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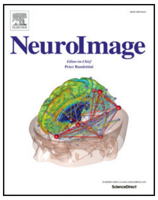

Full Length Articles

Q1 The neural correlates of processing scale-invariant environmental sounds at birth

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ABSTRACT

Sensory systems are thought to have evolved to efficiently represent the full range of sensory stimuli encountered in the natural world. The statistics of natural environmental sounds are characterized by scale-invariance: the property of exhibiting similar patterns at different levels of observation. The statistical structure of scale-invariant sounds remains constant at different spectro-temporal scales. Scale-invariance plays a fundamental role in how efficiently animals and human adults perceive acoustic signals. However, the developmental origins and brain correlates of the neural encoding of scale-invariant environmental sounds remain unexplored. Here, we investigate whether the human brain extracts the statistical property of scale-invariance. Synthetic sounds generated by a mathematical model to respect scale-invariance or violate it were presented to newborns. In alternating blocks, the two sound types were presented together in an alternating fashion, whereas in non-alternating blocks, only one type of sound was presented. Newborns' brain responses were measured using near-infrared spectroscopy. We found that scale-invariant and variable-scale sounds were discriminated by the newborn brain, as suggested by differential activation in the left frontal and temporal areas to alternating vs. non-alternating blocks. These results indicate that newborns already detect and encode scale-invariance as a characteristic feature of acoustic stimuli. This suggests that the mathematical principle of efficient coding of information guides the auditory neural code from the beginning of human development, a finding that may help explain how evolution has prepared the brain for perceiving the natural world.

Introduction

To what extent is the human brain prepared at birth to process the natural world? Natural signals such as natural environmental sounds possess characteristic statistical regularities in their structure. Accurately representing and encoding these regularities is an essential function of our perceptual systems. One such important statistical regularity of environmental sounds is scale-invariant spectro-temporal structure, i.e. the property of exhibiting similar structures or patterns at different levels of observation.

The statistical structure of scale-invariant sounds remains constant at multiple spectro-temporal scales. This feature has been identified not only for environmental sounds but also for music and speech (Voss and Clarke, 1975) and is thought to be fundamental to how the mammalian auditory system perceives acoustic signals (Pallier et al., 1998; Smith and Lewicki, 2006). At the level of neuronal responses measured in the adult animal brain, it has been shown that the auditory system encodes sounds that possess scale-invariant features more efficiently than sounds that lack this structure (Escabi et al., 2003; Rieke et al., 1995; Woolley et al., 2005). Water sounds exhibit scale-invariance, which humans perceive as an attribute of natural sounds. We constructed a generative mathematical model to create artificial sounds that either obeyed scale-invariant spectro-temporal structure or lacked this relationship. We found that human adults perceived the artificial sounds that obeyed scale-invariant statistical structure as natural, but judged those that lack it as unnatural (Geffen et al., 2011). These results point to the importance of scale-invariant spectro-temporal properties in the perception of a sound as natural. We were therefore interested in understanding whether and how sensitivity to the scale-invariant spectro-temporal structure of sounds emerges throughout development.

Young infants have sophisticated auditory abilities that support detection, processing, categorization, and learning of complex sounds (Moore, 2002; Saffran et al., 2006; Werner et al., 2012). Sounds of ecological importance, such as human speech, are processed with particular efficiency (Gervain and Mehler, 2010; Jusczyk, 1981; Werker and Curtin, 2005). Infants' auditory perception extends beyond speech to other sounds such as music or human action sounds (e.g. Trehub and Hannon, 2006; Geangu et al., 2015), and, as we recently demonstrated

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in a behavioral study, to natural sounds obeying scale-invariant spectro-temporal structure. We found that infants perceived scale-invariant water sounds generated by a mathematical model (Geffen et al., 2011) differentially as compared to variable-scale sounds, and grouped scale-invariant, but not variable-scale sounds, into one perceptual category (Gervain et al., 2014). This discrimination ability was not simply driven by increased familiarity with scale-invariant sounds, as in a control study using two categories of scale-invariant sounds (less and more familiar, as rated by adults), infants showed no preference for the more familiar sounds. This study provided the first evidence that by 5 months of age, infants can distinguish between sounds that possess and those that lack scale-invariant spectro-temporal structure at the behavioral level. Whether this ability is present even earlier in development, and if so, what is its neural substrate, is as yet unexplored. Here, we hypothesized that the differential sensitivity to scale-invariant and variable-scale sounds is driven by differences in neuronal correlates involved in processing these two classes of sounds in the infant brain from birth on.

