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Within-Day Variations in Infant Body Position Predict Caregiver Speech Input

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Research Highlights

- Tested how infants' body positions (supine, prone, sitting, upright, and held) relate to adults' speech input in naturalistic home settings.
- Machine-learning algorithms predicted infants' body positions from motion sensors embedded in custom leggings.
- Adults spoke relatively more when holding infants and while infants sat, but less frequently when infants were prone and supine.
- Results provide partial support for theorized links between motor skill acquisition and language development.

Abstract

Infants' time spent in different body positions varies substantially within a day: lying *supine* on their backs, crawling or playing while *prone* on their bellies, *sitting* on the floor or in seating devices, standing or walking *upright* on two feet, and *held* by an adult. Infants may spend long periods in one position, such as sitting in a highchair, followed by periods of switching positions (e.g., prone and upright), such as during play. Speech input has been linked with infants' placement and motor development (Karasik et al., 2014; Malachowski et al., 2023). Here, we extend past work to ask whether adults speak more frequently depending on infants' time spent in different body positions throughout the day. We gathered home recordings from 64 infants in two age groups, 4-7 months and 11-14 months, using movement sensors to measure body position and a LENA® audio recorder to estimate adult word count. Data were analyzed in 10-minute bins throughout the day to determine whether within-day differences in infants' time spent in each position were associated with the frequency of adult's speech. Indeed, increased time spent supine and prone predicted fewer adult words, whereas increased time sitting and held predicted increases in word count. Upright was age dependent, with more time spent upright predicting an increase in word count for younger infants, but a decrease for older infants. These findings reveal the importance of considering infants' body position in understanding speech input and subsequent language development.

Keywords: body position, motor development, speech input, language development, wearable sensing, machine learning

Within-Day Variations in Infant Body Position Predict Adult Speech Input

Over the course of the first year of life, infants' time spent in various body positions changes dramatically (Franchak, 2019; Franchak et al., 2023). At birth, infants have limited motor skills and are confined to positions their caregivers place them in until they eventually obtain the ability to independently choose their own positions. As a result, younger infants spend a large proportion of their time supine on their backs and held by caregivers, in contrast to older infants who spend more time in sitting and upright positions (Adolph & Berger, 2011, Franchak, 2019; Franchak et al., 2024). Acquiring new motor skills—independent sitting, crawling, walking—alters how infants engage with their environment, creating new learning opportunities and changing infant-caregiver interactions (Gibson, 1988). This is known as a developmental cascade, in which changes in one area of development lead to changes in a seemingly unrelated area. Some cascades link motor skill and cognitive development, such as the association between the onset of sitting and how infants perceive objects (Soska et al., 2010) and between crawling and the development of mental rotation ability in infants (Schwarzer et al., 2013).

The acquisition of new motor skills is also theorized to play a cascading role in language development (Karasik et al., 2014; Kretch et al., 2025; Libertus & Violi, 2016; Oudgenoeg-Paz et al., 2012; Schneider & Iverson, 2022; Verhoef et al., 2025; Walle & Campos, 2014). Libertus and Violi (2016) observed that age of sitting acquisition is related to receptive vocabulary at 10 and 14 months. Similarly, walking acquisition is associated with accelerated language development: Among a sample of 12.5-month-olds, walking infants had significantly larger receptive and productive vocabularies compared to crawling infants (Walle & Campos, 2014). Additionally, among crawling infants, action directives were found to have a positive association with receptive vocabulary size (Lopez & Walle, 2024) and the frequency of producing action directives has been shown to differ between caregivers of crawling and walking infants (Karasik et al., 2014). Other investigations showed that earlier walking onsets predicted larger productive vocabularies, (Oudgenoeg-Paz et al., 2012), although Moore and colleagues (2019) did not find a significant relation.

Despite these associations found between motor skill development and language development, more work is necessary to fully understand **why** they might be linked. If it is indeed a developmental cascade, there must be some downstream effect of acquiring or improving a motor skill that facilitates word learning. That is, developmental improvements in motor skill might lead to changes in infants' daily motor experiences that, in turn, shape the content and/or the frequency of speech input they receive from adults. Here, we focus on one type of motor experience; infants' body position (i.e., supine, prone, sitting, upright, or held by an adult). Motor **experiences** reflect what infants are doing in the moment (i.e., sitting), in contrast to motor **skill**, which reflects infants' ability to perform a movement (i.e., independent sitting ability). Developmental improvements in motor skill predict differences in motor experiences. For example, infants who can walk spend more time upright (Franchak et al., 2024). But motor experiences also relate to caregiving and daily routines; for example, infants may be placed in a sitting position in a high chair even if they cannot sit independently on the floor.

Prior work has demonstrated that the **content of speech input**—such as the specific types of speech heard by the infants—is linked to language development (Rowe, 2012; Weizman & Snow, 2001). Similarly, the overall **frequency of speech input**—how often speech is heard by the infant—has been found to promote language acquisition (Hurtado et al., 2008; Huttenlocher et al., 1991; Weisleder & Fernald, 2013). The current study tests whether the frequency of speech input varies in relation to infants' body position in everyday life. Although testing speech content is beyond the scope of our investigation, we will review the potential cascading effect motor skills and experience—specifically sitting and walking—may have on both the content and frequency of speech input to situate our study in the broader literature linking motor and language development.

Potential Cascades Between Motor Skill, Motor Experience, and Speech Input

The content of speech input changes when infants learn to sit. Acquiring the ability to sit independently facilitates perceptual-motor exploration, such as increasing interactions with objects, which may influence what adults say. For example, infants' object interactions predict the content of speech input they receive from caregivers (Tamis-LeMonda et al., 2013; West & Iverson, 2017). West and Iverson (2017) found that when infants interacted with objects, caregivers' speech contained more object labels in contrast to periods of time when infants did not interact with objects. Additionally, periods of exploration have also been associated with increased referential language (Tamis-LeMonda et al., 2013), and caregivers provide more object labels when infants are in sitting compared to non-sitting positions (Kretch et al., 2025). This demonstrates a potential cascading effect of sitting on language development, with sitting leading to more object interactions, which in turn shapes the content of the speech input directed towards infants.

Independent walking also relates to the content of speech input. When infants are crawling, their ability to interact with objects is hindered due to the physical challenges involved: Their hands are occupied with supporting their body weight and maintaining balance, making it more difficult to manipulate and transport distal objects. The acquisition of walking enables infants to navigate their environment more efficiently, while freeing the hands for easier interaction with and transportation of objects (Adolph & Tamis-LeMonda, 2014). As a result, walking infants conduct more moving bids (presenting objects to caregivers), in contrast to crawlers who present more stationary bids (Karasik et al., 2014). Caregivers' speech content varies according to bid type, with mothers using more action directives to respond to moving bids compared to stationary bids. These findings highlight how infants' motor skills and experience may shape the content of the speech input they hear.

