comment

The power of sound for brain health

We ask a lot of our brains and they comply, carrying out petaflops of computations per second. A substantial amount of this processing power is devoted to sound processing — a process that is therefore vulnerable, but also repairable.

Nina Kraus and Trent Nicol

Unlike seen objects, which are reasonably persistent, sound is fleeting. But despite the transient nature of sound and the utter relentlessness of its input as it washes over us, our ears and, in particular, our brains do an amazing job of making sense of it. By some measures, the auditory system is the most computationally intensive neural network. This is particularly true in terms of timing. No other sensory system, vision included, can approach the speed at which the auditory system processes the incoming soundscape. Much of this need for speed is due to the simple fact that sounds evolve over time. Take speech, for example. The smallest unit of speech, from an acoustic standpoint, is the phoneme. The word 'brink' has only one syllable, but it has five discrete phonemes or unique sounds. Change any one of them and the meaning is changed ('drink') or lost ('brint'). In running speech, there are as many as 25 to 30 phonemes every second, and if we do not process them properly, the message is not delivered. But, in most circumstances, this swirl of sound poses little challenge to our speedy auditory systems.

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Making sense of sound

There are many factors that influence the ability of the auditory brain to make sense of sound. Obviously, the health of the cochlea is a major factor: it is difficult to make sense of sound when its clarity and loudness are compromised due to hearing loss. However, even with a perfectly functioning ear, there are experiential factors at play that might not be so obvious. But before we get to these factors, we must discuss the brainstem and the role that it plays in making sense of sound.

Unlike the visual pathway — in which there is essentially no brainstem processing between the retina and the lateral geniculate of the thalamus — the auditory pathway involves several brainstem nuclei that process sound along the way to the corresponding auditory station in the thalamus, the medial geniculate. These nuclei — the cochlear nucleus, superior olive, lateral lemniscus and inferior colliculus (IC) — each perform crucial analysis steps that have no visual analogue. One well-studied example is the sound localization in the superior olive nucleus. Let's say a given sound arrives infinitesimally sooner at your left ear than your right ear, and is likewise slightly louder in the left. It is in the superior olive that the analysis takes place that enables you to determine that this particular sound is coming from a source on your left. This enables you to react very quickly, via orientation, flight, or whatever response is appropriate to the circumstance. In the case of interaural timing differences, humans can, amazingly, detect differences of 10 microseconds[1], a couple orders of magnitude faster than the duration of a neural action potential. The role of other subcortical nuclei continue to emerge. The IC is particularly interesting, and a compelling structure to study. As the final waystation in the brainstem, it is a major hub of activity. Not only does it transfer previously processed neural activity on to the thalamus and cortex, but is also a key point of convergence of descending neural activity. Here, corticocollicular projections fed back to the IC are subsequently routed to nearly all of the other brainstem nuclei, and to the hair cells of the cochlea itself.

Catching up to the listening brain

The brainstem as a whole, and the IC in particular, represents a goldmine to probe the computational complexity of neural sound processing and, due to its role as a nexus of top-down neural activity, it lends itself to the study of short- and long-term experiential changes in processing. A neurophysiological measure, the frequency-following response (FFR), which originates primarily in the auditory brainstem and requires only a few electrodes and a few minutes' time, gives us such a probe. Pioneered at Northwestern University, Illinois, we and others have used the FFR to offer insight into how the speedy auditory brain is negatively impacted by linguistic deprivation and, conversely, honed by musical experience, multilingualism and auditory training[2].

Linguistic deprivation

Many have heard of the 30 million word gap, a term coined some twenty years ago by Betty Hart and Todd Risley[3]. They found that, on average, young children in high socioeconomic status (SES) families heard several hundred more words per hour than children from low SES families, which accumulated to a difference of 30 million words by age three. High-SES children with augmented language exposure, usually involving a richer vocabulary and more words expressing encouragement, go on to higher language skill attainment in school. But, do all these extra words make a difference only in cognitive and language-processing areas of the brain? Or is fundamental subcortical auditory processing also involved?

In a study at Northwestern University, we used the FFR to examine automatic auditory processing in high-school children of different SES levels[4]. We used maternal education level as a proxy for SES — there is a strong correlation between household income and the number of years that the mother of the family attended school. We found that the FFR was different in low-SES children in a couple of important ways. First, the FFR requires the repeated presentations of a sound, in this case a short speech syllable. The auditory brain should respond identically to each presentation of an identical sound, ensuring that sound-to-meaning connections essential to learning take place. But, this was not the case in the children from families with low maternal education — their brains responded slightly differently every time. Next, because speech is a complex sound with complex harmonic structure, we can hone in on how the brain responds to different frequency bands in the syllable. Low-SES children had a poorer response to frequencies that are key to the identification of the syllable, but not to its pitch. So, this might suggest that the low-SES auditory brain is receiving an impoverished signal, leaving the listener at a disadvantage when it comes to making sense of the sounds they hear. Interestingly, this pattern — low consistency and poor harmonic representation — is also the hallmark of the brain of a poor reader of any SES level[5].

