*, 2009; Westerhausen *et al.*, 2015]. The Bergen Dichotic Listening Database [Westerhausen *et al.*, 2015] and the resulting normative data provided with their test manual [Hugdahl & Asbjørnsen, 2013] enables an understanding of the effects of age upon the REA-CV. There has been little discussion of these age effects in the literature but they provide valuable insight into the lengthy maturity window of the human auditory system through childhood and adolescence, and also its gradual decline, beginning as early as the sixth decade (Figure 4).

Taking the effects listed in Figure 4 in turn:

1. The AC asymmetry seems to be “in-built” and lasts a lifetime
2. If we think of the ability to use top-down attention to modulate the in-built asymmetry of the auditory system as a skill, then it seems that this corticofugal skill does not begin to develop until the end of the first decade, but it then continues to develop into adulthood
3. There is evidence (see below) which shows that the interhemispheric pathways of the corpus callosum play significant roles in the deterioration of the left ear scores (and in the development of the above corticofugal skill)

A Finnish version of the Bergen DL-CV test was developed by researchers at the University of Turku, Finland and was used in their studies concerning childhood development [see Takio *et al.*, 2009]. They too found that the top-down (corticofugal) skill to modulate the asymmetry of the auditory system does not begin to develop until the second decade. In a related study, this time in collaboration with Kenneth Hugdahl, they looked at the enhanced auditory processing skills of the congenitally and early blind [Hugdahl *et al.*, 2004]. They found, as they predicted, that the blind subjects were significantly better than the seeing (control) subjects at using their top-down corticofugal skill when instructed to attend to the left ear stimulus. Using the REA-CV test, Hugdahl & Andersson [1987] found that, in a group of children aged from 8 to 9 years, there was a

clear connection between increasing reading skills and increasing top-down corticofugal skills. In a related study, Andersson & Hugdahl [1987] found slower maturation of the corticofugal skill in a group of eight year old boys compared to a group of similarly aged girls.

Looking at the dichotic listening test results of adult individuals, rather than adult population averages, reveals that some test participants are able to entirely reverse the REA-CV when undertaking the forced left condition. Others are only able to increase their left ear score by small amounts, with the right ear score remaining considerably higher than the left ear score. The Bergen normative data [Hugdahl & Asbjørnsen, 2013] shows that there is a large between-individual variability. This leads to the proposition that, with some individuals, the skill to be able use top-down attention to modulate the asymmetry of the auditory system fails to properly develop.

An understanding as to why there is such a large between-individual variability is suggested by the dichotic listening test studies that looked at the differences between the DL-CV test scores of musicians and non-musicians. Milovanov *et al.* [2007] found that both choir-members and non-musical adults had similar REAs with the non-forced condition NF. The non-musical adults still had a clear right ear advantage with the forced left condition. The choir-members however, had a clear LEA with the forced left condition. The musicians had developed the skill to moderate the asymmetrical auditory system, while the non-musicians had not.

The nurturing of hearing skills

Several different auditory science research teams have conducted many different music related auditory studies in recent years. Most of these have concluded that with children (and young adults) there is a strong relationship between the extent of music practice and the enhancement of neural responses to speech, and as a consequence, better hearing speech-in-noise recognition

See, for example, the review paper of Strait & Kraus [2014]. These studies additionally found that the auditory training effects

1. NF Right ear scores are higher than NF Left ear scores at all ages
2. The difference between the F and NF scores (both for the Left ear and the Right ear) is minimal at first, increases through childhood and into early adulthood, and then becomes stable during middle age
3. For the Left ear (but not the Right ear) both the NF and F scores begin to decline at around 60 yrs of age, and this decline continues into old-age

Figure 4. The effects of age on the right ear advantage for consonant-vowel syllables. Normative data obtained from the 'Bergen Dichotic Listening Test with CV-Syllables Manual' [Hugdahl & Asbjørnsen, 2013].

of music continued until the end of adolescence [see [Krizman et al., 2015](#)]. The REA-CV literature reveals the same finding, and in [Figure 4](#) we can see that the difference between the forced and non-forced scores (both for the left ear and the right ear) is minimal at first, increases through adolescence and into early adulthood, and then becomes stable during adulthood. Tonal pitch processing is an important component of musical perception [[Zatorre et al., 2002](#)] and can be measured using the scalp-recorded frequency following response (FFR). [Coffey et al. \[2017a\]](#) found that the strength and fidelity of the FFR correlates well with speech-in-noise recognition scores. Also see [Du et al. \[2011\]](#). They also found that the effect was stronger with the right AC than with the left AC. With young adults, [Coffey et al. \[2016\]](#) found a strong, right-asymmetric contribution to the FFR from the human auditory cortex, and that the magnitude of the response was related to musicianship. It is well accepted that musical training enhances abilities related to such things as pitch, rhythm and melody. However, there does remain some disagreement in the literature about the benefits of music experience skills with regards to improved recognition of speech-in-noise. [Madsen et al. \[2017\]](#), for example, found that although musicians showed better fundamental frequency discrimination, this did not translate into better speech-in-noise recognition in their study. However, in their review of the results of similar studies they did find examples of a clear speech-in-noise recognition benefit of musicianship. These particular studies differed from the others (and their own) in that speech-in-noise recognition was measured using a test that spatially separated target speech from noise.

The vast majority of the speech-in-noise studies in the literature describe their use of speech audiometry tests that use headphones. Such tests do not represent realistic listening situations, and do not test speech-in-noise skills that relate to the asymmetry of the auditory system [[Coffey et al., 2017a](#); [Hewitt, 2018](#)]. Nevertheless, a recent review concerning the speech-in-noise recognition advantages of musical training was still able to conclude that, with 18 out of 20 studies showing an effect, musicians are better at hearing speech-in-noise [see [Coffey et al., 2017b](#)].

The MOC system and top-down control of the peripheral hearing system

Several research studies concerning the connections between music and speech processing have focussed upon the top-down driven control of peripheral hearing by the medial olivocochlear (MOC) system, and the enhanced MOC systems of those who have undertaken musical training. [Bidelman et al. \[2017\]](#) found that musically trained individuals show enhanced ipsilateral and contralateral cochlear gain control, and that there is a correlation between MOC strength and length of training. Musical training strengthens dynamic MOC activity, and speech-in-noise recognition is described as a likely benefit of the enhanced corticofugal control of the peripheral hearing system shown by musicians [[Perrot & Collet, 2014](#)]. Using DL-CV testing, [Markevych et al. \[2011\]](#) found that those with greater MOC strength were better at using top-down corticofugal skill to overcome their REA-CV when instructed to attend to the Left Ear stimulus.

Childhood development and the in-built asymmetry of the ACs

Recent studies made possible by non-invasive neurophysiological techniques have enabled closer inspection of the parallel processing by the two ACs during childhood. The evidence suggests that even though asymmetry is in-built, the asymmetry is relatively immature at birth, matures through childhood and adolescence, and is not mature until early adulthood.