Motor experience may also relate to the frequency, not just the content, of adults' speech input. For example, infants' time spent in seating devices has been linked with a decrease in the total number of words they heard in comparison to when they were in other placements (Malachowski et al., 2023). This decrease in exposure may be explained by the social proximity between the caregiver and infant. Malachowski and colleagues (2023) highlight how the use of seating devices allows caregivers to spend more time away from their infants, engaging in daily chores and tasks without needing to keep as close by to supervise. In fact, caregivers frequently place their children in seating devices due to the convenience they provide (Callahan & Sisler, 1997). Thus, the frequency of infants' speech input may be influenced by infants' time spent sitting restrained.

Independent walking also predicts differences in the frequency of caregiver speech input. For example, caregivers spoke more frequently during periods when infants walked compared to crawled (Schneider & Iverson, 2022). Why might walking lead to increased speech input? Infants' production of gestures has been found to double after the onset of walking (West & Iverson, 2021), which may in turn lead to increased speech responses from caregivers. Moreover, walking infants (as compared with crawling infants) more often attempted to initiate a social interaction by looking at their caregivers (Clearfield et al., 2008), which may also boost the amount of speech heard by walkers.

Although infants' time spent sitting and walking has been associated with the frequency of adult speech input, there is still much unknown about these relations. A negative association has been found between the frequency of adult speech and infants' time spent in seating devices (Malachowski et al., 2023), but does this extend to periods of overall sitting time (both restrained and unrestrained)? Sitting has been linked to increases in face looking, mutual gaze, joint attention, and object interactions compared to more restrictive positions such as being prone (Franchak et al., 2018; Soska & Adolph, 2014), which may suggest that periods of unrestrained sitting enable infants to more actively engage with their environment. Additionally, when comparing supported and independent sitting, the latter is characterized by increased object interactions and time spent facing their caregivers (Kretch et al., 2023). Infants' social interactions, specifically joint attention with caregivers, have been linked with increased communication (Tomasello & Farrar, 1986) and their object interactions have been found to shape the content of speech input they receive (Tamis-LeMonda et al., 2013; West & Iverson, 2017). Therefore, while time spent restrained has been linked to a decrease in speech input, analyzing both periods of sitting restrained and independent sitting will offer a more comprehensive understanding of how everyday sitting experiences relate to speech input.

Similarly, although increased speech input has been observed during bouts of walking (Schneider & Iverson, 2022), it is unclear whether this finding extends to when infants are simply in an upright position and not necessarily walking. These differences in frequency of input may also differ with age depending on what infants can do within a certain type of motor state. A younger infant may spend time standing upright in a jumper or exersaucer that restricts their movement, whereas an older infant standing upright might be walking from room to room collecting objects to share with their caregivers. Additionally, most research has examined these relations in limited contexts and over short observational periods (e.g., Karasik et al., 2014; Schneider & Iverson, 2022). Investigating infants' body positions and speech input across an entire day will provide better insight into whether and how they relate.

Measuring Within-Day Relations between Motor Experience and Speech Input

Infants engage in various activities throughout a day—such as playing, eating, watching media—that create within-day variation in motor experience (Franchak et al., 2021). An infant may spend an hour switching between standing, sitting, and crawling during a bout of unrestricted play, followed by half an hour eating a meal in a high chair without changing position. If speech input varies according to infants' body position, those differences should be apparent within an infant, within a day, across the natural variation contained therein. Thus, it is important to gather full-day data about infants' experiences, since shorter recordings restrict the potential for capturing variability.

Unobtrusively measuring infants and caregivers using naturalistic, non-video methods is also important for reducing participant reactivity. Comparing the speech input during a structured play session with that during a naturalistic interaction, researchers found that the two contexts yielded different pictures of infants' language exposure (Tamis-LeMonda et al., 2017). Speech input during structured play was characterized by increased frequency and diversity, while bouts of silence were more common in naturalistic interactions. Additionally, a significant difference in the content of speech input has been observed when comparing day-long audio data versus hour-long video data (Bergelson et al., 2019). In hour-long video recording noun input was more frequent, the consistency of noun input was lower, and there were fewer declaratives and more questions from caregivers. This highlights the importance of collecting data across a typical day (rather than a laboratory session) using audio rather than video recording.

Methods for long-form audio recording are well-established. Using a LENA® (Language Environment Analysis) audio recorder, which records up to 16 hours, can capture day-long data about infants' speech input (Cristia et al., 2021; Ganek & Eriks-Brophy, 2018; Wang et al., 2020). For example, Weisleder and Fernald (2013) used LENA® to capture ~11 hours of speech input to investigate the impact early exposure has on later language development. Studies using day-long audio recording found that adult speech input and infant-caregiver interactions are associated with later language skills (Gilkerson et al., 2018; Weisleder & Fernald, 2013; Zimmerman et al., 2009), highlighting the importance of investigating factors linked to changes in the speech input infants receive.

However, examining how infants' motor experience covaries with speech input requires a method for measuring real-time motor activity across the entire day. Although it is typical to observe infants' motor experiences for an hour by video recording their activity (Chen et al., 2023; Karasik et al., 2014; Schneider & Iverson, 2022), full-day video recording with a researcher following infants throughout the day is not feasible. Instead, researchers have employed wearable inertial movement unit sensors (IMUs) to gather long-form recordings of motor experience (Airaksinen et al., 2020; Franchak et al., 2021; 2023; Gallen et al., 2025). Similar to an audio recorder, IMUs can be embedded in a garment worn by the infant so that they provide data on infants' movements wherever they go without the need for video. Machine learning classifiers have been developed to automatically classify body position (e.g. supine, prone, sitting, upright, and held) from continuously-recording sensor data with high accuracy (Airaksinen et al., 2020; Franchak et al., 2021; 2023). The current study is the first to pair audio and IMU recording in day-long data collection, providing a novel way of capturing how motor experience and speech input covary across the entire variation of daily experiences.

Current Study

To summarize, infants' motor skills and experiences are associated with changes in both the content and frequency of speech input they receive from caregivers (Karasik et al., 2014; Malachowski et al., 2023; Walle & Campos, 2014; West & Iverson, 2021), and frequency of speech input is positively associated with infants' vocabulary size (Hurtado et al., 2008; Huttenlocher et al., 1991; Weisleder & Fernald, 2013). However, there is a lack of research looking specifically at the relationship between infants' body position and the frequency of speech input they receive from adults, because most prior work focused on motor skill acquisition—sitting, crawling, and walking ability (Libertus & Violi, 2016; Oudgenoeg-Paz et al., 2012)—as opposed to real-time motor experiences—the actual time at home spent sitting, prone, or upright. To our knowledge, no prior study has looked at real-time relations between motor experience and speech input across an entire day in the home. The current study addressed this by employing an innovative home-recording methodology to simultaneously measure infants' body position from a machine learning classifier of wearable movement sensors (Airaksinen et al., 2020; Franchak et al., 2021; 2023) and the speech input using a LENA® audio recording device (Cristia et al., 2021; Ganek & Eriks-Brophy, 2018; Wang et al., 2020).

