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Acoustic cue selection and discrimination under degradation: Differential contributions of the inferior parietal and posterior temporal cortices

Mathias Scharinger *, Molly J. Henry, Jonas Obleser

Max Planck Research Group "Auditory Cognition", Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany

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ABSTRACT

Auditory categorization is a vital skill for perceiving the acoustic environment. Categorization depends on the discriminability of the sensory input as well as on the ability of the listener to adaptively make use of the relevant features of the sound. Previous studies on categorization have focused either on speech sounds when studying discriminability or on visual stimuli when assessing optimal cue utilization. Here, by contrast, we examined neural sensitivity to stimulus discriminability and optimal cue utilization when categorizing novel, non-speech auditory stimuli not affected by long-term familiarity. In a functional magnetic resonance imaging (fMRI) experiment, listeners categorized sounds from two category distributions, differing along two acoustic dimensions: spectral shape and duration. By introducing spectral degradation after the first half of the experiment, we manipulated both stimulus discriminability and the relative informativeness of acoustic cues. Degradation caused an overall decrease in discriminability based on spectral shape, and therefore enhanced the informativeness of duration. A relative increase in duration-cue utilization was accompanied by increased activity in left parietal cortex. Further, discriminability modulated right planum temporale activity to a higher degree when stimuli were spectrally degraded than when they were not. These findings provide support for separable contributions of parietal and posterior temporal areas to perceptual categorization. The parietal cortex seems to support the selective utilization of informative stimulus cues, while the posterior superior temporal cortex as a primarily auditory brain area supports discriminability particularly under acoustic degradation.

Introduction

Auditory categorization is vital for human behavior in acoustic environments, where auditory stimuli need to be associated with behaviorally relevant meanings. Oftentimes, however, listening conditions are not optimal, and discrimination between two categories may be impeded by internal (e.g. hearing impairment) or external (e.g. background noise) noise that either affects overall discriminability or selectively targets specific stimulus dimensions (e.g. spectral detail; Tuomainen et al., 2013).

Discriminability of auditory stimuli of course depends on the distinctiveness of their acoustic properties. If, for instance, sounds have to be associated with distinct categories A or B, differing in pitch and duration, discriminability of a particular stimulus should improve with greater distance from a hypothetical maximally ambiguous point that could be categorized as A or B with equal likelihood. Stimuli close to this point should be harder to discriminate than stimuli far away from this point. Accordingly, Euclidean distance in acoustic space has been argued to constitute an appropriate measure of perceptual distance for separable stimulus dimensions, such as pitch and duration (Nosofsky, 1985).

Discriminability may also deteriorate as a result of degradation. Degradation may simultaneously affect all available acoustic cues (e.g. by ambient noise), or selectively affect spectral cues (e.g. pitch), leaving temporal (duration) cues intact (Tuomainen et al., 2013). In this situation, the ability to make use of the most informative cue (i.e., duration, cf. Holt and Lotto, 2006) at the expense of other available cues should prove beneficial.

Previous functional brain imaging studies have investigated aspects of discriminability (Desai et al., 2008; Guenther et al., 2004) as well as aspects of optimal cue utilization in auditory categorization (Hill and Miller, 2010; Pugh et al., 1996; Shaywitz et al., 2001). Auditory categorization in general has been found to recruit the posterior part of the superior temporal gyrus (STG) and the planum temporale (PT; Desai et al., 2008; Griffiths and Warren, 2002; Guenther et al., 2004). Desai et al. (2008) found that activation in the (left) posterior STG (y-values in Talairach space between -30 and -40, inferior to the planum temporale, cf. Westbury et al., 1999) correlated with the degree to which participants processed stimuli in a categorical way, that is, how readily they could label the respective stimulus. Note that for the remainder of this article, we refer to the posterior STG/STS if y-values of peak coordinates (in Montreal Neurology Institute [MNI] space) are <-15.

* Corresponding author at: University of Leipzig, Institute of Psychology BioCog-Cognitive Incl. Biological Psychology, Neumarkt 9-19, D-04109 Leipzig, Germany.
E-mail address: mathias.scharinger@uni-leipzig.de (M. Scharinger).

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Several studies on speech processing identified the posterior STG, including parts of the PT, as subserving categorical (speech-specific) processing (Chang et al., 2010; Jäncke et al., 2002; Turkeltaub and Coslett, 2010). While these studies suggest that the posterior STG is sensitive to aspects of discriminability (ambiguity) in auditory categorization, it is less clear whether activity in this region would scale with more fine-grained differences in discriminability between non-speech stimuli.

A recurring cortical site involved in selective stimulus cue utilization is the parietal cortex, comprising the inferior parietal lobe and intraparietal sulcus (Geng and Mangun, 2009; Hill and Miller, 2010; Pugh et al., 1996; Rinne et al., 2007; Shaywitz et al., 2001), situated within a larger network associated with executive function (Corbetta et al., 2000; Posner and Dehaene, 1994). Aside from its role in spatial auditory attention (Alain et al., 2007; Brunetti et al., 2008), the IPL has been found to support the utilization of informative acoustic cues in a given listening situation (e.g. Henry et al., 2013). Despite a strong focus on visual processing while investigating the IPL, some studies suggest that this region subserves modality-independent functions of attention switching and object representation (Cusack et al., 2000, 2010).