[Ari-Even Roth et al. \[2016\]](#) found, as have many other otoacoustic emission based studies, that the transient-evoked otoacoustic emission results of a newborn hearing screening programme demonstrated that auditory system asymmetry is already apparent shortly after birth. Using event-related potential (ERP) techniques [Musacchia et al. \[2017\]](#) found that in the first year of life, early targeted acoustic experience can accelerate the maturation of both temporal and spectral processing. Using magnetoencephalography, [Tang et al. \[2016\]](#) showed that, compared to adults, the sound envelope following response was limited in capacity in children 3 to 5 years of age. [Thompson et al. \[2016\]](#) studied children 3–5 years of age to examine the evidence for temporal asymmetry early in life. They found a leftward asymmetry for higher-frequency oscillations and that this was more pronounced for those who scored higher on a speech-in-noise test. However, they did not find any rightward asymmetry for the lower-frequency oscillations. They proposed that this was a possible consequence of the known slower development of both white and grey matter structures in the right AC, and that this reflects the greater immaturity of the right AC at this young age. [Clunies-Ross et al. \[2018\]](#) studied temporal processing in children aged 7 and 9 years and, as expected, found evidence of left hemisphere specialisation (and a right hemisphere bias for spectral processing). They suggest that at this age, as the specialisation was not as prominent as with adults, the full extent of the asymmetry has yet to be reached, and that the immaturity of the right AC is greater. Using magnetoencephalography, [Nora et al. \[2017\]](#) studied children 6 to 8 years old and found that, compared to adults, the left hemisphere has yet to become dominant with regards (native language) phonological processing. They propose that at this age the learning of new words involves the use of the prosodic processing of the right hemisphere. [Yathiraj & Vanaja \[2015\]](#) showed that, in children between 6 and 10 years, different auditory processes matured at different rates. By measuring cortical responses, a study by [Yamazaki et al. \[2018\]](#) showed that, between the ages of 5 and 15 years, there is increasing specialisation of the two ACs. Using ERP, [Mahajan & McArthur, \[2013\]](#) studied left and right hemisphere auditory processing in adolescents aged between 10 and 18 years and found that they seem to mature at different rates, with the latter taking longer and continuing well into adolescence. In their longitudinal study using auditory brainstem response, [Krizman et al. \[2015\]](#) identified change taking place in auditory brainstem function between ages 14 and 17. They concluded that compared to the first decade different kinds of maturation take place in the second, and that the beginning of adolescence marks a transitional point.

We have described how human hearing develops throughout the first two decades of life and involves a slow but ever-increasing

specialisation of the two auditory cortices. The related binaural skill of sound source localisation has also been found to gradually develop throughout childhood, adolescence and into early adulthood [see Freigang *et al.*, 2015; Glyde *et al.*, 2013; Grothe *et al.*, 2010]. Spierer *et al.* [2009] studied brain-damaged patients and showed that auditory spatial representations for both left and right hemispaces are a function of the mature right hemisphere. At *et al.* [2011] reported the same finding in a study that used single pulse transcranial magnetic stimulation (to temporarily alter normal brain function). The Freigang *et al.* [2015] study includes a description of the age effects on sound localisation; with minimum audible angle (MAA) scores for 8–12 year olds not as mature as the adult-like MAA scores of 13–18 year olds. Glyde *et al.* [2013] describe how the many studies that have used the listening in spatialized noise-sentences test (LiSN-S) to measure the ability to process the sound localisation cues (measured by the LiSN-S “high-cue” score) have shown spatial processing continuing to mature until early adulthood.

The two decade maturation of AC specialisation and sound source localisation is prohibited by single-sided deafness (SSD). An understanding of SSD outcomes therefore enables consideration of the possible outcomes of a binaural auditory system that fails to fully mature. Zhang *et al.* [2018] found that unilateral hearing impairment lasting longer than 24 months drove cortical functional changes including enhanced interhemispheric AC connectivity and altered connectivity with visual and somatosensory networks. In a review, Eggermont [2017] concluded that, irrespective of the age of induction of a single-sided hearing loss, several hearing system adaptations take place, including modified interhemispheric connectivity and the near disappearance of the contralateral dominance of the ascending pathways. These adaptations take place over a few months and this short timescale can even mean that these adaptations will affect some individuals (both children and adults) who suffer from persistent otitis media with effusion (OME). Using REA-CV testing, Asbjørnsen *et al.* [2000] found that children who had undergone a myringotomy for persistent OME (at an earlier age) were less able to modulate the REA-CV advantage. Jafari *et al.* [2016] reported similar findings. Gordon *et al.* [2013] found that after 18 months of unilateral hearing with a cochlear implant that there was a loss of the contralateral dominance of the ascending auditory pathways and that this maladaptation still remained even after 3–4 years of subsequent use of bilateral cochlear implants (see also Polonenko *et al.* [2017]). Gordon *et al.* [2015] provide a summary of the hearing problems caused by SSD and some of the consequences. These include difficulty in hearing speech in noisy situations, impaired speech and language development, reduced verbal IQ, and the frequent outcomes of behavioural problems and requirement for individualized educational assistance.

The role of the corpus callosum

In their review of the role of the corpus callosum in dichotic processing Musiek & Weihing [2011] concluded that dichotic listening scores relate to the physical development of the corpus callosum. Dichotic listening performance improves until adolescence matching the increasing size of the corpus callosum.

In their review paper Westerhausen & Hugdahl [2008] describe how the corpus callosum plays a pivotal role in the central auditory system. Sammler *et al.* [2010] show that the posterior pathways of the corpus callosum are involved in the integration of the syntax processing of the left AC and the prosody processing of the right AC. In a review, Homae, [2014] concluded that during early years, the processing of auditory stimuli changed from independent ACs to mutually inhibitive ACs and modified corpus callosum interhemispheric connectivity. As Musiek & Weihing [2011] describe, some of the interhemispheric connections (between the two ACs) resulting from the maturation process are excitatory, others are inhibitory, and the maturation involves an increased rate of transfer of information (as a consequence of fibre myelination). In a review paper Bamiou *et al.* [2007] describe how the corpus callosum size increases until the third decade of life and then decreases again after the fourth decade. They also suggest that brain lateralization depends upon fast inter-hemispheric transfer, and that the corpus callosum has an important role in the processing of binaural cues and spatial hearing. In their recent review of the white matter asymmetries of the nervous system Ocklenburg *et al.* [2016] concluded that, although further investigation is still needed to understand the detail of the pathways and the inhibition and excitation involved, the hemispheric functional asymmetries depend upon the CC and its maturation path. The importance of the corpus callosum to auditory processing means that, as it “normally ages”, it also plays a pivotal role in what has become known as central presbycusis. The review by Musiek & Weihing [2011] reports that the worsening of left ear scores in dichotic listening tests begins in the middle of the sixth decade, as the corpus callosum begins to reduce in size (see also Figure 4).

