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Incorporation of feedback during beat synchronization is an index of neural maturation and reading skills

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ABSTRACT

Speech communication involves integration and coordination of sensory perception and motor production, requiring precise temporal coupling. Beat synchronization, the coordination of movement with a pacing sound, can be used as an index of this sensorimotor timing. We assessed adolescents' synchronization and capacity to correct asynchronies when given online visual feedback. Variability of synchronization while receiving feedback predicted phonological memory and reading sub-skills, as well as maturation of cortical auditory processing; less variable synchronization during the presence of feedback tracked with maturation of cortical processing of sound onsets and resting gamma activity. We suggest the ability to incorporate feedback during synchronization is an index of intentional, multimodal timing-based integration in the maturing adolescent brain. Precision of temporal coding across modalities is important for speech processing and literacy skills that rely on dynamic interactions with sound. Synchronization employing feedback may prove useful as a remedial strategy for individuals who struggle with timing-based language learning impairments.

1. Introduction

Speech comprises acoustic events such as syllables, word boundaries, and stress relationships that unfold over time to convey meaningful rhythms and patterns. These patterns are, however, not isochronous, as they fluctuate due to intentional (e.g., expressive contrasts) or artifactual (e.g., hesitations) motivations (Martin, 1972; Patel, 2008). Despite these timing variations, articulatory and syntactic constraints provide a predictable context for deciphering these patterns, allowing us to build a perceptual scaffold for directing attention to significant sound events while listening to dynamic speech (Jassem, Hill, & Witten, 1984; Lehiste, 1977). It has been suggested that this ability stems, in part, from endogenous, neurobiological oscillatory rhythms that entrain to the rhythmic structure of speech to generate temporal expectancies and facilitate allocation of attentional resources to periodic events (Bastiaansen & Hagoort, 2006; Fitzroy & Sanders, 2015; Giraud & Poeppel, 2012; Large & Jones, 1999; Large & Snyder, 2009; Nozaradan, Peretz, & Keller, 2016; Peelle & Davis, 2012).

When attending to sound, a listener must rely on precise encoding of temporal cues to inform perception, guide actions and react, and adjust future action plans. This process requires intentional integration between neural systems involving auditory, visual, motor, parietal, and prefrontal circuits (Fetsch, Pouget, DeAngelis, & Angelaki, 2011; Nath & Beauchamp, 2011; Pasalar, Ro, & Beauchamp, 2010). From childhood to adulthood, experience-dependent learning occurs, sculpting the structural and functional architecture of these neural networks, and particularly the connections among them (Hebb, 1949). The incorporation of external experiences into mental representations allows for the construction of a neocortex capable of flexible reactions to novel exposures (Quartz & Sejnowski, 1997).

When it comes to speech communication, automatic and precise temporal coupling between auditory, visual, and motor areas in the brain is imperative for the integration of sensory perception and motor production. Work exploring auditory-motor synchronization has employed sensorimotor synchronization

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(SMS), or "beat synchronization", in which a participant is asked to entrain motor actions (e.g., tapping a finger or striking a drum with a hand) to an isochronous auditory pacing stimulus (Repp, 2005; Repp & Su, 2013). This coordination of movement with sound has been used as an index of auditory-motor timing, and research suggests beat synchronization and speech processing rely on overlapping neural resources that facilitate temporal precision. Intriguing relationships have been observed between SMS variability and neural processing of speech (Tierney & Kraus, 2013a; Woodruff Carr, Tierney, White-Schwoch, & Kraus, 2016; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014), as well as language skills—particularly with reading (Tierney & Kraus, 2013b; Woodruff Carr et al., 2014).

Unfortunately, some individuals' auditory systems struggle to keep up with these timing demands. A hypothesis has emerged implicating imprecise auditory-neural encoding of temporal cues, particularly at the prosodic rate of speech, as a challenge contributing to speech and language processing disorders such as specific language impairment and dyslexia (Abrams, Nicol, Zecker, & Kraus, 2009; Goswami, 2011). It may also be the case that these individuals exhibit neurodevelopmental delays, compared to their peers.

