RAPT Ventures, Inc.

CREATING AN OPTIMAL ACOUSTIC SLEEP ENVIRONMENT FOR INFANTS: THE SCIENCE BEHIND THE DEVELOPMENT AND EFFECTS OF THE RAPTBABY™ SMARTER SLEEP SOUND MACHINE AND THE IMPLICATIONS FOR LANGUAGE DEVELOPMENT AND LATER COGNITION

I. OVERVIEW - EARLY BRAIN AND LANGUAGE DEVELOPMENT

Brain development during infancy forms the foundation of lifelong cognitive and physical performance.

Early in life, young brains create billions of connections (synapses) among nerve cells (neurons) that organize into the networks and systems that will drive and affect future cognitive and physical performance, including in the cerebral cortex (the outer layer of the brain which is both the largest area of the brain and the one responsible for cognition).

These networks are segregated based on incoming sensory stimuli and function to which they relate; those responding to touch, for instance, are in a different brain region or sensory area than those responding to sound or auditory stimuli. Additionally, within each sensory area, neurons responding to different aspects of the relevant stimuli are segregated as well, collectively forming sensory cortical maps (Najafian et al. 2022).

Importantly, the formation of cortical maps is a hierarchical process where the wiring for areas associated with basic sensory processing, like auditory input, happen earlier than for areas that build on those sensory processes, including higher cognitive functions such as language (Kolb et al. 2017).

Experience with the environment is key to brain development, especially during *critical periods* when the brain needs and expects certain external input.

Although genes determine the basic prenatal structure of the brain, postnatal environmental input is essential to the development of neuronal connections (Huttenlocher 2002; Innocenti 2022). This phenomenon is what neuroscientists call developmental *plasticity* - the propensity of the brain to change and adapt as a result of experience (Bick and Nelson 2017; Eggermont 2008). It is the interplay between external and internal cues that guide early neural plasticity and the ongoing cortical mapping of sensory and motor functions (Singer 2018). As a result, the quality and timing of environmental input will significantly influence brain function throughout life.

Moreover, while brain plasticity appears to continue throughout the lifespan (Fuchs and Flügge 2014), plasticity in infancy is unique in its flexibility and susceptibility to experience. This is particularly the case during *critical* or *sensitive* periods when the brain is maximally receptive to outside stimuli that are relevant to, and shape, specific cognitive structures. In other words, critical periods can be viewed as windows of opportunity for the experience-dependent shaping of neural circuits responsible for particular brain functions (e.g., Cisneros-Franco et al. 2020; de Villers-Sidani et al. 2007; Voss et al. 2017).

During these windows, particular aspects of the environment profoundly shape neuronal structure and function by altering the tuning properties of neurons, i.e., their preference for specific stimuli that causes them to respond more strongly to those stimuli than others. That tuning, in turn, influences which subsets of neurons wire together to create specific function-related networks. Hence, it is highly important that the environment to which the young brain is exposed during these windows provide the stimuli most conducive to building the networks which are the brain's focus during those time periods.

II. THE ACOUSTIC MAP: SETTING THE FOUNDATION FOR LANGUAGE

The first year is a critical period for language, marked by the development of the infant's acoustic map, the network of connections that support language acquisition and processing.

One of the most important jobs of the infant brain is engaging with its environment to set itself up to become a proficient processor of its native language. *Phonemes* are the most basic units of sound that distinguish words in a given language and their number varies by language, ranging from low double digits (Hawaiian) to over 40 in English and more than 100 in the "click" heavy language of Taa, spoken in parts of Botswana. When infants are born, they are capable of distinguishing all the phonemes in the world but, to become an efficient processor of the language prevalent in their environment, they have to focus on, and discriminate, the sounds of that language (Gervain 2015; Kuhl 2004; Werker and Hensch 2015; Werker and Tees 2005).