Our first aim was to determine whether infants' time spent in particular body positions was associated with the total number of adult words they were exposed to. We predicted that more time spent sitting, held, and upright would be associated with increases in adult word count, while supine and prone positions would be associated with decreases. While Malachowski et al. (2023) found that sitting restrained was associated with a decrease in speech input, the relationship between sitting time and speech input could also be positively associated when considering all types of sitting. As mentioned, sitting facilitates object interactions, gaze following, and joint attention all of which have been linked to speech input and language development (Beuker et al., 2013; Brooks & Meltzoff, 2005; Morales et al., 1998, 2000; Tamis-LeMonda et al., 2013; Tomasello & Farrar, 1986; West & Iverson, 2017). Similarly, standing upright should enable the same opportunities, therefore resulting in more abundant adult speech input. The hypothesis that held time will be associated with increased speech input is based on increased social proximity, which has been linked to more frequent word production from caregivers (Salo et al., 2021; Suarez-Rivera et al., 2023). In contrast, supine and prone positions limit infants' object interactions (Soska & Adolph, 2014), suggesting that more time in these positions may be associated with decreases in speech input.

Our second aim was to identify whether age moderated the relation between body position and speech input. As motor skills and experiences increase with age, time spent in different body positions may function differently in older versus younger infants, and adults may respond differently to infants of varying ages. For example, sitting time for a 4-month-old may be comprised of sitting in an infant seating device, which may result in a decrease in the total number of words they are exposed to (Malachowski et al., 2023). In contrast, sitting for a 12-month-old may consist of them playing with toys and displaying more communicative gestures, potentially resulting in more adult speech input. We recruited infants ages 4-7 and 11-14-months-old to investigate how speech input varies across age during which the mastery of motor skills varies substantially: These ages were chosen because they overlap with the onset ranges of sitting and walking (Adolph & Berger, 2011).

Method

Participants and Design

Sixty-five typically developing infants, ages 4 to 7 months (*n* = 29) and 11 to 14 months (*n* = 35), were recruited via community events and advertisements posted on social media sites. Families were drawn from suburban and urban areas of Southern California. Thirty infants were male and 35 were female. The ethnicity of 30 participants was reported as Hispanic/Latino/a, 24 as non-Hispanic, and 12 caregivers chose not to respond. Participants identified their infants' race as White (*n* = 24), more than one race (*n* = 14), Asian (*n* = 3), and African American (*n* = 2), or self-described their race as not fitting into one of the above categories (*n* = 8). Fourteen participants choose not to disclose their infants' race. Caregivers reported their highest level of education: Most completed a college or university degree (*n* = 46), some had partial college or specialized training (*n* = 6), and one caregiver had a high school diploma. Caregiver education was unavailable for 11 families.

Our sample came from a culturally and linguistically diverse region (Southern California, USA) with many bilingual households. Thirty-eight families spoke only English, 19 primarily spoke English with some Spanish, seven spoke only Spanish, and one spoke another language. We reran the analyses excluding the participant whose primary language could not be identified and obtained the same results, so we included them in the final sample. Small numbers of participants in naturally occurring subgroups (i.e., English only, Spanish only, mix of English/Spanish) precluded testing for language-specific effects.

The study employed a longitudinal design with participants completing up to four monthly sessions starting when they were 4 or 11 months of age and ending by 7 or 14 months of age. The sessions were scheduled within a window of ± two weeks of their 4, 5, 6, 7 and 11, 12, 13, 14 month birthdays. There were a total of 136 sessions across all participants, with each participant completing an average of 2 sessions (64 total sessions from younger infants and 72 from older infants). For the younger group, there were 45 sessions in which the infants could not sit independently and 19 sessions in which they could sit independently. For the older group, there were 46 sessions in which infants were unable to walk independently and 26 in which they could walk independently. The sample size was determined by resource constraints: We aimed to recruit as many participants as possible during the funding period.

All caregivers provided informed consent for participation in the study. Seven additional sessions were conducted, but data were not included due to caregivers not following instructions about placing the leggings (2 sessions), sensor malfunction (2 sessions), or sessions were too short (< 2 hours) to be included (3 sessions). Only one participant was completely excluded from the analyses because they only completed one session that was less than two hours in duration. To determine whether participant attrition was related to demographic characteristics, we compared participants who completed only one session with those who completed four. We found no significant differences in race ($X^2(3) = 2.25$, p = .522) or ethnicity ($X^2(1) = 0.05$, p = .826), suggesting attrition was not associated with these variables.

Participants were compensated $30 for each session they completed. The study procedures underwent thorough review and approval by the University of California, Riverside Institutional Review Board. Fifty-seven participants gave permission for their data to be shared on Databrary (https://nyu.databrary.org/volume/1637)

Apparatus

Infant body position was recorded using four MC10 Biostamp IMU sensors, with each sensor measuring 6.6 cm in length, 3.4 cm in height, and weighing 6 grams. Having built-in storage, the sensors recorded 12 hours of gyroscope data for angular acceleration and accelerometer data for linear acceleration at 62.5 Hz. The IMUs were embedded in a tightlyfitted pair of custom-made leggings that had four pockets sewn into the inside located at the hips and ankles on both legs (Figure 1). The sensors could be placed into pairs of leggings in various sizes to ensure an optimal fit for each infant, with a visual cue on the backside helping caregivers to correctly orient the leggings on infants' bodies.

A LENA® recording device measured speech input throughout the day. The device is a lightweight audio recorder with software that provides automated quantitative analyses of children's auditory environment with an algorithm designed to identify and provide estimates of speech near and clear to the infant (Cristia et al., 2021; Ganek & Eriks-Brophy, 2018; Wang et al., 2020). It has been validated as a reliable measure for both English and Spanish (Cristia et al., 2021; Weisleder & Fernald, 2013), making it suitable for our sample. The recorder was placed inside a LENA® shirt in a pocket situated on the infant's chest (Figure 1). With a 16 hour battery life, the device allowed for full-day recording.

