

## Hearing and orally mimicking different acoustic-semantic categories of natural sound engage distinct left hemisphere cortical regions

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### ABSTRACT

Oral mimicry is thought to represent an essential process for the neurodevelopment of spoken language systems in infants, the evolution of language in hominins, and a process that could possibly aid recovery in stroke patients. Using functional magnetic resonance imaging (fMRI), we previously reported a divergence of auditory cortical pathways mediating perception of specific categories of natural sounds. However, it remained unclear if or how this fundamental sensory organization by the brain might relate to motor output, such as sound mimicry. Here, using fMRI, we revealed a dissociation of activated brain regions preferential for hearing with the intent to imitate and the oral mimicry of animal action sounds versus animal vocalizations as distinct acoustic-semantic categories. This functional dissociation may reflect components of a rudimentary cortical architecture that links systems for processing acoustic-semantic universals of natural sound with motor-related systems mediating oral mimicry at a category level. The observation of different brain regions involved in different aspects of oral mimicry may inform targeted therapies for rehabilitation of functional abilities after stroke.

### 1. Introduction

Anthropological theories of glottogenesis (evolution of spoken language systems) propose a ‘default’ mouth-gesture hypotheses behind transitions from episodic to mimetic cultures in hominins (Condillac, 1746 (1947); Darwin, 1871/1981; Donald, 1991; Johannesson, 1950; Paget, 1944, 1963; Sterelny, 2012; Tylor, 1868; Wallace, 1895). Anthropological and cognitive psychology theories converge on the view that conceptual systems associated with oral mimicry of events of the observed world are likely to have played a central role in both the ontogenesis and phylogenesis of communication and language abilities (Arbib, 2005; Hewes, 1973; Imai, Kita, Nagumo, & Okada, 2008; Jackendoff, 2003; Ramachandran and Hubbard, 2001). As such, oral communication form should show a resemblance to properties of sensory-motor and affective referents, as addressed in theories of sound symbolism (Asano et al., 2015; Imai and Kita, 2014; Kanero, Imai, Okuda, Okada, & Matsuda, 2014; Sapir, 1929; Taylor and Taylor, 1962; Weiss, 1964) and iconicity (Perniss and Vigliocco, 2014). Recent theories further posit that the ability to both perceive and orally mimic events depicting incidental sounds of locomotion and tool-use (action sounds), as well as mimicry of animal calls (vocalizations), were likely

to have represented some of the most rudimentary semantic categories of natural sound that contributed to the early stages of hominin oral communication (Falk, 2004; Larsson, 2014, 2015). Moreover, in stroke recovery models, observation therapies (observation with intent to imitate or mirror) can facilitate the voluntary production of movement: However, there remains a need for advances in neuroscientific frameworks of goal-directed motor production and communication to enable rigorous testing of rehabilitation hypotheses (Garrison, Aziz-Zadeh, Wong, Liew, & Winstein, 2013; Garrison, Winstein, & Aziz-Zadeh, 2010; Pomeroy et al., 2005). In sum, it remains unclear if, or the extent to which, neuronal systems mediating oral mimicry might be rooted in networks associated with sensory systems (e.g. auditory perception), reflecting potential vestiges of earlier modes of communication at a semantic category level.

From the perspective of hearing perception, we recently developed a neurobiological model for the processing of different acoustic-semantic categories of real-world natural sounds that may apply to all social mammals with hearing ability (Brefczynski-Lewis and Lewis, 2017): This model (Fig. 1) was based largely on neuroimaging results from both human adults (Belin, Zatorre, Lafaille, Ahad, & Pike, 2000; Clarke, Bellmann, de Ribaupierre, & Assal, 1996; Engel, Frum, Puce,

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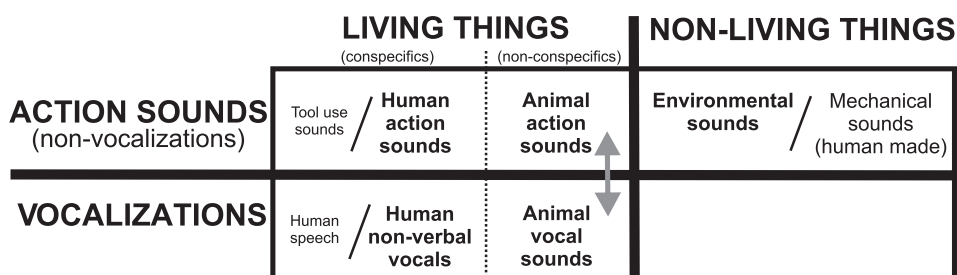


Fig. 1. A neurobiological model of the organization of the human brain for processing and recognizing different acoustic-semantic categories of natural sounds [from [Brefczynski-Lewis and Lewis \(2017\)](#)]. Bold text in the boxed regions depict rudimentary sound categories proposed to represent ethologically relevant categories germane to sound recognition for all mammalian species. Human speech, tool use sounds, and human-made machinery sounds are represented as extensions of these categories. Vocal and instrumental music sounds are re-

garded as higher forms of communication, which rely on other networks. The present study is testing the putative functional boundary (double headed arrow) of cortical networks for mimicking action sounds versus mimicking vocalizations using animal (non-conspecific) sound stimuli. Refer to text for other details.