The task of identifying relevant phonemes in an incoming language stream is made more difficult because the differences between them may only consist of a very brief (in the tens of milliseconds) spectral (frequency of sounds) and/or temporal (timing of sounds) variation – an *acoustic cue* that is a property of a speech sound such as a variation in pitch, duration or intensity (Figure 1). Yet, because the "precise identification and analysis of acoustic cues [is]. . . mandatory for language acquisition,"

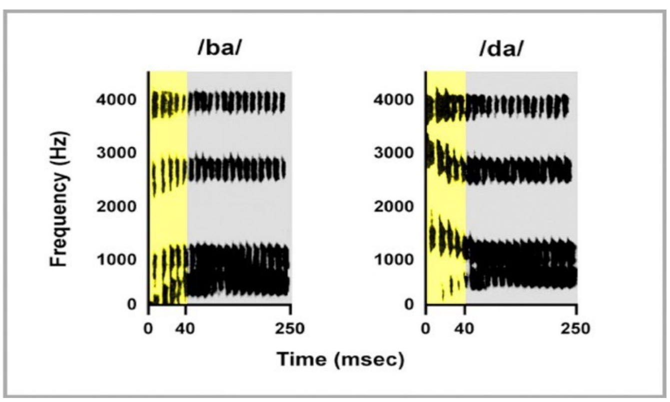

FIGURE 1. ACOUSTIC CUES: Registering the difference between these two phonemes, /ba/ and /da/, depends on hearing and discriminating the transition acoustic cue. As shown in the yellow highlighted area, this cue is a tiny variation in direction lasting only 40ms, with an upward slope signaling that the sound is a *b* and a downward slope.

the infant must be capable of recognizing or "decoding" such fine differences between sounds at the speed that they occur during ongoing speech (Telkemeyer et al. 2009). Fortunately, the infant brain is programmed to support this rapid decoding, establishing connections among the neurons whose joint response is required to process each of the individual phonemes of the child's native language.

This activity begins as early as the last trimester of gestation (Partanen et al. 2013), in the prenatal infant. Even though infants can parse speech across all languages when they are born, as they listen to speech sounds and discriminate among them, they are actually performing a detailed statistical analysis to determine which occur most often, i.e., those of their primary language(s) (Saffran et al. 1996; Saffran and Kirkham 2018; Werker and Yeung 2005). By focusing on those native phonemes, the neurons which fire closely in time to process each of them not only form connections but also get repeated experience with that processing, strengthening their interneural connections and thus the effectiveness of their joint response to the sound over time.

This ongoing activity has been described as "neurons that fire together wire together," capturing the essentials of Hebbian theory (Hebb 2002) which postulates that neurons responding to the same input over time will form synaptically connected ensembles to strengthen their coordinated firing. In the case of language processing, the connections among the set of neurons which respond to each phoneme significantly enhance the speed of response to that particular sound - which is, of course, enormously important if the infant is going to be able to proficiently discriminate among sounds important to language in the miniscule periods of time that those are manifested.

By the end of this first year critical period, the young brain will have completed its basic *acoustic map*, the network of the multiple neuronal connections that process all the individual phonemes of the child's native language(s) (Kuhl 2000; Kuhl 2004; Ortiz-Mantilla et al. 2019) (Figure 2). With that map in place, the child is set up to take the steps necessary to "acquire" language: accurately identifying the phonemes relevant to native language; recognizing patterns in those phonemes that create words; and then attaching meaning to those words (Kuhl 2004). However, the extent to which a child can adeptly perform those steps, and indeed process language throughout life, is heavily influenced by how well the acoustic map is constructed and the response time and accuracy with which it handles incoming sounds (Benasich et al. 2014; Patterson et al. 2006; Werker et al. 2012).

Perceptual Narrowing

At the same time that the brain is building the neural networks pertinent to native language, attention to non-native phonemes is reduced. In a process called *perceptual narrowing*, the brain gradually loses its ability to identify those non-native phonemes (Ortiz-Mantilla et al. 2016; Werker and Yeung 2005). Note: there is good evidence that infants raised in bilingual environments demonstrate a more protracted and slower rate of perceptual narrowing and perhaps a broader range of retained phonemes (Antovich and Graf Estes 2018; Singh et al. 2017). However, older monolingual learners generally find it challenging to attain the same level of competence and fluency in a second language as native learners because they have lost the ability to easily discriminate among the phonemes of a new language (for example, native Japanese speakers have well-documented difficulties differentiating the /r/ and /l/ sounds in English (Goto 1971)).