Procedure

We followed a previously-validated procedure for gathering IMU sensor data to measure body position (Franchak et al., 2021; 2023). A researcher arrived at the participant's home with the devices already configured and placed inside the garments. The caregiver was asked to place the LENA® shirt and IMU-leggings on the infant. With the infant wearing both sensors, caregivers were instructed to go about their day as usual and to keep the infant wearing the equipment until bedtime. Caregivers were asked to log the start and end times of any periods when the equipment was removed. This included excursions outside of the home, diaper changes, and naps so that those times could be excluded from analysis (gray and white areas in Figure 2). Excursions outside of the home were excluded because the machine learning model used to classify body position was trained only on in-home data and is not a valid measure for outdoor behaviors such as riding in cars or strollers. The following day a researcher picked up the equipment and downloaded the data from each device in the lab.

Data Analysis

Although the goal was for participants to wear the sensors for the entire day, the actual usable data was less after excluding nap times and other times caregivers removed the sensors (e.g., excursions out of the house). Sessions contained 2.0-10.5 hours of usable data to analyze (M = 5.5, SD = 1.9). We analyzed within-day variation in movement and speech input by dividing each day into 10-minute bins from the earliest to latest times in each recording, with each bin overlapping with the previous by 5 minutes, resulting in a total of 8,974 bins across the entire dataset. Figure 2 shows a timeline for one participant's session to illustrate the adult word count and body position with columns indicating each 10-minute bin. Ten-minute bins were chosen to provide enough time for infants to potentially demonstrate various body positions and for adults to provide speech input, allowing for us to observe the variability across the day. Shorter bins (e.g. 30 s) might sample too little behavior for a stable measurement (producing many outliers and too many periods with no adult speech), whereas longer bins (e.g. thirty minutes) might obscure within-day variations. Slightly longer bins allow for more accurate measures and are more commonly used (Gilkerson et al 2015; Malachowski et al., 2023). Moreover, averaging data within 10-minute bins minimized the influence of any potential issues in synchronizing data between LENA and body position time series (which would be on the order of seconds).

Infant body position across the day was predicted from the IMU data using a previously-validated machine learning method (Franchak et al., 2021; 2023). The machine learning algorithm was trained to make a body position classification for each 4-s interval of sensor data.

For each 4-s interval, motion features were calculated to summarize the raw accelerometer and gyroscope data within each bin. Those motion features were used to train the machine learning model based on a “training” dataset of 80 sessions from this dataset whose body position was scored from video by trained human coders. Random forest models used the human-annotated body positions to learn to classify position from the sensor data alone. A leave-one-out cross-validation revealed that the model had high overall accuracy (M = 89.5%) and strong correlations between coded and predicted durations for each position (rs = .80-.98). A final model trained on all data in the training set was created and used to predict body position for every participant’s session throughout the day.

The model was trained to classify infant body position into five categories (supine, prone, sitting, upright, and held) based on the following definitions that human coders used to score ground truth body position categories from video. Supine was classified when the infant was lying on their back, lying on their side, or reclined in an infant restraint device. The infant was considered prone when lying on their stomach or in a crawling position where their spine was parallel to the ground. Sitting was classified when sitting on a surface, either on the floor, a seating device, or an adult’s lap. The infant was also considered to be sitting when in a kneeling position with their buttocks touching the backside of their legs/heels. Upright included times when the infant was kneeling on their knees, but their spine and legs were perpendicular with the ground, or they were standing on two feet. Any instance of the infant being carried by an adult was considered held. However, if the adult was sitting and the baby was in their lap, the infant’s body position was scored as if the adult was a surface (i.e., sitting if the infant sat in the adult’s lap, supine if the infant laid across the adult’s lap). Body position was scored irrespective of locomotion; therefore, when crawling infants were classified as prone and when walking they were scored as upright.

The LENA® device algorithm was used to automatically estimate the total number of adult words, both child and adult directed, over the course of the session. Using the ITSBin package (Anderson et al., 2021), we calculated adult word counts for each 10-minute bin from the .its file. Overall, research suggests that LENA® has good performance for various language communities, including children learning American English, Spanish, European French, Shanghai dialect and Mandarin (Canault et al., 2016; Gilkerson et al., 2015; Weisleder & Fernald, 2013; Xu et al., 2009) demonstrating high overall accuracy (Casillas & Cristia, 2019). When comparing LENA® generated adult word counts with human coders there is a strong association, with one study finding an ICC of .76 and another of .85 (Cristia et al., 2021; Malachowski et al., 2023). To check accuracy in our sample, we randomly selected 50 recording sessions and transcribed a random 5-minute clip from each. The correlation between our transcribed AWC and LENA's automated estimates was .78, suggesting that the AWC estimates in our data set are comparable to prior estimates. Timestamps were used to synchronize the LENA® data with the IMU-predicted body position time series.

We fit five linear mixed-effect models to associate time spent in each body position with adult word count. Each model included time spent in one of the five body positions as a fixed effect (supine, prone, sitting, upright, or held), age as a fixed effect, and the position*age interaction to predict adult word count using data from each 10-minute bin. Each fixed effect was mean-centered. Additionally, each individual participant was modeled as a random effect, with both random intercepts and random slopes for the time spent in each position (e.g. *AWC ~ held_time_centered * age_centered + (1 + held_time_centered | participant_id)*). We fit separate models for each body position because time spent in different positions is interdependent—more time spent in one position means less time spent in another—which violates the assumption of independence among predictors (if fit in a single model). Data processing and analyses were conducted using the tidyverse (Wickham et al., 2019), lme4 (Bates et al., 2015), and interactions (Long, 2019) packages in R version 4.3.2 (R Core Team, 2023).

Results

We examined the relation between infant body position and the speech input infants encountered throughout the day. Table 1 shows the results of each mixed-effect model predicting adult word count from the time spent in each position, infant's age, and their interaction. Although age was analyzed as a continuous variable, Table 2 provides descriptive statistics broken into younger (4-7 months) and older (11-14 months) groups to aid interpretation.

As a preliminary step before analyzing whether body position related to adult word count, we tested whether age was related to adult word count. Consistent with past findings we did not find an effect of age (Gilkerson & Richards, 2008; Rowe, 2012). Figure 3 shows that the average number of adult words was similar across ages ($p = .769$), but varied substantially between participants/sessions. Across ages, the total adult word count averaged $M = 255.0$ words per 10-minute bin ranging from 0 to 523.9.

Supine and Prone: Negative Associations with Adult Word Count

Across 10-minute bins throughout the day, longer supine durations within a bin predicted fewer adult words (Figure 4A). For every one-minute increase in time spent supine, adults produced ~11 fewer words per 10-minute bin. The linear mixed-effects model confirmed a significant negative association (Table 1), indicating fewer adult words when infants spent more time in a supine position. Additionally, there was no significant interaction found between age and supine time.

Adult word count was negatively associated with infants' duration of time spent in a prone position (Figure 4B). Specifically, for every one-minute increase in time spent in a prone position, total adult word count decreased by approximately 12 words per 10-minute bin. No significant interaction between age and prone time was found (Table 1).