Discussion

We have learnt about how the peripheral auditory system and central auditory system work together by looking at dichotic listening literature and the auditory science literature. In the dichotic listening literature review we re-examined and re-interpreted the effects of age data, and then went on to look at the different DL-CV test scores of musicians and those with no sight. With the auditory science literature review we focussed upon the relationship between musical training and auditory processing skills, the enhanced corticofugal control of the individual cochlea by musicians, the slowly maturing specialisation of the two auditory cortices, and the pivotal role of the corpus callosum in the increasing AC asymmetry during the first two decades of life. Additionally, the SSD literature was examined to consider the possible outcomes of a binaural auditory system that fails to fully mature. The findings of this set of literature reviews are highly consistent and complementary, and have led to a set of conclusions about the human auditory system.

The human auditory system has evolved to be capable of performing the real-time processing of complex acoustical stimuli such as speech and music. Some individuals can even manage this task in the presence of competing background noises. With these individuals, it seems that they have specially trained their auditory system through more frequent binaural intensive and challenging listening experiences. This extensive training seems to result in increased asymmetry, increased neural enhancement, and greater corticofugal control of the individual cochlea. With

greater maturity, the sense of hearing has been divided into two, with the left AC responsible for temporal processing and the right AC responsible for spectral processing [also see [Sininger & Bhatara, 2012](#); [Zatorre et al., 2002](#)], and spatial representation. The processing of stop consonants for example requires millisecond differences to be detected and is a function of the left AC. The changing melody of musical notes occurs over seconds and its processing is a function of the right AC. When listening to speech-in-noise, these individuals are able to use parallel processing, with the heavy myelination of corpus callosum fibres enabling fast interhemispheric communication between the two ACs. To enable speech recognition in noise, right AC neuron populations (measured using the scalp-recorded frequency following response) are phase-locked onto the low-to-middle-frequency periodical acoustical features of the sound source [[Du et al., 2011](#)], sound source locations are more precise, and corticofugal control of OHCs is able to modulate cochlea sensitivity and to restore lost dynamic range [[Perrot & Collet, 2014](#)]. By contrast, the adult outcome for those who are limited to small numbers of binaural intensive listening experiences during the first two decades, is an untrained and immature auditory system. They are unable to use parallel processing, the phase locking to an individual sound source is imprecise, they have little corticofugal control of the OHCs, and they struggle to understand speech in the presence of background noise. In sum, while some asymmetry exists at birth, it is life experience that shapes the detail of the auditory processing capability and the functional asymmetry of an individual's auditory system.

The auditory system maturation window seems to be open from birth until the beginning of adulthood with the maturation taking place during the first decade relating more to the temporal processing specialisation of the left AC. The maturation taking place in the second decade appears to relate more to the right AC and its spectral processing and sound location specialisations. A significant outcome of the maturation during the second decade is the establishment, or not, of corticofugal control of the peripheral auditory system, via the descending efferent pathways. The review paper by [Terreros & Delano \[2015\]](#), as well as discussing the MOC control of the OHCs, describes the recent findings concerning the efferent control of the inner hair cells (IHCs) of the cochlea via the lateral olivocochlear (LOC) neurons. Their working model proposes that there are three afferent-efferent feedback loops that enable the dynamic corticofugal modulation of the IHCs and OHCs. They describe the LOC/MOC control of the IHCs/OHCs as a top-down frequency filter that facilitates, for example, speech recognition in noisy environments.

A model of the auditory system

1. The mature auditory system is to some extent asymmetrical and with some individuals the two ACs are capable of parallel processing
2. With regards the processing of speech, the asymmetry equates to a left AC (right ear) responsible for phoneme processing and a right AC (left ear) responsible for prosody processing. Temporal (phoneme) processing mostly matures during the first decade of life, whereas spectral (prosody) processing takes longer to mature. The

mature right AC is responsible for the neural representation of both the left and right hemispaces.

3. The more extensive and challenging the auditory listening experience leading up to adulthood, with regards the need to simultaneously process both temporal and spectral features, the greater the asymmetry, the greater the neural enhancement, and the more refined the auditory processing skills
4. Musical training is known to improve sensory representation, sequencing skills, working memory, auditory attention, stream segregation, and top-down expectations; resulting in “musicians” having superior speech perception in noise ability, compared with “non-musicians” [[Chandrasekaran & Kraus, 2010](#)]
5. Very different childhood/adolescent listening experiences mean that auditory processing capability and the extent of asymmetry varies considerably—between children, between adolescents, between young adults, and between adults. These differences are “completely hidden from” and not measurable using standard audiometry tools ([Hewitt, 2018](#); [Musiek et al., 2017](#))
6. With some individuals top-down attention is able to modulate auditory system asymmetry. This corticofugal “skill” is well-developed in some adults but hardly at all in others. It appears connected with the maturation of the prosody processing of the right AC and its development occurs (or not) during the second decade of life.
7. The corticofugal “skill” involves all of the auditory pathways. This includes the ascending afferent pathways, the two ACs, the interhemispheric pathways of the corpus callosum, the descending efferent pathways (including the olivocochlear efferent fibres), and ultimately the dynamic control of the hair cells of the two cochlea (see [Figure 5](#)).

The “asymmetric sampling in time” model

The “structural model” of Doreen Kimura [[Kimura, 1961](#); [Kimura, 2011](#)] was a precursor to the “asymmetric sampling in time” (AST) model [[Poeppel, 2003](#)]. The AST model equally aims to provide a framework for understanding the asymmetry of the function of the two ACs. It describes them as anatomically similar but functionally specialised, with the left AC adapted to extracting information from shorter (20–40 ms) time windows, and the right AC adapted to extracting information from longer (150–250 ms) time windows. In attempting to aid the understanding of the asymmetry of the human auditory system this article shares the objectives of the Doreen Kimura “structural model”, the David Poeppel AST model, and the series of Hugdahl *et al.* and Westerhausen *et al.* dichotic listening studies ([Westerhausen & Hugdahl \[2008\]](#) provide references to most of these). In a related review [Tervaniemi & Hugdahl \[2003\]](#) describe the lateralisation differences between the encoding of speech and the encoding of music. This article, however, has an objective over and above an updated review of our knowledge concerning the asymmetrical auditory system—that of translating the knowledge into the availability of improved rehabilitation in the audiology clinic.

Figure 5. The fully mature asymmetrical human auditory system. The right ear feeds sounds to the left auditory cortex (AC) and the left ear feeds sounds to the right AC, using the crossed ascending pathways. When listening to speech, the left AC is responsible for phoneme processing and the right AC is responsible for prosody and spatial processing. The corpus callosum interhemispheric pathways connect the two ACs together. Top-down attention can modulate the asymmetry and involves the descending (efferent) pathways and the dynamic control of the hair cells of the two cochlea.