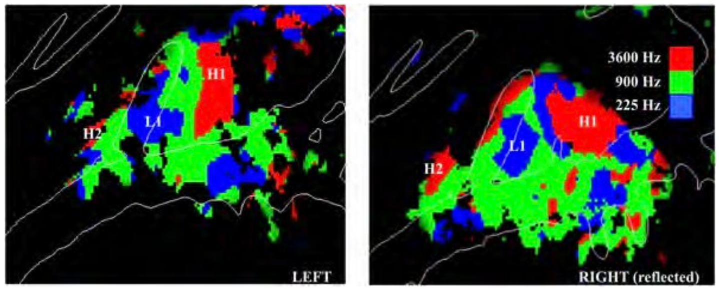

FIGURE 2. HUMAN ACOUSTIC MAPS (Woods et al, 2009) These images, collected via functional magnetic resonance imaging (fMRI) and population-based cortical surface analysis, show the *tonotopic* organization of human auditory cortex. Tonotopic refers to the arrangement of neurons at various levels in the auditory pathway, and their grouping by the frequency to which they best respond (frequency is the number of brain waves or oscillations per second generated by the brain in response to sounds). Tonotopy specifically refers to the mapping of these sound frequencies from the lowest to the highest frequency across auditory cortex, as well as in subcortical regions such as the cochlea. This type of organization allows the same frequency placements in the cochlea to connect to the like regions in auditory cortex, thus permitting the precise neuronal coding that seems to be crucial for efficient speech perception in more complex situations and allowing for perception of tiny differences in spatiotemporal excitation patterns which represent auditory temporal fine structure (Oxenham et al. 2004). Both left and right adult auditory cortex are shown here and there is a mirror-image organization of auditory cortex for the left and right hemispheres. The plots show regions with significant activations coded by the frequency that produced maximal activation at that point in the brain.

Indeed, if poorly formed, acoustic maps can negatively impact language fluency due to poor phonological processing (including reduced phonological awareness, i.e., less ability to discriminate one phoneme from another), as well as the later and effortful development of reading skills, because difficulty perceiving phonemes impedes the ability to perform efficient and accurate phoneme (sound) to grapheme (letter) mapping (Tallal and Benasich 2002) (Figure 3). There are a number of interventions that focus on improving pre-reading skills by supporting early phonological awareness skills in preschool children (e.g., Forné et al. 2022; Lohvansuu et al. 2014; Lovio et al. 2012). However, it is clear from various longitudinal predictive studies (assessing outcomes from infancy to early reading) that improving phoneme mapping in early infancy would be a much more effective way to insure good phonemic skills well before they are required for pre-reading (Choudhury et al. 2011; Kujala et al. 2017; Leppänen et al. 2010).

Word-Reading Development		
Grade	Phonological Skill	Word-Reading
PreK-K	**Early phonological awareness**: rhyming, alliteration, first sounds	**Letters & sounds:** requires simple phonology to learn sounds that correspond to letters
K-1	**Basic phonemic awareness:** blending, segmenting	**Phonic decoding:** requires letter sound knowledge and blending; a gateway to orthographic mapping
2-3+	**Advanced phonemic awareness:** phonemic proficiency including phoneme manipulation such as deleting, reversing, and substituting phonemes in spoken words	**Orthographic mapping:** requires letter-sound skills and advanced phonemic awareness to move from basic decoding to reading words with automaticity

FIGURE 3: PHONEMES TO WORDS TO READING: Discrimination of phonemes is critically important as children learn words, letters, sounds and ultimately reading; the inability to do so well has negative implications for language and reading skills formed in childhood and, as a result, lifelong cognitive performance. Orthographic mapping is the process of linking sounds to letters within a word to spell those words and critically depends, as depicted above, on letter-sound knowledge (table adapted from Kilpatrick 2015).

III. THE IMPACT OF THE AUDITORY ENVIRONMENT ON ACOUSTIC MAP FORMATION, INCLUDING DURING SLEEP

The efficiency of an acoustic map is highly influenced by the quality of the auditory environment during the critical period in which it develops.

To establish the neuronal connections underpinning acoustic maps, infants start by paying attention to small, rapid changes in sound occuring in the environment which stimulate the infant brain to focus on the critical acoustic cues that differentiate phonemes (Kuhl 2004). Multiple studies demonstrate the importance of this foundational activity showing, for instance, that passive engagement by infants with spectrotemporally-modulated non-speech, that is sounds that are not language but contain acoustic cues *pertinent* to the perception of language, bootstraps the processing of native speech and facilitates the establishment of the accurate and enduring phonemic representations necessary for optimal acoustic processing (Benasich et al. 2014; Ortiz-Mantilla et al. 2022). An infant's ability to attend to and discriminate among these tiny differences in pitch, duration, intensity, modulation, and/or pattern of non-speech sounds, in other words, efficient processing of pre-linguistic acoustic cues, has also been shown to predict language outcomes at 2, 3 and 4 years of age (e.g., Cantiani et al. 2016; Choudhury and Benasich 2011).