Sitting and Held: Positive Associations with Adult Word Count

Increased sitting time was linked with an increase in speech input (Figure 4C). For every one-minute increase in time spent sitting, total adult word count increased by ~10 words per 10-minute bin. The results from the linear mixed-effects model confirmed a significant positive association (Table 1), indicating an increase in word count when infants were sitting. Additionally, no interaction was found between age and time spent sitting.

Increased time held by an adult predicted an increase in adult word count (Figure 4E). Specifically, for every one-minute increase in time spent held the total adult word count increased by ~40 words per 10-minute bin. The model confirmed a significant positive association (Table 1), indicating increased speech input when infants spent more time held. Additionally, there was no interaction found between age and held time.

Upright Position: Age-Dependent Association with Adult Word Count

The linear mixed-effects model predicting adult word count from time spent upright and age revealed a significant interaction, but no significant main effects of age or upright time (Table 1). As Figure 4D shows, time spent upright was positively associated with adult word count for younger infants, but negatively associated with adult word count for older infants. Separate follow-up models within each age group were conducted to confirm this interaction. For younger infants, a one-minute increase in upright time predicted ~19 more adult words per 10-minute bin ($\beta = 19.2$, $p < .01$). In contrast, for older infants, a one-minute increase in upright time predicted ~12 fewer words per 10-minute bin ($\beta = -11.754$, $p < .01$).

Discussion

This study examined how time spent in different body positions (supine, prone, sitting, upright, and held) predicts differences in adult speech frequency within a day, using full-day sensing to measure body position data across hours of naturalistic behavior. Our findings revealed a significant within-day relationship between infant body position and the number of adult words infants were exposed to. Specifically, periods of the day with longer durations of time spent sitting and held by an adult were associated with higher counts of speech input. In contrast, periods of the day with more supine and prone durations were linked to decreases in speech input. Only the effect of time spent upright varied significantly by age. For younger participants, more time spent upright predicted increases in adult word count, whereas for older infants more time spent upright predicted decreased in adult word count.

These findings are consistent with prior research showing that adult speech input varies across the day (Clemens & Kegel, 2021; Soderstrom & Wittebolle, 2013). Contextual factors and daily activities, such as book reading and playtime, mark changes in the frequency and content of speech input. The current findings identify infant body position as another factor that relates to within-day variations in the frequency of adult speech input. This builds on past research that associated infants' locomotor skills and both the frequency and content of speech input (Karasik et al., 2014; Schneider & Iverson, 2022), which in turn promotes vocabulary development (Hurtado et al., 2008; Huttenlocher et al., 1991; Rowe, 2012; Weisleder & Fernald, 2013; Weizman & Snow, 2001). Our study goes beyond past work to show that within-day differences in how much adults speak is associated with variations in motor experience, or how infants actually move, providing further insight into the relationship between motor development and speech input at the scale of a day.

Moreover, these findings help constrain the potential cascading mechanisms theorized to link motor development to vocabulary development (Libertus & Violi, 2016; Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014). Associations between the onset of independent sitting and vocabulary (Libertus & Violi, 2016; Oudgenoeg-Paz et al., 2012) could be facilitated by increases in speech frequency (in addition to or in combination with differences in content), since infants heard more speech while sitting across the age range tested. In contrast, associations between walking onset and vocabulary size (Walle & Campos, 2014) are unlikely to be mediated by changes to adult speech frequency, since we found that older infants (around the age of typical walking onset) heard less speech the more time they were upright. Instead, walking is more likely to influence language development through changes to the content of what adults say (Karasik et al., 2014).

Recent work provides support for this cascading effect. Independent motor skills, such as standing and walking, have been associated with prelinguistic communication and social development, suggesting that advanced motor skills may promote social behaviors that in turn support language development (Gallen et al., 2025). Consistent with this, motor skills have been linked to socially oriented activities and symbolic actions, which in turn are associated with language outcomes, further providing evidence of a developmental cascade in which motor development facilitates social development that then fosters language learning (Verhoef et al., 2025). In the remainder of the discussion, we consider potential explanations for why adults spoke more frequently when infants were sitting and held, but less frequently when infants were prone and supine.

Social Attention

Social interactions, such as joint attention and gaze following, play a role in shaping communication between adults and infants. For example, periods of joint attention have been linked to increases in communication between mothers and infants (Tomasello & Farrar, 1986). Body positions that enable more social attention may promote adult speech, while positions that hinder social attention may decrease speech input. Specifically, this might explain why sitting (as well as upright time for younger infants) predicted more frequent speech, whereas prone time predicted less frequent speech. Being prone limits infants' field of view, resulting in reduced opportunities for shared attention (Franchak et al., 2018). In contrast, sitting and upright positions enable a greater field of view, affording more joint attention and gaze following. However, one finding from the current study breaks from this pattern—time spent upright was associated with decreases in the frequency of speech input for older infants—so is likely explained by either social proximity or object interactions, which we discuss below.

Social Proximity

Social proximity to adults is another possible explanation for some of the observed findings. Proximity has been shown to shape infants' language environment. For example, Salo et al. (2021) found that the amount of time children spent in close proximity to their caregivers was positively associated with adult word count and conversational turns. Similarly, Suarez-Rivera and colleagues (2023) found that mothers tended to produce a higher quantity and diversity of words when they were within close proximity to their infants compared to when they were farther away. This may help explain why upright time was negatively associated with adult word count for older infants. The acquisition of walking is associated with a significant reduction in infant-caregiver proximity (Chen et al., 2023). Thus, walking infants may hear less speech because they spend less time near caregivers and other adults in the environment. While prior research has found speech input to be more likely when infants were walking (Schneider & Iverson, 2022), this may be moderated by the social proximity to adults. Similarly, the negative association between speech input and time spent prone may also reflect the role of social proximity. When prone, infants may be crawling, which, like walking, increases the distance between themselves and adults, potentially leading to a reduction in the speech input they receive.

In contrast, being held must, by definition, foster closer proximity to adult speakers, thereby enhancing opportunities for verbal interaction and engagement. When held, adults are more inclined to socially engage with infants, and infants themselves, through communicative behaviors such as pointing and smiling, promote social interactions (Vallotton, 2009). Even if the infant is not initiating a social interaction or the adult is not actively focused on the infant, they are still being exposed to the adult's speech as a result of the proximity. This may help explain why infants' time spent held was associated with increases in adult speech input.

Proximity between caregivers and infants may also explain why we found a decrease in adult words when infants spent more time supine. Supine included times that caregivers placed their infants in reclined devices, such as car seats and rockers. With infants contained, caregivers can leave infants' proximity to go about household tasks (Crouchman, 1986; Zhang et al., 2022), which may help explain the decrease in adult word count. Periods of time supine might have also preceded naps, leading caregivers and other adults in the environment to speak less frequently. However, it is important to note that all data we analyzed were while infants were awake, thus, the association between supine time and speech input cannot be explained by nap time.