Walker, & Lewis, 2009; Engelen et al., 2006; Lewis et al., 2009; Lewis, Brefczynski, Phinney, Janik, & DeYoe, 2005; Lewis, Talkington, Puce, Engel, & Frum, 2011; Lewis, Talkington, Tallaksen, & Frum, 2012; Webster et al., 2017) and infants (Geangu, Quadrelli, Lewis, Macchi Cassia, & Turati, 2015). This included three basic categories of sound-source: (1) action sounds (non-vocalizations) produced by ‘living things’, with human (conspecific) and non-human animal sources representing two subcategories; (2) action sounds produced by ‘non-living things’, including environmental sounds and human-made machinery; and (3) vocalizations (‘living things’), with human versus non-human animals as two subcategories therein. This model was supported in a study that utilized non-human animal action sounds and vocalizations (also used in the present study), which minimized potential confounds related to the processing of deeper semantic encodings in meaning conveyed by commonly experienced (“over-learned”) human conspecific sounds (Webster et al., 2017). The goal of the present study was to determine if this same basic organizational principle, namely the processing along separable cortical pathways, might also be respected in some of the cortical regions involved in planning and orchestrating oral mimicry of these same sounds at a categorical level.

Our first (null) hypothesis was that brain regions involved in oral mimicry of the two distinct categories would show no major network-level differences in activation (given the resolution of fMRI), apart from potential differences in primary motor cortices involved directly in laryngeal versus oral-facial muscle control or from issues of mimicry difficulty. Our second (main, alternative) hypothesis was that, similar to the double-dissociation of brain networks we recently revealed mediating activation preferential for perception of one versus another acoustic-semantic category of natural sounds, there would also be a dissociation of brain regions showing specificity for oral mimicry for one versus another category of natural event type. Evidence in support of this latter hypothesis would potentially identify gross-level network mechanisms for how different types or aspects of semantic information representations are routed. This could reflect different form-meaning mappings or working memory operations between hearing acoustic-semantic universals characteristic of different categories of natural sound events and oral mimicry of those same categories of events. Identifying such mechanisms would have significant implications for future studies designed to further understand models of oral communication acquisition and production, both in terms of neurodevelopment of mimicry during infancy and potentially in rehabilitative strategies to facilitate recovery from aphasia after stroke or traumatic brain injury.

## 2. Methods

### 2.1. Participants

We recruited 16 English speaking participants (19–26 years of age, 9 female, 15 right-handed, and 15 native English speakers). Participants had no previous history of major neurological or psychiatric disorders, and a self-reported normal range of hearing with no auditory or vocal

production impairments. Informed consent was obtained for all participants following guidelines approved by the West Virginia University Institutional Review Board.

### 2.2. Sound stimuli

The sound stimulus set consisted of 20 animal vocalizations and 20 animal action sounds, which were a subset of those used in our earlier study of categorical sound processing (Webster et al., 2017). Rationale for selecting these sound stimuli, which were professional recordings of isolated animals (Sound Ideas, Inc., Richmond Hill, Ontario, Canada), was both the perceived ability for them to be mimicked orally and the clarity of their semantic category membership (clearly non-human animal sounds, and being a vocalization or non-vocal action sound, as detailed in our earlier study). After fMRI participant interviews from the present study, two sound stimuli per category were deemed as being perceived as slightly ambiguous as to category, and were subsequently censored from all analyses, retaining 18 stimuli in each category (Table 1) for use in the data analyses described below. The two categories of sound stimuli were matched for duration ( $2.7 \pm 0.2$  s) and total root mean squared power ( $-17.6 \pm 0.5$  dB), converted to one channel (mono, 44.1 kHz, 16-bit; Adobe Audition 3.0, Adobe Systems Inc.) but presented to both ears, thereby removing any binaural spatial cues. Because emphasis of the study was based on sound categories representing ethologically valid events, they necessarily differed in several acoustic signal attributes, including those summarized in Table 1. The animal vocalizations were psychophysically assessed as having a relatively negative emotional valence overall ( $n = 15$ , 8 female; Likert scale:  $-2 =$  very negative,  $0 =$  neutral,  $+2 =$  very positive:  $\text{Avg} \pm \text{SD} = -0.84 \pm 0.72$ ), while the ratings of the animal action sounds were more neutral ( $+0.39 \pm 0.35$ ), which were ratings that significantly differed from one another (single factor ANOVA,  $F_{1,34} = 42.7$ ,  $p < 10^{-7}$ ).

### 2.3. Scanning paradigms

#### 2.3.1. Scanning preparation

All participants practiced the oral mimicry task under two or three listening conditions. This first included practicing the mimicry of all sounds while seated in a sound isolation booth (Model 800A-RF shielded, Industrial Acoustics Co., North Aurora, IL, USA) and repeating practice with difficult sounds as needed. A second practice session involved lying down inside the bore of a simulation MRI scanner (Model PST-100444; Psychology Software tools, Inc., Sharpsburg, PA, USA) with a microphone apparatus positioned near their mouth until participants were comfortable with performing mimicry of all sound stimuli. This practice regimen cycle was repeated as necessary (1 or 2 sessions, and repeating individual sounds) to minimize activation of networks that might simply be associated with sound novelty, attentional demands, laughter, or potential motoric mimicry difficulty across the two sound categories, especially for the action sounds.

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