As importantly, the infant brain is primed to engage with these transitions; in this sense, acoustic map formation is experience-expectant "simply waiting for almost guaranteed environmental input to be set" (Frankenhuis and Walasek 2020; Werker and Gervain 2013). However, just because the brain is open and waiting for input does not mean it will get the type of input it needs or is capable of handling. For instance, newborns and infants preferentially attend to certain sounds reflective of their still developing auditory capabilities, e.g., broadband noise over simple tones and high frequency over low frequency (Kushnerenko et al. 2013), and their response to sound will reflect those capabilities. As a result, it is essential that a child's auditory environment provide the salient acoustic cues that signal that "language" may be present and does so within a clear and accessible sound landscape supporting - and consistent with - the infant brain's developing ability to perform the automatic analysis that helps it parse and decode sounds and detect those acoustic cues (Saffran and Kirkham 2018; Werker et al. 2012).

If, however, a sound environment is suboptimal, it may cause an infant to experience disrupted mapping which can slow and potentially impair later language development. For example, infants in Neonatal Intensive Care Units (NICUs) are exposed to noisy environments which research has shown "disrupts the functional organization of auditory cortical circuits. As a result, . . . the ability to tune out noise and extract acoustic information … may be impaired leading to increased risks for a variety of auditory, language, and attention disorders" (Best et al. 2018; Lahav and Skoe 2014). Infants in other settings with high amounts of background noise, such as from TV or media or vehicular traffic, may also have difficulty perceiving or attending to the signals or stimuli important to developing language (Erickson and Newman 2017).

Of additional concern is infant exposure to environments which simply lack the natural environmental variation the infant brain is expecting. White noise, for example, has become a prominent element in sleep sound environments generated by sound machines which parents employ to mask noise that might disrupt their child's sleep. Yet, by its nature, white noise is devoid of the acoustic cues the infant brain requires to build its language networks (Figure 4a); the lack of variation is evident when comparing white noise to soundscapes which include acoustic cues (Figure 4b).

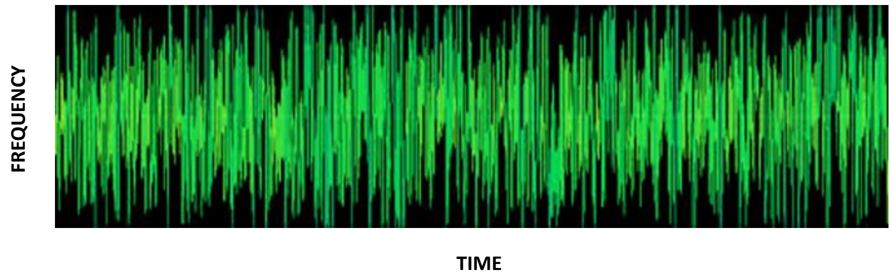

FIGURE 4a: WHITE NOISE WAVEFORMS (complex waveform of 10 seconds of full spectrum white noise). ***White noise*** is a random signal that contains many frequencies but, even if filtered, has equal intensity at each differing frequency, which produces a constant power spectral density and thus lacks the auditory variation that supports language development.

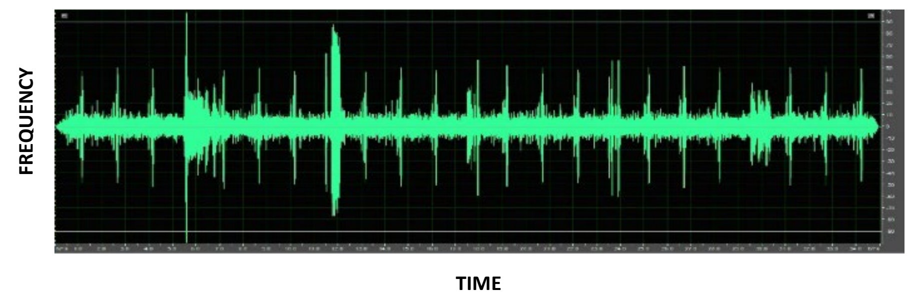

FIGURE 4b: BIRDS OVER STREAM (background sounds with acoustic cues). This spectrogram displays a background track of sounds mimicking running water into which an auditory sequence of artificially constructed acoustic cues (transitions between standards and deviants using "nature" sounds such as birds and crickets) was embedded.