Sitting might promote or hinder social proximity depending on the context. In our study, sitting included both times that infants sat in devices, such as high chairs, and sat on the floor or adult furniture, making it difficult to disentangle this association. Infants' time spent sitting restrained has been associated with a decrease in the frequency of speech input (Malachowski et al., 2023), which may be due to the decrease in caregiver proximity. For example, some daily instances of restrained sitting might allow caregivers to leave infants to do household chores. However, during other instances of restrained sitting caregivers might actively engage with infants, such as during mealtimes when infants are in a highchair (Clerkin et al., 2017; Harding et al., 2013). In addition, as infants get older they transition from breast-feeding or bottle feeding in a held position to eating in a highchair while seated. When infants sit unrestrained, caregivers may be physically closer and more engaged with the infants, which could lead to increased opportunities for verbal interactions.

Object Interactions

Infant object interactions have been found to shape infant-caregiver interactions. For example, during periods of object interactions caregivers use more referential language (Tamis-LeMonda et al., 2013; West & Iverson, 2017). However, when infants are lying prone or supine, they face challenges in observing and interacting with objects (Soska & Adolph, 2014). Their field of view is restricted when prone, making it harder to notice and reach for objects around them (Luo & Franchak, 2020). Furthermore, the physical constraints of lying on their back or stomach may limit their ability to grasp and manipulate objects effectively (Soska & Adolph, 2014). Thus, being in a supine or prone position presents unique biomechanical challenges that can affect an infant's ability to engage with objects. In contrast, sitting allows infants to have a better view of objects in their environment and easier manipulation of those objects, which can also lead to increased speech input from a caregiver, specifically in the form of referential language (Kretch et al., 2025).

Advantages and Disadvantages of a Wearable Sensing Approach

While this study has many strengths, such as extensive in-home data collection, it is important to acknowledge the limitations of our approach. First, both variables, body position and adult word count, were calculated through algorithms rather than manually coded. For both speech (i.e., transcription) and motor (i.e. scoring behaviors from video), human scoring is the gold standard for accuracy. However, given the scope of the current project (748 hours of data) manual scoring would not be feasible. Human transcription of speech takes ~7 hours per hour of audio (Casillas & Cristia, 2019), which would amount to approximately 5,236 hours of transcription for our dataset. Scoring body position from video takes 2-5 hours per hour of video (Franchak et al., 2023), which would require between 1,496 and 3,740 hours (if video were collected for the entire ~748 hours). Automatic coding enables the ability to analyze full-day data more efficiently, which would be prohibitively time-consuming with manual coding. Although automatic detection is less accurate than manual coding, both automatic measures are sufficiently accurate for the purposes of the current study, which focused on relative differences in experiences within an infant, within a day. Because of the demanding full-day data collection procedure and need to fit participants with specialized equipment, the sample size was relatively small. Thus, some analyses (e.g., interactions between body position and age) might suffer from low power.

Another limitation in using wearable sensor data is that it lacks the richness and context provided by video recordings. While the benefit of using sensors is that they allow researchers to capture longer durations of the behavior of interest, shorter video recordings offer more detailed information about a variety of factors, such as the proximity between adults and infants, bouts of social attention, and object interactions. They also do not allow distinction between different contexts within the same body position (e.g., sitting at mealtime vs. sitting during play), or between independent versus supported posture. These factors likely influence the speech input infants hear, but are treated the same by our classification. Future studies could combine these methods, using both wearable sensors and video recordings, to obtain a better insight into the relation between infant body position and changes in speech input.

Finally, LENA does not distinguish between infant-directed speech and overheard speech. Therefore, while larger word counts are interpreted as infants' receiving more speech input from adults, we cannot determine whether the input was directed to the infant versus other individuals in the environment. Although infant directed speech and interactions are found to be ideal for learning (Weisleder & Fernald, 2013), there are still opportunities for learning in observed or overheard social encounters (Shneidman & Woodward, 2016).

Conclusion

In conclusion, the current study looked at real-time differences examining how infants' time spent in various body positions was associated with total adult speech input over an extensive period. The novel approach of pairing IMU sensors and LENA® allowed for continuous, full-day data collection without the need for manual transcription, which allowed us to study the full variability of behavior across a day. Our findings provide evidence that within-day variations in infants' body positions are related to changes in the frequency of adult speech input, which builds on past research linking motor development and speech input (e.g., Karasik et al., 2014; Walle & Campos, 2014). The results provide insight into the potential cascading effects motor milestones have on language development, emphasizing the importance of considering both moment-to-moment interactions in infants' daily lives along with long-term developmental trajectories.

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Table 1

Linear Mixed-Effect Model Results for Adult Word Count

[Table follows on next page]

Note. Asterisk (*) indicates *p* value of less than 0.001.

Predictor		Unstandardized β [95%CI]	Standardized β [95% CI]	SE	*t*	*p*
Supine	Intercept	262.97 [240.66, 285.27]	0.03 [-0.05, 0.11]	11.38	23.11	<.001*
	Minutes Supine	-11.28 [-15.08, -7.47]	-0.13 [-0.18, -0.09]	1.94	-5.81	<.001*
	Age	-5.53 [-11.80, 0.74]	-0.07 [-0.16, 0.01]	3.20	-1.73	.086
	Supine×Age	0.03 [-1.00, 1.06]	-.0001 [-0.04, 0.04]	0.52	0.05	.955
Prone	Intercept	262.68 [240.31, 285.05]	0.03 [-0.05, 0.11]	11.41	23.02	<.001*
	Minutes Prone	-11.64 [-17.16, -6.12]	-0.09 [-0.13, -0.05]	2.82	-4.13	<.001*
	Age	-3.08 [-9.37, 3.22]	-0.04 [-0.12, 0.04]	3.21	-0.96	.340
	Prone×Age	-1.45 [-3.04, 0.13]	-0.04 [-0.08, 0.00]	0.81	-1.80	.077
Sitting	Intercept	268.54 [245.47, 291.60]	0.05 [-0.04, 0.14]	11.77	22.82	<.001*
	Minutes Sitting	10.24 [5.99, 14.48]	0.13 [0.07, 0.18]	2.17	4.72	<.001*
	Age	-3.65 [-10.14, 2.84]	-0.05 [-0.13, 0.04]	3.31	-1.10	.273
	Sitting×Age	-0.22 [-1.42, 0.97]	-0.00976 [-0.06, 0.04]	0.61	-0.36	.717
Upright	Intercept	274.95 [251.59, 298.31]	0.07 [-0.01, 0.16]	11.92	23.07	<.001*
	Minutes Upright	-2.11 [-7.05, 2.82]	-0.02 [-0.07, 0.03]	2.52	-0.84	.403
	Age	-1.42 [-8.02, 5.18]	-0.02 [-0.11, 0.07]	3.37	-0.42	.674
	Upright×Age	-3.14 [-4.58, -1.70]	-0.11 [-0.16, -0.06]	0.73	-4.28	<.001*
Held	Intercept	262.21 [241.28, 283.14]	0.03 [-0.05, 0.10]	10.68	24.55	<.001*
	Minutes Held	40.45 [32.60, 48.30]	0.24 [0.19, 0.29]	4.01	10.10	<.001*
	Age	1.15 [-4.74, 7.04]	0.02 [-0.06, 0.09]	3.00	0.38	.702
	Held×Age	1.69 [-0.53, 3.90]	0.04 [-0.01, 0.08]	1.13	1.49	.138