Using the model of the asymmetrical auditory system

The original articles of Kimura [1961]; Kimura [1967] and Poeppel [2003] have been cited thousands of times in the literature and yet, now nearly 60 years since the first of these articles, audiological rehabilitation continues to fail to recognize the existence of any asymmetry in the human auditory system [Hewitt, 2018; Musiek *et al.*, 2017]. One important outcome concerns speech audiometry. With a lack of consideration of the binaural nature of hearing and the asymmetry of the central auditory system, most speech audiometry tools are unable to determine speech-in-noise recognition capabilities reliably [Hewitt, 2018]. Their lack of usefulness has meant little use in the audiology clinic and their use restricted to auditory science research laboratories. Most of these tests use headphones and “one ear” testing (see, for example, Hewitt [2008]). Such tests involve the perception of sound inside the head, do not represent realistic listening situations, do not involve spatial cues, do not test the speech-in-noise skills that relate to the asymmetry of the auditory system, and do not test prosody (e.g. emotion recognition) [Coffey *et al.*, 2017a; Hewitt, 2018]. As a consequence there are limitations to the validity of the results and conclusions of the auditory science research studies that have used such “one ear” speech testing. This is the case with the majority of the hearing research published in the academic literature, with the validity of the results of those studies concerned with speech recognition in noise being more in question (see also Phatak *et al.* [2018]).

The model of the asymmetrical human auditory system (and those of the past) leads us to the conclusion that changes to the current practices of both audiologists and auditory science researchers are needed. The suggestions included in this and subsequent sections of this article are intended to stimulate discussion about the required nature of these changes.

Greater knowledge of how human hearing works improves our abilities to assess hearing, to diagnose hearing problems and to

manage those with hearing difficulties. The model suggests, for example, that there is a need for:

1. Wider-scope hearing test tools (for the audiology clinic and auditory science laboratory) that involve the “exercising” of both cochlea, both auditory afferent pathways, both auditory cortices, the corpus callosum, and both auditory efferent pathways.
2. Hearing test tools that provide normative data for the lifespan (i.e. separate normative data for children, adolescents, young adults, adults, and old adults).
 - a. Not unlike height and weight, auditory system development during childhood requires close monitoring, with the appropriate interventions used when developmental problems are identified.
 - b. Auditory system aging (presbycusis) requires close monitoring, with the appropriate interventions used sooner rather than later (see also Glick & Sharma [2017]).
3. The development of auditory training modules (ATMs), for the lifespan (i.e. different ATMs for children, adolescents, young adults, adults, and old adults).

Extending the model of the asymmetrical auditory system

The simple model described in Figure 5 generates as many questions as it answers; the following are only some of these questions.

The model supports the use of ATMs for those with hearing problems based on the premise that “real life” hearing training for subsets of the population, such as musicians or the blind, bestows auditory skills such as speech recognition in noise. Assuming that practical (and perhaps personalisable) ATMs can be developed

then there is a prospect that they will be able to play a significant role in:

- The rehabilitation of cochlear implant recipients [see [Anderson & Kraus, 2013](#)]
- The management of those suspected to have Auditory Processing Disorder [see [Moore et al., 2018](#); [Weihing et al., 2015](#)]
- Childhood Speech and Language development [see [Clunies-Ross et al., 2018](#)]

And perhaps they hold out the promise of:

- Effective speech perception in noise for the majority of adults
- Prolonging hearing skills into old-age [see [Strait & Kraus, 2014](#)]
- Delaying the aging of the auditory system and cognitive decline [see [Hewitt, 2017](#); [Humes & Young, 2016](#); [Livingston et al., 2017](#); [Lin et al., 2013](#); [Loughrey et al., 2018](#)]

Can a form of dichotic listening test be developed that will reliably and efficiently predict speech recognition in noise ability? There is a case for using the existing REA-CV test as a screening tool. Also see [Asbjørnsen et al. \[2000\]](#) and [Jafari et al. \[2016\]](#).

Unfortunately, unlike with the DL-CV studies, the literature does not provide significant amounts of data from the use of dichotic listening-prosody testing. Would such data provide further insight into the slower development of the right AC?

Hidden hearing loss

It is well accepted that standard pure tone audiometry (PTA) is unsuitable for measuring speech in noise recognition capability [[Musiek et al., 2018](#)]. More recently it has been shown to be insensitive to cochlear synaptopathy (CS). CS can result from excessive noise and from aging. Standard PTA is unable to detect CS until it becomes extreme, and as a consequence the condition has become known as “hidden hearing loss” [[Kujawa & Liberman, 2009](#); [Liberman et al., 2016](#)]. Ipsilateral (“one ear”) speech-in-noise testing was used by [Liberman et al. \[2016\]](#) to compare a group of people with normal sensitivities up to 16 kHz with a group of people with normal sensitivities up to 8 kHz but threshold elevation for the 10–16 kHz range. The latter showed worse speech-in-noise discrimination scores. The study concluded that to increase the possibility of CS detection, both high-frequency audiometry and speech recognition testing should be used in the audiology clinic with greater regularity. The model of the asymmetrical auditory system leads us to proposed extensions to the recommendations made by [Liberman et al. \[2016\]](#). While the more commonly used speech audiometry tools are designed for ipsilateral presentation of speech and noise to a single ear using headphones, a small number of sound field speech audiometry tools are currently available that use loudspeakers for spatially separated speech and noise presentation. Although normative data is perhaps limited,

such sound field speech audiometry tools enable some degree of measurement of actual binaural speech-in-noise recognition capability. Therefore:

- To increase the sensitivity to hearing loss not detectable using standard PTA, high-frequency audiometry and sound field speech audiometry testing should be used in the audiology clinic with greater regularity.
- To increase the sensitivity to speech-in-noise recognition capability, sound field speech audiometry testing should replace headphone based (“one ear”) speech audiometry in the auditory science laboratory.

Sound field speech audiometry additionally supports “before and after” hearing aid evaluation [[Hewitt, 2018](#)].

- To improve speech-in-noise recognition outcomes when fitting hearing aids, less reliance should be placed upon the results of PTA scores, with more reliance placed upon “before and after” sound field speech audiometry results

[Gordon et al. \[2015\]](#) reached a similar conclusion: that standard paediatric audiology clinic test procedures require modification, as they fail to be sensitive to the increased risk of educational difficulties that result from single-sided hearing. See also [Musiek et al. \[2018\]](#).

Conclusion

This article extends a listening model first published nearly 60 years ago. The extended model describes a human auditory system that, while some asymmetry exists at birth, requires extensive and challenging binaural listening experiences leading up to adulthood to ensure the full maturation of the asymmetry and the associated speech-in-noise recognition capabilities.

Only when the depth of our knowledge of the central auditory system (CAS) matches that of the peripheral auditory system, and audiological practice is informed by the integration of this knowledge, can we expect to effectively rehabilitate those with hearing problems. While our knowledge of the CAS remains far from complete and this study and model make only a minor contribution in this respect, one clear conclusion has been arrived at—auditory science is compromised by a lack of “asymmetry sensitive” tools.

We have hitherto thought of hearing as nature. We now know that plasticity is a defining feature of the auditory system during its maturation, middle age, and the years of presbycusis. We need to think more seriously about how best the auditory system can be nurtured.

Data availability

No data is associated with this article.

Competing interests

No competing interests were disclosed.

Grant information

The author(s) declared that no grants were involved in supporting this work.