Materials and methods

To test our hypothesis, we performed an optical brain imaging study with newborns, who were presented with scale-invariant and variable-scale water sounds. Previously, we developed a 3-parameter mathematical model (Eq. (1)) that generates sounds that are classified as "water" by adult observers if they are scale-invariant, and as a variety of other, non-natural sounds (e.g. robot sounds, grease sizzling, hissing, etc.) if they are variable-scale (Geffen et al., 2011). These sounds consisted of a population of randomly spaced gamma tone chirps from a wide range of frequencies (Geffen et al., 2011; and Fig. 1A). The gammatone transform is widely used to approximate the transformation of a sound into spectral bands at the cochlear stage (Goblick and Pfeiffer, 1969; Depireux et al., 2001). Each chirp was characterized by its frequency, amplitude, and cycle constant of decay (Eq. 1).

$$G_n(t) = \int_{\tau=0}^{\infty} (t-\tau)e^{-f_n\tau/Q} \sin(2\tau f_n\tau)y(t-\tau)d\tau \qquad (1)$$

where $y(t)$ is the signal, G_n is the gammatone transform in frequency band n, f is the center frequency, τ is the delay time, and Q is the bandwidth or cycle constant of decay.

This allowed us to directly manipulate whether the water sounds generated by the model respected scale-invariance across spectral bands or not. Scale-invariant sounds were generated when the temporal structure of the chirps scaled relative to their center frequency. For variable-scale sounds, the chirps in different spectral bands varied in their temporal structure relative to their center frequency (Fig. 1). We used near-infrared spectroscopy to test whether the newborn brain is already able to discriminate between these artificially generated scale-invariant and variable-scale water sounds, similarly to adults (Geffen et al., 2011) and 5-month-old infants (Gervain et al., 2014).

Participants

Twenty-two healthy, full-term neonates (9 females; mean age 1.73 days, range 0–3 days; Apgar score ≥ 8) born in the Vancouver area participated. Data from 8 additional infants were collected, but excluded from the data analysis as they (i) failed to complete the experiment due to fussiness and crying (5), or (ii) provided poor quality data due to large motion artifacts or thick hair (3). All parents gave informed consent prior to participation. The Ethics Boards of the University of British Columbia and BC Women's Hospital, where the experiments took place, granted permission.

Material

Stimuli in the scale-invariant and variable-scale categories were generated using our computational model of water sounds (Geffen et al., 2011; and Fig. 1A). Sounds in both categories were matched for the frequency range, sound pressure level (amplitude root mean square), amplitude and timing parameters of the chirps. Chirps were gamma tone functions with parameters amplitude, frequency f, onset time, and cycle constant of decay Q drawn randomly from distinct probability distributions.

The only difference between the sounds in the two categories was the relation between Q and f. For both types of sounds, the distribution

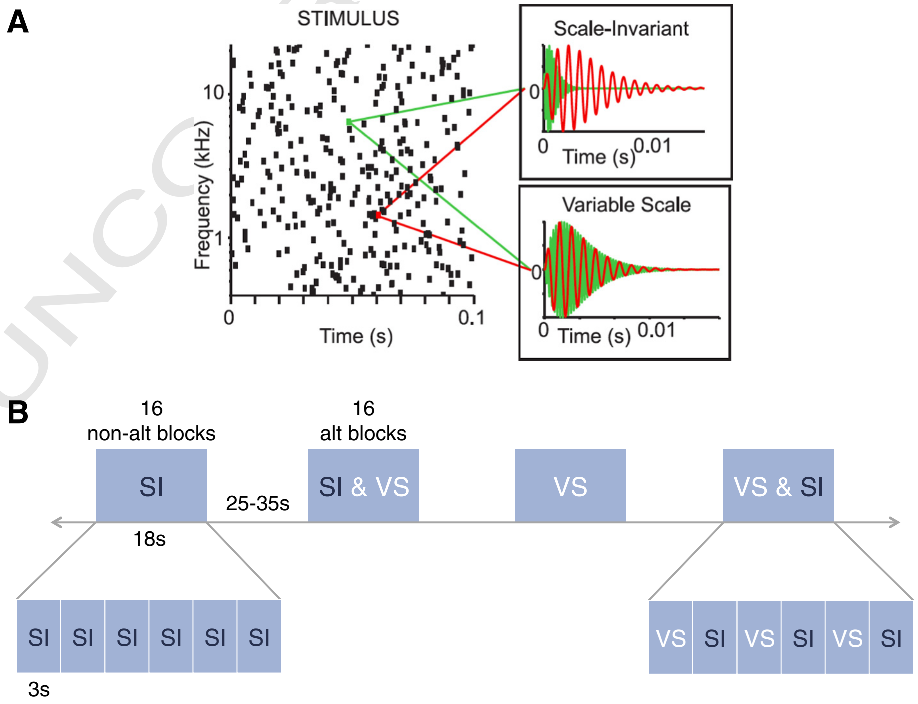

Fig. 1. A. The generative model used to synthesize the sound stimuli presented in the current study. B. The experimental design. SI: scale-invariant; VS: variable-scale.

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