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Sleep confers a benefit for retention of statistical language learning in 6.5 month old infants

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ABSTRACT

Infants show robust ability to track transitional probabilities within language and can use this information to extract words from continuous speech. The degree to which infants remember these words across a delay is unknown. Given well-established benefits of sleep on long-term memory retention in adults, we examine whether sleep similarly facilitates memory in 6.5 month olds. Infants listened to an artificial language for 7 minutes, followed by a period of sleep or wakefulness. After a time-matched delay for sleep and wakefulness dyads, we measured retention using the head-turn-preference procedure. Infants who slept retained memory for the extracted words that was prone to interference during the test. Infants who remained awake showed no retention. Within the nap group, retention correlated with three electrophysiological measures (1) absolute theta across the brain, (2) absolute alpha across the brain, and (3) greater fronto-central slow wave activity (SWA).

1. Introduction

The mechanisms supporting language learning in early infancy are of great interest with much work investigating infants' ability to acquire statistical properties of language. Infants as young as a few days old demonstrate encoding of statistical information in auditory and visual domains that aids them in segmenting a continuous string of stimuli into singular items in the seconds and minutes after familiarization (Bulf, Johnson, & Valenza, 2011; Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002; Marcovitch & Lewkowicz, 2009; Saffran, Aslin, & Newport, 1996; Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009; Thiessen & Saffran, 2003). Specifically in language, this encoding mechanism allows infants to identify distinct words within a fluid string of speech. By attending to the statistical regularities within language, 8-month-old infants track the transitional probabilities between syllables (Saffran et al., 1996), and use this information to distinguish words (syllables that have higher transitional probabilities) from part-words (syllables that have lower transitional probabilities).

While infants show encoding of statistical properties before 6 months of age, no studies have investigated retention across a delay in very young infants; hence the fate of new encoding is unknown. This creates a gap in understanding because long-term memory formation goes through distinct phases of induction, stabilization and consolidation that unfold in the seconds, minutes and hours after encoding (McGaugh, 2000).

Benavides-Varela et al. (2011) investigated retention in newborns, questioning whether the addition of novel auditory stimuli during the interval between encoding and test would increase the rate of forgetting. Newborn infants heard one word repeatedly followed by a test after a delay of 2 min. Retention was unaffected by the presentation of musical stimuli during the retention interval, but when infants heard a novel word during the delay they did not recognize the original word at test. These results demonstrate how novel linguistic interference can disrupt the retention of newly encoded word forms. Swain, Zelazo, and Clifton (1993) similarly demonstrated memory retention across a 24 h period in newborns after extensive exposure to a novel word at encoding. Infants heard a singular word over 35 trials with multiple exposures on each trial. They then heard the same or a different word over 35 trials the next day. Newborns who listened to the same word repeatedly on both days showed retention in the form of savings in learning. They habituated more quickly on the second day than infants who heard two different words across days.

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Although infants show evidence of recognizing frequently encountered word forms by 6 months of age (e.g., Bergelson & Swingley, 2012; Tincoff & Jusczyk, 1999) memory for new words is still prone to interference. Friedrich and Friederici (2011) reported an N400 event-related potential, indicative of semantic memory, for newly encoded word forms at 6 months that diminished significantly the next day. However, sleep soon after encoding aids new language retention in infants age 9 months and older (Friedrich, Wilhelm, Born, & Friederici, 2015; Gómez, Bootzin, & Nadel, 2006; Horváth, Myers, Foster, & Plunkett, 2015; Hupbach, Gómez, Bootzin, & Nadel, 2009). This led us to ask whether sleep will affect retention of new word learning at an earlier age.

Sleep undergoes extensive organization in the first few months of life, raising questions about the degree to which sleep physiology will support memory retention in very young children.

