

Pupillary synchrony to natural speech in 6-month-old infants

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During the first year of life, infants use multiple cues—including syllabic and prosodic regularities—to segment speech into potential word candidates [1-4]. However, how infants discover these regularities, and how they determine which are most relevant for segmentation, remains debated [3,4]. Here, we propose that part of the answer lies in how the brain synchronizes to temporal structure during speech perception. For example, neural oscillations in the auditory cortex track the speech amplitude envelope at syllabic and prosodic timescales from early in development [5,6], an ability that could selectively enhance infants' attention to either syllabic or prosodic regularities during segmentation. Motivated by recent findings that changes in pupil size also synchronize with auditory rhythms [3,7,8], we tested whether infants' pupils synchronize with natural speech and how this ability relates to speech segmentation during the first months of life.

German-learning 6-month-old infants ($N = 70$) were tested using a central fixation paradigm [9]. They heard passages of infant-directed speech, each containing 6 sentences ending with the same nonce word (*rieken*, *tuhpen*, *wühnen*, or *pahlen*). Infants were familiarized with passages containing 2 of these nonce words until they accumulated 45s of listening time per passage. At test, infants heard 12 trials in which an isolated word (familiar or novel) was repeated for up to 21 s or until they looked away for 2 consecutive seconds. Half of the infants heard full words (e.g., *pahlen*) and half heard lexical stems (e.g., *pahl*). Pupil size was recorded with a Tobii Pro Spectrum eye tracker at 600Hz, and infants' looking behavior was manually coded throughout the experiment.

Infants' pupillary responses during the familiarization, compared to a silent baseline, showed an increase in power between 1 and 6Hz (Figure1C). These frequencies overlap with the peaks in the cochlea-filtered amplitude modulation spectrum [10] of the sentences (Figure 1A). Because these frequencies correspond to prosodic and syllabic regularities in speech [5], we filtered the speech envelope and the pupillary signal into Delta (prosodic rate: 1–3Hz) and Theta (syllabic rate: 4–6Hz) frequency bands and computed the phase-locking value (PLV) at lags of 0–500ms. Z-normalized PLV values (Figure1C) revealed a significant increase in synchrony from chance that peaked at ~200ms for Delta ($M=0.40$, $SD=1.53$, $p<0.01$) and ~275ms for Theta frequencies ($M=0.37$, $SD=1.16$, $p<0.001$). Therefore, infants' pupils spontaneously synchronize with the speech envelope at prosodic and syllabic timescales.

Crucially, infants' proportional looking times to novel versus familiar test trials revealed a significant cross-over interaction between synchronization and the two frequency bands (Figure1D; $B=0.15$, $SE=0.04$, $p<.01$). Higher pupillary synchrony at prosodic rates (Delta, 1-3Hz) predicted a preference for familiar words at test ($Est.=-0.05$, $SE=0.02$, $p=.020$), and synchrony at syllabic rates (Theta, 4-6Hz) a preference for novel ones ($Est.=0.11$, $SE=0.04$, $p=.010$). This cross-over interaction suggests that both Theta and Delta synchrony can help infants to segment words, with the differences in Theta/Delta synchrony likely reflecting task difficulty. Specifically, higher synchrony at the syllabic rate (theta, 4–6 Hz)—which was associated with a novelty preference that has been linked to cognitively less demanding tasks [11]—appears to make the word segmentation task easier for infants acquiring a morphologically rich language such as German as early as 6 months of age.