References

- Andersson B, Hugdahl K: **Effects of sex age, and forced attention on dichotic listening in children: A longitudinal study.** *Dev Neuropsychol.* 1987; **3**(3–4): 191–206.
[Publisher Full Text](#)
- Anderson S, Kraus N: **Auditory Training: Evidence for Neural Plasticity in Older Adults.** *Perspect Hear Hear Disord Res Res Diagn.* 2013; **17**: 37–57.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Ari-Even Roth D, Hildesheimer M, Roziner I, *et al.*: **Evidence for a Right-Ear Advantage in Newborn Hearing Screening Results.** *Trends Hear.* 2016; **20**: pii: 2331216516681168.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Asbjørnsen A, Holmejord A, Reisaeter S, *et al.*: **Lasting auditory attention impairment after persistent middle ear infections: a dichotic listening study.** *Dev Med Child Neurol.* 2000; **42**(7): 481–486.
[PubMed Abstract](#) | [Publisher Full Text](#)
- At A, Spierer L, Clarke S: **The role of the right parietal cortex in sound localization: a chronometric single pulse transcranial magnetic stimulation study.** *Neuropsychologia.* 2011; **49**(9): 2794–97.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Bamiou DE, Sisodiya S, Musiek FE, *et al.*: **The role of the interhemispheric pathway in hearing.** *Brain Res Rev.* 2007; **56**(1): 170–82.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Bidelman GM, Schneider AD, Heitzmann VR, *et al.*: **Musicianship enhances ipsilateral and contralateral efferent gain control to the cochlea.** *Hear Res.* 2017; **344**: 275–283.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Chandrasekaran B, Kraus N: **Musical, noise-exclusion, and learning.** *Music Percept.* 2010; **27**: 297–306.
[Publisher Full Text](#)
- Clunies-Ross KL, Campbell C, Ohan JL, *et al.*: **Hemispheric asymmetries in rapid temporal processing at age 7 predict subsequent phonemic decoding 2 years later: A longitudinal event-related potential (ERP) study.** *Neuropsychologia.* 2018; **111**: 252–260.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Coffey EBJ, Chepesiuk AMP, Herholz SCs, *et al.*: **Neural Correlates of Early Sound Encoding and their Relationship to Speech-in-Noise Perception.** *Front Neurosci.* 2017a; **11**: 479.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Coffey EB, Herholz SC, Chepesiuk AM, *et al.*: **Cortical contributions to the auditory frequency-following response revealed by MEG.** *Nat Commun.* 2016; **7**: 11070.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Coffey EBJ, Mogilever NB, Zatorre RJ: **Speech-in-noise perception in musicians: A review.** *Hear Res.* 2017b; **352**: 49–69.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Du Y, Kong L, Wang Q, *et al.*: **Auditory frequency-following response: a neurophysiological measure for studying the “cocktail-party problem”.** *Neurosci Biobehav Rev.* 2011; **35**(10): 2046–2057.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Eggermont JJ: **Acquired hearing loss and brain plasticity.** *Hear Res.* 2017; **343**: 176–190.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Freigang C, Richter N, Rübsem R, *et al.*: **Age-related changes in sound localisation ability.** *Cell Tissue Res.* 2015; **361**(1): 371–86.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Glick H, Sharma A: **Cross-modal plasticity in developmental and age-related hearing loss: Clinical implications.** *Hear Res.* 2017; **343**: 191–201.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Glyde H, Cameron S, Dillon H, *et al.*: **The effects of hearing impairment and aging on spatial processing.** *Ear Hear.* 2013; **34**(1): 15–28.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Gordon K, Henkin Y, Kra A: **Asymmetric Hearing During Development: The Aural Preference Syndrome and Treatment Options.** *Pediatrics.* 2015; **136**(1): 141–153.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Gordon KA, Wong DD, Papsin BC: **Bilateral input protects the cortex from unilaterally-driven reorganization in children who are deaf.** *Brain.* 2013; **136**(Pt 5): 1609–1625.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Grothe B, Pecka M, McAlpine D: **Mechanisms of sound localization in mammals.** *Physiol Rev.* 2010; **90**(3): 983–1012.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Hewitt D: **Evaluation of an English Speech-in-Noise Audiometry Test.** MSc Thesis, Faculty of Engineering, Science, and Mathematics, University of Southampton, UK. 2008.
- Hewitt D: **Age-Related Hearing Loss and Cognitive Decline: You Haven’t Heard the Half of It.** *Front Aging Neurosci.* 2017; **9**: 112.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Hewitt D: **Audiometry and Its Discontents.** *Hearing Review.* 2018; **25**(1): 20–23.
[Reference Source](#)
- Homae F: **A brain of two halves: insights into interhemispheric organization provided by near-infrared spectroscopy.** *NeuroImage.* 2014; **85**(Pt 1): 354–362.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Hugdahl K, Andersson B: **Dichotic listening and reading acquisition in children: a one-year follow-up.** *J Clin Exp Neuropsychol.* 1987; **9**(6): 631–49.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Hugdahl K, Andersson L: **The “forced-attention paradigm” in dichotic listening to CV-syllables: A comparison between adults and children.** *Cortex.* 1986; **22**(3): 417–432.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Hugdahl K, Asbjørnsen A: **Bergen Dichotic Listening Test with CV-Syllables Manual.** (Updated March 2013); Stockholm: Psykologiförlaget. 2013.
- Hugdahl K, Ek M, Takio F, *et al.*: **Blind individuals show enhanced perceptual and attentional sensitivity for identification of speech sounds.** *Brain Res Cogn Brain Res.* 2004; **19**(1): 28–32.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Hugdahl K, Westerhausen R, Alho K, *et al.*: **Attention and cognitive control: Unfolding the dichotic listening story.** *Scand J Psychol.* 2009; **50**: 11–22.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Humes LE, Young LA: **Sensory-Cognitive Interactions in Older Adults.** *Ear Hear.* 2016; **37**(Suppl 1): 52S–61S.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Jafari Z, Malayeri S, Bahramian E: **The Effect of Age and History of Recurrent Otitis Media on Dichotic Listening and Verbal Memory in Children.** *Ann Otol Rhinol Laryngol.* 2016; **125**(12): 1015–1024.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Kimura D: **Cerebral dominance and the perception of verbal stimuli.** *Can J Exp Psychol.* 1961; **15**(3): 166–171.
[Publisher Full Text](#)
- Kimura D: **Functional Asymmetry of the Brain in Dichotic Listening.** *Cortex.* 1967; **3**(2): 163–178.
[Publisher Full Text](#)
- Kimura D: **From ear to brain.** *Brain Cogn.* 2011; **76**(2): 214–217.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Krizman J, Tierney A, Fitzroy AB, *et al.*: **Continued maturation of auditory brainstem function during adolescence: A longitudinal approach.** *Clin Neurophysiol.* 2015; **126**(12): 2348–2355.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Kujawa SG, Liberman MC: **Adding insult to injury: cochlear nerve degeneration after “temporary” noise-induced hearing loss.** *J Neurosci.* 2009; **29**(45): 14077–14085.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Ley RG, Bryden MP: **A dissociation of right and left hemispheric effects for recognizing emotional tone and verbal content.** *Brain Cogn.* 1982; **1**(1): 3–9.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Liberman MC, Epstein MJ, Cleveland SS, *et al.*: **Toward a Differential Diagnosis of Hidden Hearing Loss in Humans.** *PLoS One.* 2016; **11**(9): e0162726.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Lin FR, Yaffe K, Xia J, *et al.*: **Hearing loss and cognitive decline in older adults.** *JAMA Intern Med.* 2013; **173**(4): 293–299.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Livingston G, Sommerlad A, Orgetta V, *et al.*: **Dementia prevention, intervention, and care.** *Lancet.* 2017; **390**(10113): 2673–2734.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Loughrey DG, Kelly ME, Kelley GA, *et al.*: **Association of Age-Related Hearing Loss With Cognitive Function, Cognitive Impairment, and Dementia: A Systematic Review and Meta-analysis.** *JAMA Otolaryngol Head Neck Surg.* 2018; **144**(2): 115–126.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Madsen SMK, Whiteford KL, Oxenham AJ: **Musicians do not benefit from differences in fundamental frequency when listening to speech in competing speech backgrounds.** *Sci Rep.* 2017; **7**(1): 12624.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Mahajan Y, McArthur G: **Maturation of the auditory t-complex brain response across adolescence.** *Int J Dev Neurosci.* 2013; **31**(1): 1–10.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Markevych V, Asbjørnsen AE, Lind O, *et al.*: **Dichotic listening and otoacoustic emissions: shared variance between cochlear function and dichotic listening performance in adults with normal hearing.** *Brain Cogn.* 2011; **76**(2): 332–339.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Milovanov R, Tervaniemi M, Takio F, *et al.*: **Modification of dichotic listening (DL) performance by musico-linguistic abilities and age.** *Brain Res.* 2007; **1156**: 168–173.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Moore DR, Sieswerda SL, Grainger MM, *et al.*: **Referral and Diagnosis of Developmental Auditory Processing Disorder in a Large, United States Hospital-Based Audiology Service.** *J Am Acad Audiol.* 2018; **29**(5): 364–377.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Musacchia G, Ortiz-Mantilla S, Choudhury N, *et al.*: **Active auditory experience in**