In this study, we were interested in the role of the posterior STG in responding to fine-grained differences in discriminability of non-speech stimuli, and in the role of the IPL for optimal acoustic cue utilization depending on varying listening situations. Using non-speech stimuli ensured that categories were not *overlearned*; that is, participants had no prior experience with our experimental stimuli. In contrast to previous studies, our stimulus distributions and manipulation allowed us to examine discriminability and acoustic cue utilization within one experimental paradigm. We hypothesized that if the posterior STG supports discriminability in auditory categorization, activation there should be sensitive to changes in discriminability of auditory, non-speech stimuli. Further, if the IPL subserves optimal cue utilization in a domain-general manner (Henry et al., 2013), shifts in informativeness of acoustic cues should lead to increased activation in this region.

Materials and methods

Participants

Thirty-six healthy volunteers were recruited from the participant database of the Max Planck Institute for Human Cognitive and Brain Sciences (all right-handed, 18 females, age range 20–31 years, mean age 25.7; standard deviation [*SD*] = 2.8 years). They were native speakers of German with no self-reported hearing impairments or neurological disorders. Participants gave written informed consent and received financial compensation for their participation. All procedures followed the guidelines of the local ethics committee (University of Leipzig) and were in accordance with the Declaration of Helsinki.

Stimuli

Auditory stimulus tokens differed in spectral and durational properties. The base for all stimuli was an inharmonic narrow-band sound composed of 17 components. The lowest component frequency was 500 Hz, and the frequencies of the additional 16 components were related to each other by a ratio of 1.15 (Fig. 1A, bottom; Goudbeek et al., 2009; Scharinger et al., 2014). Spectral manipulations constituted filtering the base sound with a band-pass filter (second-order infinite-impulse response, IIR) with a single frequency peak that was unique

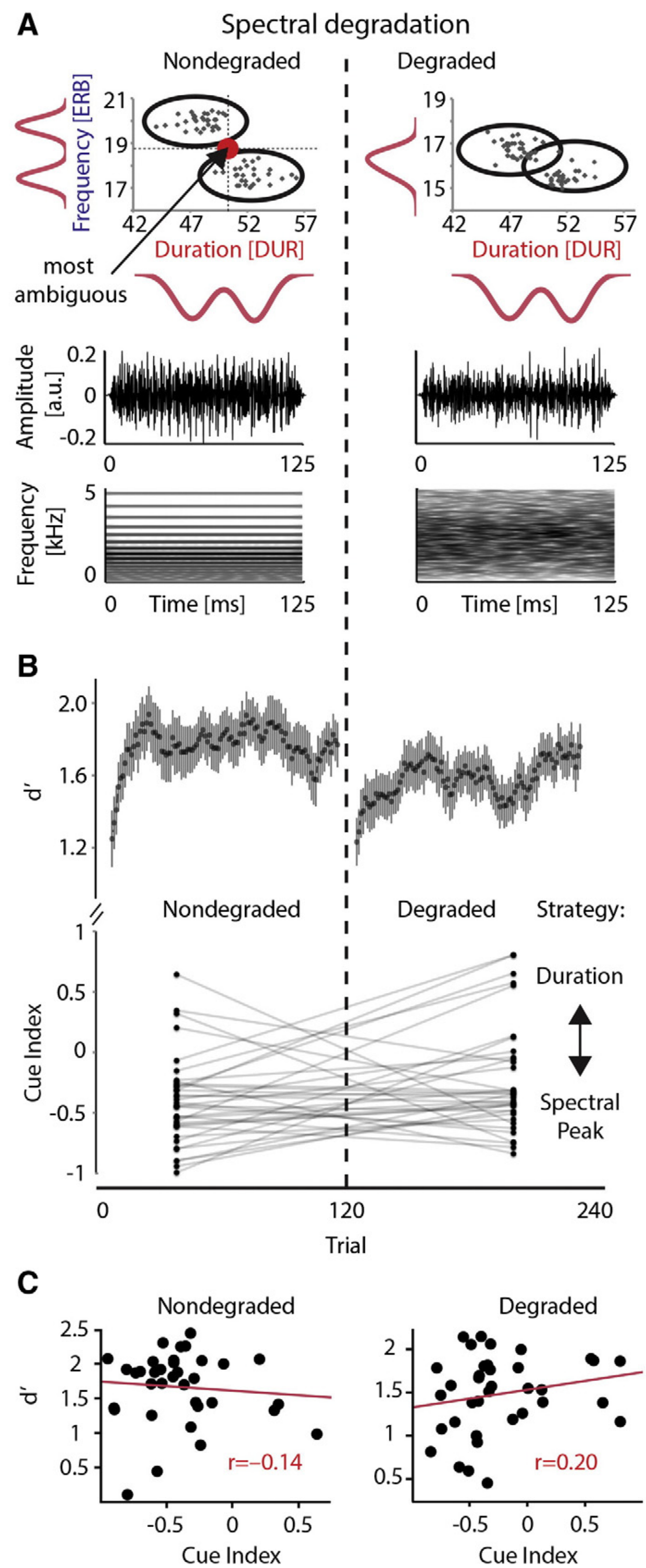

Fig. 1. Stimulus characteristics and behavioral results. A. Top: Representation of sounds with varying spectral peaks (ERB; y-axis) and durations (DUR; x-axis). Distributions are indicated by ellipses; black dots show exemplary distributions for a representative participant. Bottom: Acoustic properties of sounds in the nondegraded (left) and degraded (right) conditions. Duration and amplitude envelope were unaffected by degradation, while spectral properties were smeared. B. Behavioral performance results. Top: Perceptual sensitivity (d') over time, obtained from sliding windows over nondegraded and degraded trials per participant (window size = 20 trials, step size = 1 trial). Error bars show the standard error of the mean. Bottom: Comparison of cue indices across conditions; black dots show individual participant data. Mean cue index values between conditions are connected for each participant. C. Correlations of d' and cue index in the nondegraded (left) and degraded (right) conditions.