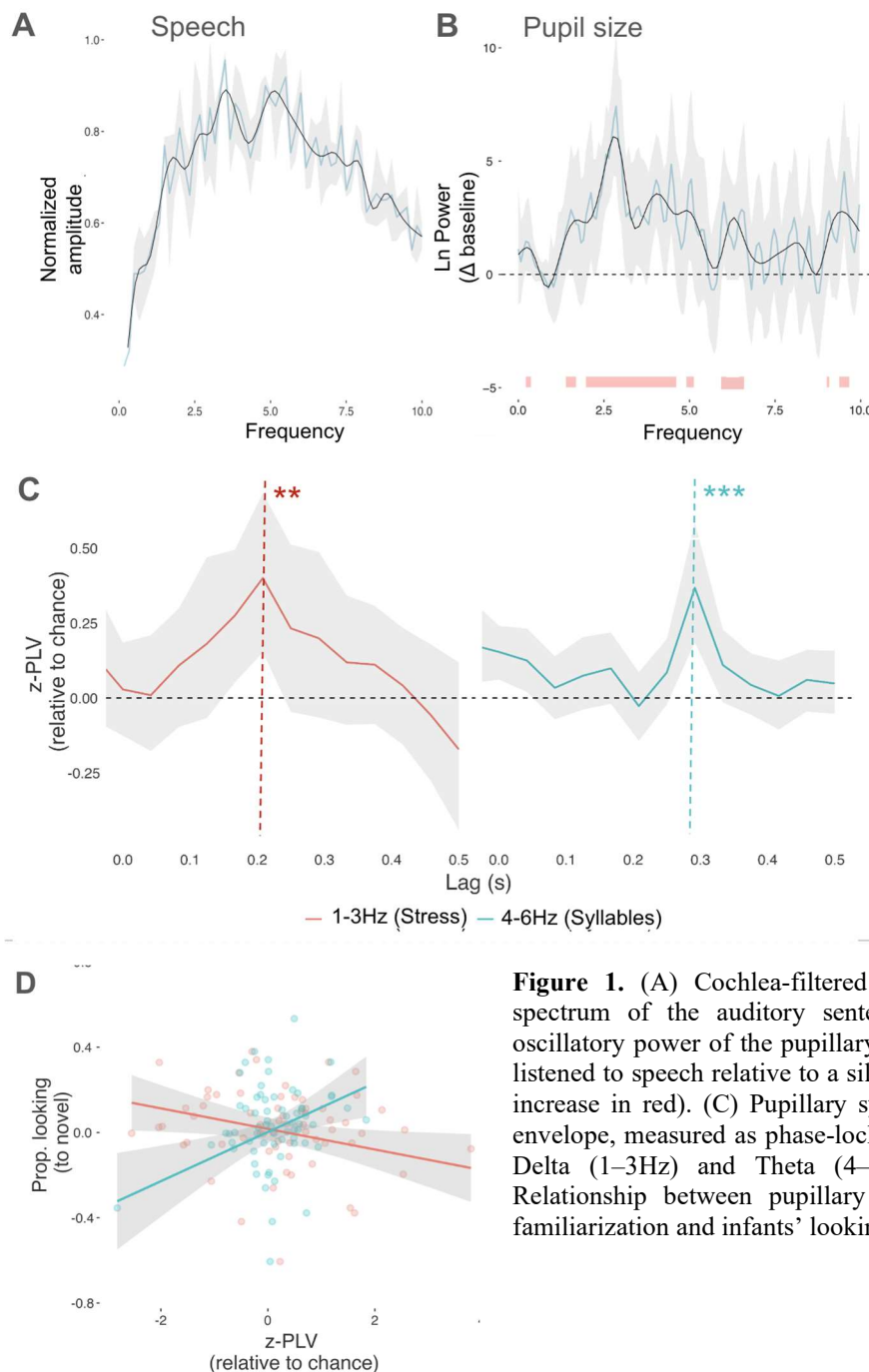


Figure 1. (A) Cochlea-filtered amplitude modulation spectrum of the auditory sentences. (B) Increase in oscillatory power of the pupillary response while infants listened to speech relative to a silent baseline (significant increase in red). (C) Pupillary synchrony to the speech envelope, measured as phase-locking value (PLV) in the Delta (1–3Hz) and Theta (4–6Hz) frequencies. (D) Relationship between pupillary synchrony during the familiarization and infants' looking times at the test.

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