Not a lost cause

An auditory brain that has not received the preferred level of linguistic priming and so is underequipped to process sound in the most accurate and precise way is not a lost cause. The brain is a remarkably plastic organ and the subcortical auditory brain is no exception. Once thought to be relatively immutable, we are learning that the auditory brainstem is not a 'set it and forget it' device. We are learning more and more about the factors — both good and bad — that influence auditory processing. As much as exposure to noise interrupts our listening, experience with 'good' sound tunes the auditory brain through the integration of sensorimotor, cognitive and reward circuitry[2]. Two very positive experiences with sound — speaking a second language and playing a musical instrument — have a lasting impact on sound processing, as measured by FFR. They also have especially important implications for battling the deficit that low-SES individuals contend with.

> The brainstem […] represents a goldmine to probe the computational complexity of neural sound processing.

Music

Music experience has proven to be a powerful experimental model for addressing the effects of experience on the auditory brain. Over the past couple of decades, a number of fascinating studies have looked at the effect that music playing (not listening!) has on the structure and function of the brain[6]. Drawbacks of this line of research, however, include the longstanding 'nature versus nurture' conundrum and the question of specificity. If Johnny the musician's brain is bigger/stronger/faster in some way than Suzy the non-musician's brain, is it due to Johnny playing music? Or was Johnny's brain inherently bigger/stronger/faster all along, and it was this enhanced brain that motivated him to pursue music training? Similarly, is it the discipline of music training rather than the music itself that is the beneficial factor? What about an activity that is not sound-based, but equally rigorous in cognitive engagement and commitment? We were fortunate to form partnerships with two music programs that helped to address both questions. In one case, equally motivated low-SES primary-school students were either enrolled in a community music program or waitlisted for a year due to space constraints — selection was random. So, there was no bias in terms of whatever pre-existing brain wiring might motivate the pursuit of music training. In the other case, low-SES high-school students either enrolled in music training or a Reserve Officers' Training Corps (ROTC) program that was equally rigorous in terms of required discipline. In both cases, longitudinal designs confirmed equivalent FFR function before beginning the music training (or ROTC) program, and then FFR testing was repeated after being in the program for some years.

In both projects[7,8], we saw FFR enhancements in the response properties that are signifiers of linguistic deprivation. Harmonic representation is increased and variability is decreased. The improvements took some time — at least two years was required to effect these changes. The controls (waitlisted or ROTC students) did not exhibit any improvements in their frequency following responses.

Bilingualism

The centuries-old debate on the pros and cons of speaking more than one language continues. While there are certain disadvantages to being a bilingual, such as a smaller vocabulary in both languages, there are advantages as well. The challenge of juggling two languages bolsters the auditory system and greatly contributes to improvements in cognitive functions such as attention[9], and may even serve as insurance against dementia[10]. We examined whether bilingualism, too, might offset the negative effects of the linguistic deprivation faced in low-SES households[11]. In the US, a disproportionate number of bilingual speakers come from low-SES households — so we wondered whether monolingual and bilingual adolescents from the same low-SES communities would have differences in their auditory processing. In this otherwise well-matched group, we did indeed find that response consistency, which is one of the hallmarks of low SES, was higher in bilinguals.

What have we learned and what should we do?

Invisible sound, then, is not only more complicated than we think, but more powerful too. Neuroscience has shown that, for better or worse, our experience with sound represents a form of biological time travel. Our past experiences with sound shape our sensory worlds today; and the care and feeding of our learning brains today shapes our futures[2]. So, what can we do to tone and hone our listening brains? For one, whatever your linguistic background, playing a musical instrument has a huge payoff cognitively and emotionally for children and adults alike. For another, we can exercise our auditory brains by learning a second language.

Making sense of meaningful sounds has a positive effect on how we think, feel and move. And, in turn, auditory learning takes place not in a vacuum, but with the engagement of the cognitive, reward and sensorimotor systems[2]. We learn best when attention and memory are engaged, when we are motivated and we care about what we are learning, and when our motor systems are involved. This last point is well illustrated by the fact that playing rather than listening to music has a deep impact on reorganizing and strengthening the nervous system. We would do well to pay more attention to the invisible, powerful sounds around us and appreciate the amazing network of neurons that brings our auditory world to life — appreciate how the sounds of our lives change our brains, as an ally or enemy. ❐

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Competing interests

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