- infancy promotes brain plasticity in Theta and Gamma oscillations. *Dev Cogn Neurosci*. 2017; **26**: 9–19.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Musiek FE, Chermak GD, Bamio DE, *et al.*: **CAPD: The Most Common 'Hidden Hearing Loss'. Central auditory processing disorder—and not cochlear synaptopathy—is the most likely source of difficulty understanding speech in noise (despite normal audiograms).** *ASHA Lead*. 2018; **23**: 6–9.
[Publisher Full Text](#)
- Musiek FE, Shinn J, Chermak GD, *et al.*: **Perspectives on the Pure-Tone Audiogram.** *J Am Acad Audiol*. 2017; **28**(7): 655–671.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Musiek FE, Weihing J: **Perspectives on dichotic listening and the corpus callosum.** *Brain Cogn*. 2011; **76**(2): 225–232.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Nora A, Karvonen L, Renvall H, *et al.*: **Children show right-lateralized effects of spoken word-form learning.** *PLoS One*. 2017; **12**(2): e0171034.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Ocklenburg S, Friedrich P, Güntürkün O, *et al.*: **Intrahemispheric white matter asymmetries: the missing link between brain structure and functional lateralization?** *Rev Neurosci*. 2016; **27**(5): 465–480.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Perrot X, Collet L: **Function and plasticity of the medial olivocochlear system in musicians: a review.** *Hear Res*. 2014; **308**: 27–40.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Phatak SA, Sheffield BM, Brungart DS, *et al.*: **Development of a Test Battery for Evaluating Speech Perception in Complex Listening Environments: Effects of Sensorineural Hearing Loss.** *Ear Hear*. 2018; **39**(3): 449–456.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Poeppel D: **The analysis of speech in different temporal integration windows: cerebral lateralization as asymmetric sampling in time.** *Speech Commun*. 2003; **41**(1): 245–255.
[Publisher Full Text](#)
- Polonenko MJ, Gordon KA, Cushing SL, *et al.*: **Cortical organization restored by cochlear implantation in young children with single sided deafness.** *Sci Rep*. 2017; **7**(1): 16900.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Sammler D, Kotz SA, Eckstein K, *et al.*: **Prosody meets syntax: the role of the corpus callosum.** *Brain*. 2010; **133**(9): 2643–2655.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Sininger YS, Bhatara A: **Laterality of basic auditory perception.** *Laterality*. 2012; **17**(2): 129–149.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Spierer L, Bellmann-Thiran A, Maeder P, *et al.*: **Hemispheric competence for auditory spatial representation.** *Brain*. 2009; **132**(Pt 7): 1953–1966.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Strait DL, Kraus N: **Biological impact of auditory expertise across the life span: musicians as a model of auditory learning.** *Hear Res*. 2014; **308**: 109–121.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Takio F, Koivisto M, Jokiranta L, *et al.*: **The effect of age on attentional modulation in Dichotic listening.** *Dev Neuropsychol*. 2009; **34**(3): 225–239.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Tang H, Brock J, Johnson B: **Sound envelope processing in the developing human brain: A MEG study.** *Clin Neurophysiol*. 2016; **127**(2): 1206–1215.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Terreros G, Delano PH: **Corticofugal modulation of peripheral auditory responses.** *Front Syst Neurosci*. 2015; **9**: 134.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Tervaniemi M, Hugdahl K: **Lateralization of auditory-cortex functions.** *Brain Res Brain Res Rev*. 2003; **43**(3): 231–246.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Thompson EC, Woodruff Carr K, White-Schwoch T, *et al.*: **Hemispheric Asymmetry of Endogenous Neural Oscillations in Young Children: Implications for Hearing Speech in Noise.** *Sci Rep*. 2016; **6**: 19737.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Weihing J, Chermak GD, Musiek FE: **Auditory Training for Central Auditory Processing Disorder.** *Semin Hear*. 2015; **36**(4): 199–215.
[PubMed Abstract](#) | [Publisher Full Text](#) | [Free Full Text](#)
- Westerhausen R, Bless JJ, Passow S, *et al.*: **Cognitive control of speech perception across the lifespan: A large-scale cross-sectional dichotic listening study.** *Dev Psychol*. 2015; **51**(6): 806–815.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Westerhausen R, Hugdahl K: **The corpus callosum in dichotic listening studies of hemispheric asymmetry: A review of clinical and experimental evidence.** *Neurosci Biobehav Rev*. 2008; **32**(5): 1044–1054.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Yamazaki H, Easwar V, Polonenko M, *et al.*: **Cortical hemispheric asymmetries are present at young ages and further develop into adolescence.** *Hum Brain Mapp*. 2018; **39**(2): 941–954.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Yathiraj A, Vanaja CS: **Age related changes in auditory processes in children aged 6 to 10 years.** *Int J Pediatr Otorhinolaryngol*. 2015; **79**(8): 1224–34.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Zatorre RJ, Belin P, Penhune VB: **Structure and function of auditory cortex: music and speech.** *Trends Cogn Sci*. 2002; **6**(1): 37–46.
[PubMed Abstract](#) | [Publisher Full Text](#)
- Zhang Y, Mao Z, Feng S, *et al.*: **Monaural-driven Functional Changes within and Beyond the Auditory Cortical Network: Evidence from Long-term Unilateral Hearing Impairment.** *Neuroscience*. 2018; **371**: 296–308.
[PubMed Abstract](#) | [Publisher Full Text](#)

