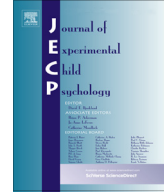




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The role of age and executive function in auditory category learning



Rachel Reetzke^a, W. Todd Maddox^{b,c,d,e}, Bharath Chandrasekaran^{a,b,c,d,*}

^a Department of Communication Sciences and Disorders, Moody College of Communication, The University of Texas at Austin, Austin, TX 78712, USA

^b Department of Psychology, College of Liberal Arts, The University of Texas at Austin, Austin, TX 78712, USA

^c Institute of Mental Health Research, College of Liberal Arts, The University of Texas at Austin, Austin, TX 78712, USA

^d Institute for Neuroscience, College of Liberal Arts, The University of Texas at Austin, Austin, TX 78712, USA

^e Center for Perceptual Systems, College of Liberal Arts, The University of Texas at Austin, Austin, TX 78712, USA

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ABSTRACT

Auditory categorization is a natural and adaptive process that allows for the organization of high-dimensional, continuous acoustic information into discrete representations. Studies in the visual domain have identified a rule-based learning system that learns and reasons via a hypothesis-testing process that requires working memory and executive attention. The rule-based learning system in vision shows a protracted development, reflecting the influence of maturing prefrontal function on visual categorization. The aim of the current study was twofold: (a) to examine the developmental trajectory of rule-based auditory category learning from childhood through adolescence and into early adulthood and (b) to examine the extent to which individual differences in rule-based category learning relate to individual differences in executive function. A sample of 60 participants with normal hearing—20 children (age range = 7–12 years), 21 adolescents (age range = 13–19 years), and 19 young adults (age range = 20–23 years)—learned to categorize novel dynamic “ripple” sounds using trial-by-trial feedback. The spectrotemporally modulated ripple sounds are considered the auditory equivalent of the well-studied “Gabor” patches in the visual domain. Results reveal that auditory categorization accuracy improved with age, with young adults outperforming children and adolescents. Computational modeling analyses indicated that the use of the task-optimal strategy (i.e., a conjunctive

* Corresponding author at: Department of Communication Sciences and Disorders, Moody College of Communication, The University of Texas at Austin, Austin, TX 78712, USA. Fax: +1 512 471 2957.

E-mail address: bchandra@utexas.edu (B. Chandrasekaran).

rule-based learning strategy) improved with age. Notably, individual differences in executive flexibility significantly predicted auditory category learning success. The current findings demonstrate a protracted development of rule-based auditory categorization. The results further suggest that executive flexibility coupled with perceptual processes play important roles in successful rule-based auditory category learning.

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Introduction

Auditory category learning is a fundamental cognitive process that allows for the organization of high-dimensional, continuous acoustic information into discrete representations (Gifford, Cohen, & Stocker, 2014). Whether it is speech, musical scales, auscultation, or sound patterns (e.g., Morse code), learning to categorize new auditory information progresses throughout the lifespan. The ability to learn natural speech and musical categories is well studied during infancy and adulthood (Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 1997; Chandrasekaran, Yi, & Maddox, 2014; Kuhl, 2004; Trainor & Trehub, 1992; Yi, Maddox, Mumford, & Chandrasekaran, 2014). To our knowledge, there has been little attempt to *compare* the extent to which children and adults learn novel auditory categories. The current study focused on tracking the development of rule-based (RB) auditory category learning using artificial, experimenter-constrained category structures.

Previous work has shown that speech and musical categories are easily acquired during early infancy (Kuhl, 2004; Trainor & Trehub, 1992). The consensus is that speech and musical categories are optimally acquired via implicit learning processes (Kuhl, 2004) that are dependent on early maturing neural circuitry (Chandrasekaran, Yi, Blanco, McGeary, & Maddox, 2015; Yi et al., 2014). Learning speech and musical categories during adulthood, however, is known to be a more laborious process, requiring extensive auditory training (Lively, Logan, & Pisoni, 1993; Wong, Morgan-Short, Ettlinger, & Zheng, 2012). Several examples come from the speech domain; infants can rapidly acquire fine-grained speech categories within the first year of life (Kuhl, 2004). For example, within the first year of life, infants exposed to English are able to distinguish between the phonemes /l/ and /r/, both of which are phonemic in English (Kuhl, 2004). In contrast, Japanese-speaking adults struggle to learn the category distinction between /l/ and /r/, which are not phonemic in Japanese, even after extensive auditory training (Lively et al., 1993). These studies suggest fundamental differences in learning capacities as a function of age, with a potential disadvantage for acquiring speech categories later in life (Wong et al., 2012). Whether the general finding that poorer auditory category learning in adults relative to children generalizes to rule-based auditory categories has not been examined.

In the visual domain, extensive neuropsychological, neuroimaging, behavioral, and computational modeling studies have identified a fast-mapping and slow maturing rule-based, hypothesis-testing learning system *in addition* to a slow-mapping and earlier maturing implicit, procedural-based learning system (Ashby & Maddox, 2011; Ashby, Paul, & Maddox, 2011). Dual-learning system theoretical frameworks, such as the COVIS (Competition between Verbal and Implicit Systems), posit that the two learning systems are at least partially dissociable, with an early dominance for the rule-based, hypothesis-testing system in humans (Ashby & Maddox, 2011; Ashby et al., 2011). The rule-based system is dependent on working memory and executive attention to generate and maintain rules based on the visual dimensions underlying the stimuli. In contrast, the implicit, procedural-based learning system is not under conscious control (Ashby & Maddox, 2011). In this form of learning, striatal neurons learn to associate a group of sensory units with a motor response when learning is rewarded (Ashby & Maddox, 2011). The systems are neurally dissociable. The implicit learning system is critically dependent on the striatum and is likely to mature early in infancy (Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Nomura et al., 2007; Seger, 2008). In contrast, the rule-based,

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