Research on rat pups has shown that exposure to continuous white noise delayed the organizational maturation of the auditory cortex well beyond normal benchmarks (although activation of the auditory cortex appeared to be restored after return to a typical auditory environment). The study's authors note that the degradation in maturation induced by the initial exposure to white noise demonstrates that the development of the auditory cortex "is powerfully affected by the spectro-temporal input structures delivered from the acoustic environment during a critical period of postnatal development" and, further, that "environmental noise, which is commonly present in contemporary child-rearing environments, can contribute to auditory- and language-related developmental delays" (Chang and Merzenich 2003; Chang et al. 2005).

Numerous other animal studies also show that exposure to continuous white noise delays or impedes auditory tuning and development of the auditory cortex (Xu et al. 2010; Seidl et al. 2005; Zhang et al. 2001, 2002). In total, there is a substantial and growing body of work demonstrating the impact that the auditory environment, and the appropriateness of the auditory experiences it provides to a child during postnatal development, has on shaping the functional auditory cortical maps the child carries into adulthood. (Eggermont 2008; Kuhl 2004; White-Schwoch et al. 2015; Zhang et al. 2001).

Sleep plays an essential role in infant brain development in general, and the creation of language structures specifically; because of its ability to affect ongoing development, it is important that the auditory environment to which a sleeping infant is exposed is optimally supportive.

An accumulating literature on adults and children demonstrates that the sleeping brain can and does actively interact with external environmental cues, even during consolidated stages of sleep (Blume et al. 2018; Friedrich et al. 2015; Wislowska et al. 2022). This interaction includes the detection of novel sounds in the environment (Ruby et al. 2008) as well as the discrimination of sounds that contain both semantic (Perrin et al. 2005) and lexical (Flo et al. 2022; Kouider et al. 2014) information (lexical items are the individual words and phrases that make up a language, while semantics refers to the meaning of those words and phrases). The brain can also distinguish familiar sounds from one another during sleep (Blume et al., 2018) and detect the emotional tone of words and phrases (del Giudice et al. 2016). It has also been reported that the brain can track continuous speech during sleep (Legendre et al. 2019), something that was always thought to be quite unlikely. And there are a large number of studies that confirm that the sleeping brain supports and enhances learning and memory (e.g., Kurth et al. 2012; Stickgold and Walker 2007; Yoo et al. 2007) as well as ongoing brain plasticity in both children (Gomez et al. 2011) and adults (Maquet et al. 2003; Walker and Stickgold 2006).

While sleep is important to brain function at all ages, it is particularly critical in the first year of life given the intense brain reorganization and plasticity that is taking place during that early period (Mason et al. 2021). Infants spend an extraordinary amount of their time sleeping, around 14–15 hours a day at 6 months (10 hours at night) tapering to 7-8 hours of total sleep a night by adulthood. Of the billions of neural connections that are formed in infancy, the vast majority are created during sleep (Dang-Vu et al. 2006; Blumberg et al. 2022). Rapid Eye Movement or REM sleep (also called "active sleep" in infants, as opposed to Non-Rapid Eye Movement (NREM) which is termed "quiet sleep") specifically contributes to neural plasticity in early development (Blumberg et al. 2022; Cao et al. 2020). Over time, the percentage of NREM sleep increases from approximately 50% early in life to nearly 75-80% by the age of five (El Shakankiry 2011).

The maturation of NREM sleep is a key activity in infant brain development, as it not only coincides with the formation of long-range connections and intense local connectivity (thalamocortical and intracortical patterns of innervation and periods of heightened formation of synapses) but is also associated with important processes in synaptic remodeling that change neural connections (Bear and Malenka 1994; Cramer and Sur 1995; Tononi and Cirelli 2014). Hence sleep, and sleep cycles, are highly involved in the development of the neurosensory and motor systems in both the fetus and newborn as well as in memory consolidation and language learning (Friedrich et al. 2015; Peirano and Algarín 2007; Tham et al. 2017). This is particularly true for auditory processes since "even during sleep, an infant's brain is processing information about the environment and performing computations" that reflect the acoustic cues in the environment, core activity required for language-learning (Gilley et al. 2017).