Table 2

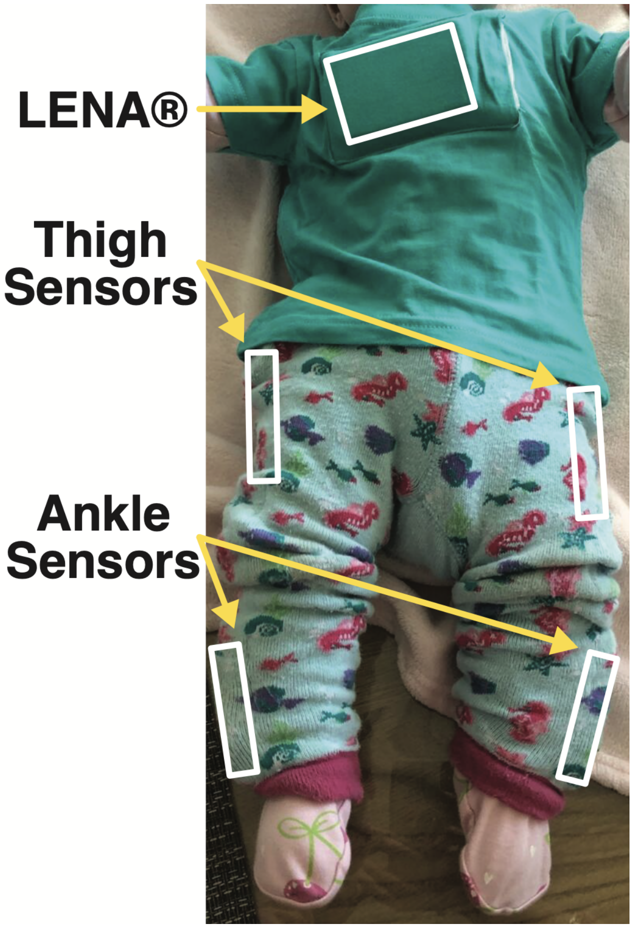
Descriptive Statistics for Age, Adult Word Count, and Minutes Spent in Each Body Position (per 10-minutes)

Predictor	Overall	Younger	Older
Age in months	9.49 (3.54)	5.70 (1.15)	12.46 (1.11)
Word Count/10-min	254.96 (268.89)	267.54 (99.37)	253.82 (85.70)
Supine/10-min	2.02 (3.17)	3.27 (0.90)	0.94 (0.99)
Prone/10-min	1.10 (2.01)	1.34 (1.19)	1.02 (0.70)
Sitting/10-min	4.07 (3.35)	3.29 (0.67)	4.64 (0.54)
Upright/10-min	1.95 (2.60)	0.95 (1.08)	2.69 (0.64)
Held/10-min	0.86 (1.60)	1.14 (0.72)	0.71 (0.49)

Note. Mean and standard deviation in parentheses for each predictor. Summary statistics were calculated for all participants overall, as well as separately for the younger and older infants.

Figure 1

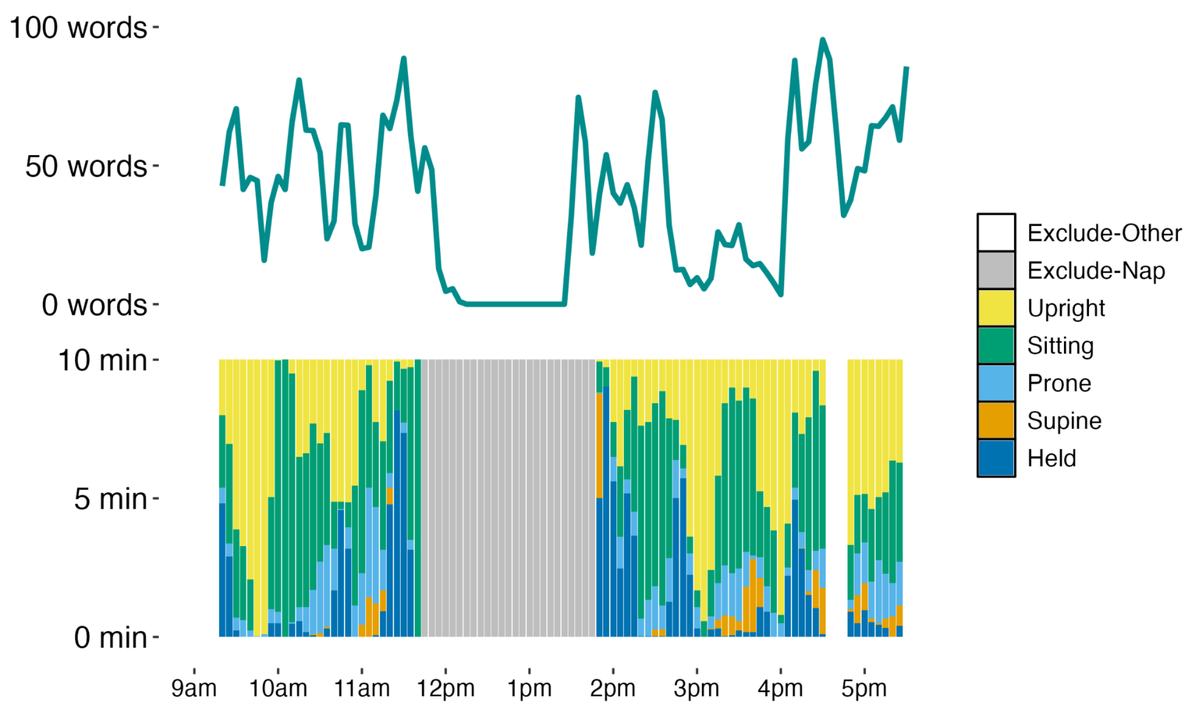
Infant Sensor Garments



Note. Leggings and shirt worn by infants. The leggings had four pockets located on the interior which held four IMUs at both thighs and ankles. The LENA audio recorder was placed in a pocket of the shirt located on the chest.