1.1. Development of sleep physiology in early infancy

Behavioral and physiological aspects of sleep change dramatically over the first six months of life. At full term, neonates display polyphasic sleep cycles comprising three types of sleep: Active Sleep, Quiet Sleep, and Indeterminate Sleep (Ednick et al., 2009; Jenni, Borbéoy, & Achermann, 2004; Kurth, Olini, Huber, & LeBourgeois, 2015). Proportionally, as a neonate, total sleep time includes more active sleep and less quiet sleep (Ednick et al., 2009; Jenni et al., 2004). Early signs of maturing sleep are the development of a circadian rhythm (LeBourgeois et al., 2013; McGraw, Hoffmann, Harker, & Herman, 1999; McMillen, Kok, Adamson, Deayton, & Nowak, 1991; Mirmiran & Kok, 1991; Mirmiran, Kok, Boer, & Wolf, 1992; Serón-Ferré, Torres-Farfán, Forcelledo, & Valenzuela, 2001), sleep homeostasis (Fattinger, Jenni, Schmitt, Achermann, & Huber, 2014; Jenni et al., 2004), and the consolidation of nighttime sleep concomitant with a decrease in napping behavior (Iglowstein, Jenni, Molinari, & Largo, 2003). Electroencephalogram (EEG) profiles of the sleep stages suggest that active sleep matures to rapid eye movement (REM) and quiet sleep to non-rapid eye movement (NREM) (Jenni et al., 2004). By 6 months of age, these adult-like stages of sleep are readily identifiable (Anders & Keener, 1985; Ednick et al., 2009; Galland, Taylor, Elder, & Herbison, 2012; Grigg-Damberger et al., 2007; Jenni et al., 2004; Novelli, Ferri, & Bruni, 2010; Tarullo, Balsam, & Fifer, 2011). Furthermore, sleep spindles manifesting as high amplitude bursts of brain activity within the broad 10–16 Hz range are evident as early as 2–4 months. At this time K-complexes, waveforms exhibiting a strong negative then positive component lasting longer than 0.5 s, become numerous and easily identifiable (Jenni et al., 2004; Scholle, Zwacka, & Scholle, 2007; Tarullo et al., 2011). Sleep spindles are notable for their association with better retention in studies of memory formation in adults (De Gennaro & Ferrara, 2003; Fogel & Smith, 2011; Loomis, Harvey, & Hobart, 1937).

1.2. The present study

Here we investigate whether sleep supports retention of statistical language acquisition in 6-month-old infants and whether electrophysiological markers of sleep correlate with infants' retention. Infants heard an artificial language composed of 4 bisyllabic novel words strung together in random order to produce a continuous stream with no pauses. Words were dapu, dobi, diti, and bugo from Thiessen and Saffran (2003) who demonstrated infants' success at extracting the words from continuous speech by tracking the transitional probabilities between syllables. Transitional probability is defined as the probability that Syllable B will follow Syllable A and is computed by dividing the frequency of AB syllables by the frequency of A. For a word AB, Syllable B always follows Syllable A, such that the computed transitional probability is 1. For transitional probabilities between words AB and CD, one divides the frequency of e.g., BC by the frequency of B. Between-word transitional probabilities depend on the number of unique syllables and their frequencies in the artificial language but are always less than 1 (Aslin, Saffran, & Newport, 1998). Using statistical information to identify words (e.g., diti) from part words (e.g., godi, a transition that occurs when *diti* follows *bugo*), infants use transitional probabilities to segment words in running speech, reflected in differences in listening times to Word and Part-word stimuli at test (e.g., Saffran et al., 1996; Thiessen & Saffran, 2003).

We familiarized infants with an artificial language of this form and asked whether they could retain the segmented words across a delay. We predicted better retention after a period of sleep compared to a similar period of wakefulness. We also administered polysomnography (PSG) during the sleeping period to investigate if sleep electrophysiology is a useful index of individual differences in retention.

2. Method

2.1. Participants

37 full-term 6.5-month-old infants (M = 6 months 21 days, range = 6 months 4 days to 7 months 2 days) were randomly assigned to an experimental nap condition (n = 21, M = 6 months 23 days, range 6 months 10 days to 7 months 2 days) or a yoked-control wakefulness condition described below (n = 16, M = 6 months 20 days, range 6 months 10 days to 7 months 1 day). The age of infants was equivalent across groups, $t(30) = -1.1660$, $p = 0.252$. Encoding and retention test occurred in the morning and appointment times did not differ between groups, (M_{Nap} = 8:57 AM, SD = 55.1 min, $M_{Wakefulness}$ = 8:58 AM, SD = 112.4 min; $t(1,35) = -0.04$, $p = 0.968$). Furthermore, each infant in the nap condition was matched with a wakefulness infant in terms of the interval between encoding and test with the experimenter quietly entertaining the infant in the wakefulness condition for the same amount of time the yoked nap infant slept. Thus, in addition to controlling for time of encoding and retention test, the delay between encoding and test was the same for the yoked nap and wakefulness infants. Five nap infants were not matched to wakefulness infants due to sleep durations that were too long for infants this age to stay awake taking into account waking from a prior nap, preparing for the lab visit, and driving from the infant's home to the lab. The data from these five infants were included in the spectral analyses but not in the behavioral analyses between groups. These infants did not have yoked wakefulness controls who were exactly matched for the delay between encoding and retention test. Thus, including these infants would not be an accurate test of our hypothesis.

We excluded 13 infants who did not meet our inclusion criteria. This included significant foreign language exposure (1), fussiness during the testing procedure that interfered with infants completing the behavioral protocol (3), a history of speech therapy or language delay in the immediate family (2), speech or language delay that was identified at an older age (1), developmental delay identified at an older age (1), exposure to drugs in the womb (1), experimenter deviation from protocol (1), equipment malfunction (1), or delayed sleep latency of greater than 30 min (2). Regarding exclusion criteria, all studies of language exclude children with significant foreign language exposure unless the topic of the study is bilingualism. This is because materials differ by language. If we were to include infants with significant exposure to a language other than English, that experience would conflict with their ability to encode the language materials in our study, which uses English