Postnatal human cortical development unfolds over a much lengthier period than our mammalian relatives, with structural and functional plasticity extending into adulthood. The development of cortical regions is nonuniform, and longitudinal neuroimaging studies have discovered structural evidence that sensory regions such as the auditory cortex exhibit changes in white and gray matter through adolescence (Giedd et al., 1999; Paus et al., 1999; Whitford et al., 2007), while higher-order heteromodal association cortices mature subsequently (Gogtay et al., 2004). These structural findings are complemented by electrophysiological functional observations of the maturation of auditory-evoked potentials (Albrecht, Suchodoletz, & Uwer, 2000; Whitford et al., 2007). Cortical auditory evoked potentials (CAEPs) have been tracked through adolescent development, with the reduction of P1 and the increase of N1 amplitudes used as markers of auditory processing maturation (Bishop, Hardiman, Uwer, & von Suchodoletz, 2007; Fitzroy, Krizman, Tierney, Agouridou, & Kraus, 2015; Mahajan & McArthur, 2012; Ponton, Eggermont, Kwong, & Don, 2000).

Neural oscillatory activity also develops over the lifespan (Clarke, Barry, McCarthy, & Selikowitz, 2001; Whitford et al., 2007) and has been linked to brain maturation (John et al., 1980). Maturational changes have particularly been observed over adolescence in the gamma band, with resting-state gamma activity decreasing into adulthood (Tierney, Strait, O'Connell, & Kraus, 2013). This developmental trend may have functional cognitive and linguistic consequences: as resting gamma increases with age in early childhood, infants with more gamma activity at rest develop better language skills (Benasich, Gou, Choudhury, & Harris, 2008), while adolescents with less resting gamma perform better on reading-related tasks, following the developmental trend of decreasing gamma activity into adulthood (Tierney, Strait, & Kraus, 2014).

Insight into the development of timing-based multimodal integration during adolescence might be accomplished through an SMS task that requires online incorporation of performance feedback. Synchronization with feedback requires intentional, cognitive control of a typically automatic process. During synchronization tasks, humans tend to anticipate the beat (Aschersleben, 2002). With the incorporation of feedback, participants may be forced to inhibit this natural tendency while correcting their timing to more accurately align with the beat onset. Given that prefrontal cortex and inhibitory processes are developing during adolescence, this could make synchronizing with feedback a useful metric for the maturation of attentional control and multi-modal integration mechanisms.

We suspect integration across auditory, visual, and motor modalities can reveal maturity of these systems; in particular the prefrontal circuitry involved in sensorimotor synchronization. To test this hypothesis, we had adolescents perform a beat synchronization task with and without visual feedback, and compared their ability to incorporate feedback to language skills, cortical processing of speech, and oscillatory activity. We predicted that individuals better able to incorporate feedback during beat synchronization would exhibit more mature neural processing of sound and advanced reading skills relative to their peers. This would provide both a lens into neurodevelopment and further evidence for the use of synchronization—with feedback—as a strategy for remediation.

2. Materials and methods

2.1. Participants

Adolescents ($N = 74$, 38F, $M = 17.96$, $SD = 0.98$ years) were recruited from the Chicago area. All participants had normal pure tone hearing thresholds (<20 dB normal hearing level air conduction thresholds for octaves from 125 to 8000 Hz, with no apparent air-bone conduction gap), passed a screening of peripheral auditory function (normal otoscopy, distortion product otoacoustic emissions at least 6 dB above the noise floor from 750 to 8000 Hz) and click-evoked auditory brainstem response latency (identifiable wave V latency within lab-internal normal limits of 5.24–6.30 ms). No participant reported cognitive or neural deficits, nor did they report diagnosis of attention deficit or reading disorder. Parental/guardian informed consent and adolescent informed assent (or participant consent if the participant was over 18 years old) were obtained. The Institutional Review Board of Northwestern University approved all procedures, and participants were monetarily compensated for their participation.

2.2. Beat synchronization

Beat synchronization was assessed using Interactive Metronome® (ClearTech Interactive), with the participant instructed to clap two hands together in a fluid circular motion against a hand trigger in time with a pacing tone delivered over headphones. Synchronization was performed at a rate of 0.9 Hz under two conditions: without feedback (No Feedback) for 1 min, followed by synchronization with Feedback for 3 min. During the Feedback condition, the participant saw a visual indicator on a computer screen of the asynchrony between their last clap and the 'target' beat (milliseconds before or behind the target beat); see Fig. 1 for a schematic representation of the Feedback computer screen. These millisecond offset indications appeared in a colored box spatially corresponding to their offset in relation to the target, with each box representing a 30 ms window. If the participant clapped ±15 ms in relation to the target, the offset in milliseconds appeared in the central green[3] box. The example in Fig. 1 represents a hit that was 27 ms early, so it appears in the yellow box to the left of the target.

Interactive Metronome® provided hardware, software, and financial support for this project but were not involved in research design, analysis, or interpretation of results. The authors declare no personal conflicts of interest in Interactive Metronome®.

[3] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.