Figure 2

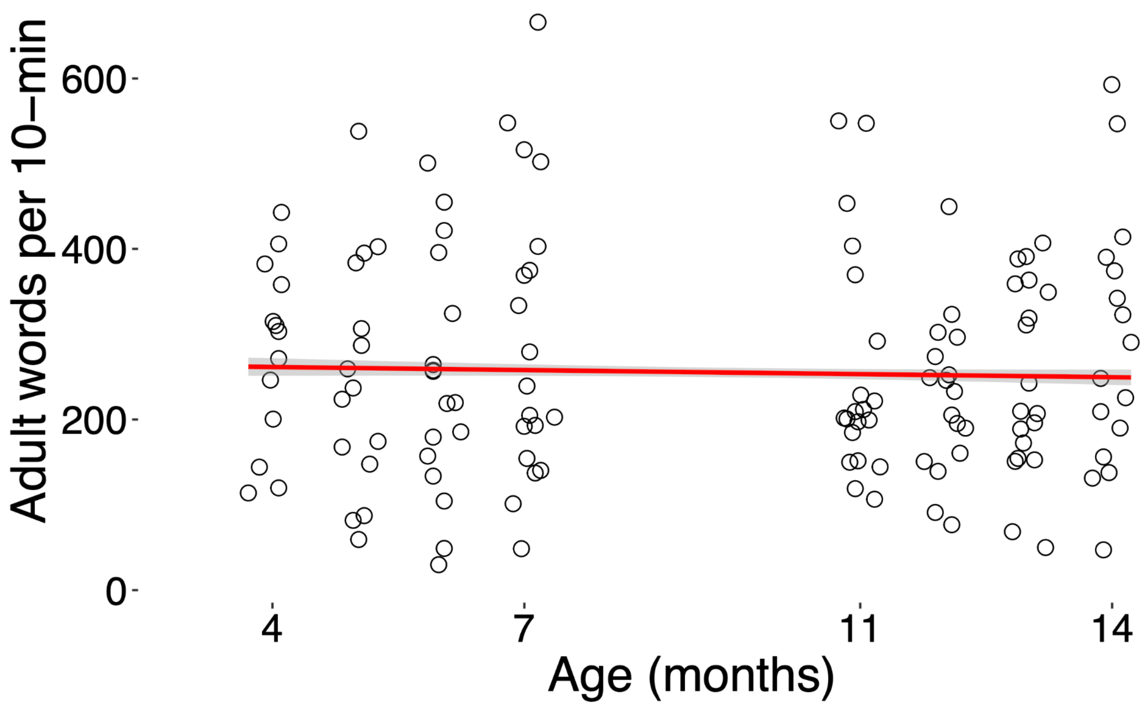
Exemplar Timeline Data from One Day-Long Session



Note. A figure shows a timeline from one participant's session. The top shows variations in adult word count for each 10-minute bin throughout the day. The bottom section displays the distribution of time spent in each body position, with each bar indicating one 10-minute bin. Bar color indicates each of the five body positions, with gray bars representing excluded nap times and white bars indicating missing data (e.g., trips out of the house).

Figure 3

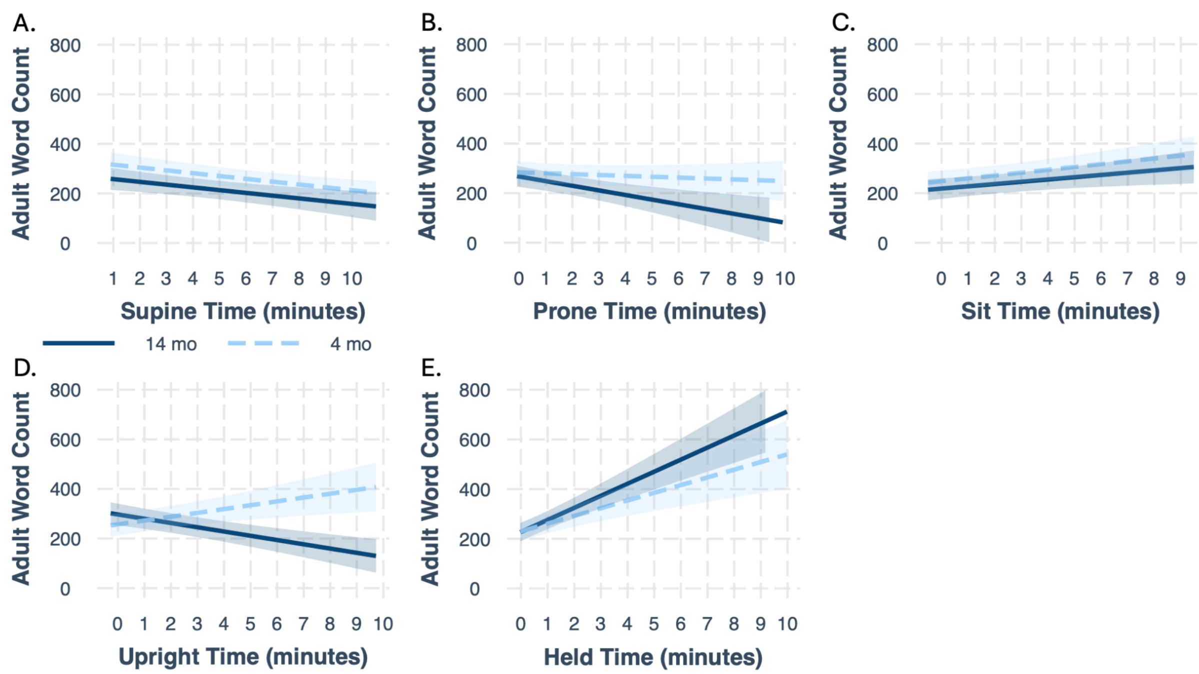
Relationship between Age and Adult Word Count



Note. The scatterplot shows adult word count was similar across age but varied widely at every time point. Each circle indicates a session, and the red line represents the line of best fit across all infants. The shaded area around the red line represents the 95% confidence interval. Age was not a significant predictor of adult word count (β = –0.94, 95% CI [–7.26, 5.38], p = .769). The y-axis represents the average number of words heard for each 10-minute bin for each session while the x-axis represents participant age at the time of the session.

Figure 4

Model Predictions Relating Age, Body Position Time, and Adult Word Count



Note. Interaction plots, depicting model predictions with one standard error, predicting adult word count from each body position: A) Supine, B) Prone, C) Sitting, D) Upright, E) Held. The solid dark blue line represents the model prediction for the older infants (11-14 months) while the dashed light blue line represents the model prediction for the younger infants (4-7 months). The shaded region around each regression line represents 95% confidence intervals.