Open Peer Review

Current Peer Review Status: ? ✓

Version 1

Reviewer Report 26 July 2018

<https://doi.org/10.5256/f1000research.16310.r35836>

© 2018 Bleeck S. This is an open access peer review report distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Stefan Bleeck

Institute of Sound and Vibration Research, University of Southampton, Southampton, UK

This is a well written piece that in my opinion is important and justified to index. The author makes the argument that current clinical practice does not recognise asymmetries in the central auditory system that might be responsible for individual differences in speech in noise perception. The author gives a critical literature review about research in the asymmetric auditory system with regards to structure, function, development and modelling. This is an excellent review in this area that has been lacking so far. The authors conclusion is that the observed asymmetry could be (partially) also responsible for observed individual differences in speech in noise performance. This connection has – to my knowledge – never been made and is an interesting suggestion. There is certainly not enough research in this area (as the author points out) and the question of causal relationships needs deeper investigation, but the conclusion that today's clinical speech tests that are performed mostly unilaterally are difficult to interpret is (in my opinion) absolutely justified. The author concludes with recommendation for clinical work that are straightforward and should be considered: more use of high frequency audiometry (which is not related to the topic in this paper, but absolutely justified from existing literature), and more performance of free field speech audiometry (before and after fitting).

A few points could improve the paper further:

The superior olives and the inferior colliculus are generally thought to be the first fully bilateral sound processing stations in the auditory pathways and many authors suspect that they are involved in the speech of noise task. To my knowledge there has never been an asymmetry been observed (or even suspected) in the brainstem processing. However, from there, the auditory streams go to either auditory cortex. So, it is not quite the case that (as implied in figure 1), the information stream goes straight from the ears to the contralateral cortex. I don't immediately see how this affects the main argument of AC asymmetry, but I feel for completeness that this should be discussed. Many authors don't give the brainstem the due recognition in the role for speech understanding – understandable as there is little research in this area.

The Bergen experiment is central and explanation takes up a lot of space, however, it is not explained well. I needed to reread the page several times before I understood what the bars in

figure 3 are. Also: where is the data from? Error bars? What does 'contrived' mean in the legend. Please rephrase the legend so that this interesting experiment becomes understandable to the non-expert reader.

Same with figure 4: where is the data from? Re-worked? What are the error bars? You are talking about the inter-individual difference later, but it's not clear here how large the effect is in relationship to their variance.

The paragraph about the hidden hearing loss actually doesn't add anything to the discussion about asymmetry or did I miss that? It's all correct, but what is the point of it for this paper, other than giving a second clinical recommendation (as much as I support it!)

In conclusion, I really enjoyed reading this and am planning some undergrad experiment later this year to find out more about the asymmetry of speech in noise recognition.

Is the topic of the opinion article discussed accurately in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Are arguments sufficiently supported by evidence from the published literature?

Yes

Are the conclusions drawn balanced and justified on the basis of the presented arguments?

Yes

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 28 June 2018

<https://doi.org/10.5256/f1000research.16310.r35211>

© 2018 Iliadou V. This is an open access peer review report distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Vasiliki Iliadou

Neuroscience, Medical School, Aristotle University of Thessaloniki, Thessaloniki, Greece

This very interesting and well-written article: "Life experience and the asymmetry of the human auditory system/ clinical and auditory science laboratory implications" taps into a very important issue. Laterality of the auditory system although widely recognised is not yet fully implemented in

clinical evaluation in everyday audiological practice. This leads to less than optimal management of hearing impairment as this is not restricted to hearing loss but extends to auditory processing disorder. The author should more clearly include auditory processing disorder (APD/CAPD) and its test battery approach which includes dichotic listening. Especially since APD evaluation is the only case in clinical audiology where asymmetry of the auditory system is measured, accounted for and remediated. Dichotic listening tests are at the core of APD test battery that lead to APD diagnosis. The author should refrain from using the term “suspected APD” as this is misleading and is not a diagnostic label. The term APD should be used referring to properly evaluated and diagnosed individuals.

Both abstract and keywords should include Auditory Processing Disorder as it is during an auditory processing evaluation that asymmetries in the HAS are studied and revealed. When present. For example, the right ear advantage during a dichotic test evaluation may reveal typical development and the absence or reversal of asymmetry may indicate an individual with pathological evidence concerning the central auditory nervous system.

Introduction is very well written and it should lead up to how important clinical evaluation of auditory processing is to be able to better describe, evaluate and rehabilitate speech in noise difficulties for example.

The dichotic listening test: The text provides a good description of dichotic listening tests with different stimuli and conditions. It lacks the inclusion and description of clinical populations. To be able to tap into hearing as a whole and not focus on the peripheral hearing alone, clinical populations and their results showing how asymmetry is presented or if it is still present should be discussed and compared with that of normal populations. The latter is very well presented but clinical population results should be included in this section.

The corticofugal modulation of the asymmetrical auditory system: In this section the author writes: “The Bergen Dichotic Listening Database [Westerhausen *et al.*, 2015] and the resulting normative data provided with their test manual [Hugdahl & Asbjørnsen, 2013] enables an understanding of the effects of age upon the REA-CV. There has been little discussion of these age effects in the literature but they provide valuable insight into the lengthy maturity window of the human auditory system through childhood and adolescence, and also its gradual decline, beginning as early as the sixth decade.” These databases however do not usually include the hearing threshold that represents the state of the peripheral hearing. If the author has these data he should present them and so how even though loss of hearing sensitivity is present with the ageing process, this can be clearly separated from the differences in dichotic listening results in younger and older adults. In the case that data of the pure tone audiometry (hearing threshold across tested frequencies) are not present the author should rephrase this section to include the possibility that the results showing in the dichotic listening may be the result of presbycusis.

AC asymmetry: Please spell out AC. What does it stand for?

The author states that: “The Bergen normative data [Hugdahl & Asbjørnsen, 2013] shows that there is a large between-individual variability.” Can he really rule out that this may be due to different hearing thresholds (peripheral hearing)?

It would add to the value of this paper to include results of studies regarding medial **olivocochlear**

system functionality (otoacoustic emissions suppression). In these studies there is a documented asymmetry as well that is part of the HAS and it should be included. Examples of such studies are:

Iliadou, V. V., Weihing, J., Chermak, G. D., & Bamiau, D. E. Otoacoustic emission suppression in children diagnosed with central auditory processing disorder and speech in noise perception deficits¹. Section 4.3. is discussing "Mechanism for laterality differences".

S. Khalfa, L. Collet Functional asymmetry of medial olivocochlear system in humans. Towards a peripheral auditory lateralization Neuroreport².

E. Veuillet, A. Magnan, J. Ecalle, *et al.*

Auditory processing disorder in children with reading disabilities: effect of audiovisual training³.

S.G.G. Sanches, R.M. Carvallo

Contralateral suppression of transient evoked otoacoustic emissions in children with auditory processing disorder⁴.

The author writes that: "The vast majority of the speech-in-noise studies in the literature describe their use of speech audiometry tests that use headphones. Such tests do not represent realistic listening situations, and do not test speech-in-noise skills that relate to the asymmetry of the auditory system". Although this may be partly true, it should be made clear that the reason behind this testing methodology is to ensure that even in cases when the testing environment does not permit for ideal acoustic conditions (sound treated booths instead of soundproof ones, for example or a quiet room vs a sound treated booth) testing is accurate. This should be included to balance the information provided in this section.

In the section: "Childhood development and the in-built asymmetry of the ACs" the author should rephrase results concerning OAE suppression providing insight into laterality/asymmetry. Please see paper by Gkoritsa et al 2007 indicating that (i) MOCB maturation is thought to be complete before the age of five in children and (ii) the presence of suppression laterality indicates full maturation⁵.

In discussion (last sentence of the second paragraph) the author states that: "In sum, while some asymmetry exists at birth, it is life experience that shapes the detail of the auditory processing capability and the functional asymmetry of an individual's auditory system."

Life experience with an intact and fully functioning peripheral and central auditory system should be added to stress the fact that this will be altered if a hearing loss or an auditory processing disorder is present.

In the section: "Using the model of the asymmetrical auditory system" auditory processing test battery approach that is used in specialised APD/CAPD clinics throughout the world should be mentioned and described. See references in⁶.

In the section "Extending the model of the asymmetrical auditory system" the phrase "The management of those suspected to have Auditory Processing Disorder" SHOULD change to "The management of those diagnosed with Auditory Processing Disorder" and the reference of Moore

et al, 2018 should be omitted as not relevant. It is not acceptable to mix populations together and it is not acceptable to manage suspected and not diagnosed individuals. We do not manage suspected hearing loss for example, we have to first diagnose it to know how to manage it. The same is true for APD. Include references:

Iliadou V and Kiese-Himmel C. Common Misconceptions Regarding Pediatric Auditory Processing Disorder⁷.

Sharma M, Purdy SC, Kelly AS. A randomized control trial of interventions in school-aged children with auditory processing disorders⁸

Iliadou V, Sirimanna T, Bamiou DE. CAPD is classified in ICD-10 as H93.25 and hearing evaluation-not screening-should be implemented in children with verified communication and/or listening deficits⁹.

Musiek FE, Chermak GD, Weihing J, Zappulla M, Nagle S. Diagnostic accuracy of established central auditory processing test batteries in patients with documented brain lesions¹⁰.

The section on Hidden hearing loss should be preceded by one on APD. See Musiek, F. E., Chermak, G. D., Bamiou, D. -, & Shinn, J. (2018)¹¹. CAPD: The most common 'hidden hearing loss' central auditory processing disorder-and not cochlear synaptopathy-is the most likely source of difficulty understanding speech in noise (despite normal audiograms).

References

1. Iliadou V, Weihing J, Chermak G, Bamiou D: Otoacoustic emission suppression in children diagnosed with central auditory processing disorder and speech in noise perception deficits. *International Journal of Pediatric Otorhinolaryngology*. 2018; **111**: 39-46 [Publisher Full Text](#)
2. Khalfa S, Collet L: Functional asymmetry of medial olivocochlear system in humans. Towards a peripheral auditory lateralization. *Neuroreport*. 1996; **7** (5): 993-6 [PubMed Abstract](#)
3. Veuillet E, Magnan A, Ecalle J, Thai-Van H, et al.: Auditory processing disorder in children with reading disabilities: effect of audiovisual training. *Brain*. 2007; **130** (Pt 11): 2915-28 [PubMed Abstract](#) | [Publisher Full Text](#)
4. Sanches SG, Carvallo RM: Contralateral suppression of transient evoked otoacoustic emissions in children with auditory processing disorder. *Audiol Neurotol*. 2006; **11** (6): 366-72 [PubMed Abstract](#) | [Publisher Full Text](#)
5. Gkoritsa E, Korres S, Segas I, Xenelis I, et al.: Maturation of the auditory system: 2. Transient otoacoustic emission suppression as an index of the medial olivocochlear bundle maturation. *Int J Audiol*. 2007; **46** (6): 277-86 [PubMed Abstract](#) | [Publisher Full Text](#)
6. Iliadou VV, Ptok M, Grech H, Pedersen ER, et al.: A European Perspective on Auditory Processing Disorder-Current Knowledge and Future Research Focus. *Front Neurol*. 2017; **8**: 622 [PubMed Abstract](#) | [Publisher Full Text](#)
7. Iliadou V, Kiese-Himmel C: Common Misconceptions Regarding Pediatric Auditory Processing Disorder. *Front Neurol*. 2017; **8**: 732 [PubMed Abstract](#) | [Publisher Full Text](#)
8. Sharma M, Purdy SC, Kelly AS: A randomized control trial of interventions in school-aged children with auditory processing disorders. *Int J Audiol*. 2012; **51** (7): 506-18 [PubMed Abstract](#) | [Publisher Full Text](#)
9. Iliadou V, Sirimanna T, Bamiou D: CAPD Is Classified in ICD-10 as H93.25 and Hearing Evaluation—Not Screening—Should Be Implemented in Children With Verified Communication and/or Listening Deficits. *American Journal of Audiology*. 2016; **25** (4). [Publisher Full Text](#)
10. Musiek FE, Chermak GD, Weihing J, Zappulla M, et al.: Diagnostic accuracy of established central auditory processing test batteries in patients with documented brain lesions. *J Am Acad Audiol*. 2011; **22** (6): 342-58 [PubMed Abstract](#) | [Publisher Full Text](#)

11. Musiek F, Chermak G, Bamiou D, Shinn J: CAPD: The Most Common 'Hidden Hearing Loss'. *ASHA Leader*. 2018; **23** (3). [Publisher Full Text](#)

Is the topic of the opinion article discussed accurately in the context of the current literature?

Partly

Are all factual statements correct and adequately supported by citations?

Partly

Are arguments sufficiently supported by evidence from the published literature?

Partly

Are the conclusions drawn balanced and justified on the basis of the presented arguments?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Auditory Processing Disorder

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

The benefits of publishing with F1000Research:

- Your article is published within days, with no editorial bias
- You can publish traditional articles, null/negative results, case reports, data notes and more
- The peer review process is transparent and collaborative
- Your article is indexed in PubMed after passing peer review
- Dedicated customer support at every stage

For pre-submission enquiries, contact research@f1000.com

F1000Research