Recognizing the extent of brain development that occurs during sleep, including processing of acoustic input that supports language acquisition, it is important that a child sleeps in an environmentally supportive sound environment that not only facilitates the sleep important to brain development, but also provides the salient auditory input the infant brain expects, including during sleep.

IV. SUPPORTING SLEEP AND LANGUAGE DEVELOPMENT DURING SLEEP: THE SMARTER SLEEP OPTION

The Smarter Sleep sound machine was developed to provide an auditory environment that recognizes and supports the multiple functions that sleep is intended to serve, particularly during infancy and early childhood.

Given what is known about the specific information the infant brain expects, analyzes, and processes in the surrounding environment, even during sleep, the RAPTbaby™ team created Smarter Sleep to give parents the opportunity to facilitate their baby's sleep while supporting cognitive development during sleep. In contrast to other sound machines, Smarter Sleep delivers a sound environment that not only promotes sleep but is also enriched with the salient acoustic cues that keep the active part of the sleeping brain engaged in the development and maintenance of the neural interconnections which form the foundation of efficient language processing. It does this by providing blended soundtracks explicitly designed to encourage the infant brain to pay attention to critical, brain-building sound changes while also inducing *alpha* waves that encourage relaxation and sleep as well as *delta* waves that promote and sustain deep sleep (Figure 5).

Smarter Sleep's patented design (US Patent No. 10,916,155) builds on the peer-reviewed, clinically validated neuroscience described above including studies on: the experience-driven activity the infant brain requires to build its language networks; the existence of infant auditory processing during sleep; and the negative effects of suboptimal auditory environments, such as those dominated by white noise or prevalent in NICUs, on acoustic mapping in animals and infants. In aggregate, this research not only attests to the brain's reliance on structured auditory input – including during sleep - to establish language networks but also highlights the potential for impaired language development among children exposed to less optimal auditory environments. Smarter Sleep responds to this research by generating auditory environments optimized to support sleep while also ensuring that sleeping babies receive the

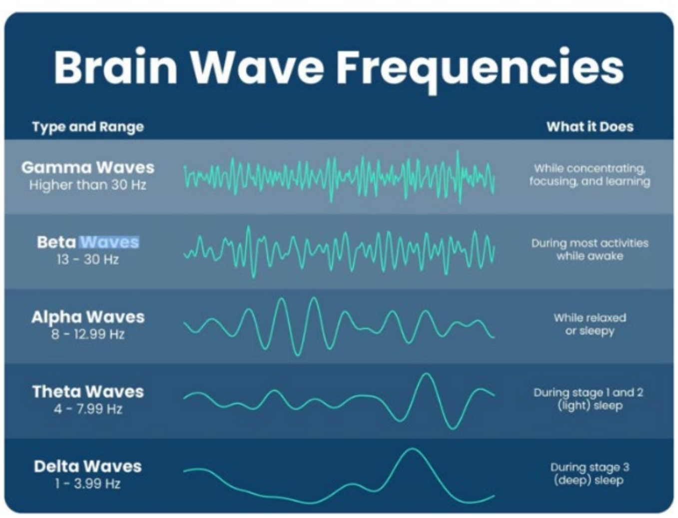

FIGURE 5: BRAIN WAVE FREQUENCIES. Brain cells constantly communicate with each other through electrical pulses during both wake and sleep states. These electrical pulses create brain waves that can be tracked and recorded using an Electroencephalogram (EEG) measuring the number of brain waves or oscillations per second that emerge from the brain (i.e., brain wave frequency). While there are many ways to analyze brainwaves, researchers often divide brain oscillations into the five categories depicted above. Alpha is the main brain wave pattern that develops when a person becomes drowsy and transitions from wakefulness to sleep and continues during the early phase of sleep until those waves are replaced by slower Theta waves. Delta waves, the deep, slow waves at the bottom of the spectrum, are the waves that dominate in periods of deep, restorative sleep (Patel et al. 2022). Chart Source: The Sleep Foundation, 2022, OneCare Media, LLC.

specific acoustic input their brains need and expect, which is a benefit that other sound machines and less enriched environments generally fail to provide.

Smarter Sleep achieves its benefits by engineering each of its soundtracks according to a two-layered design process with one layer devoted to promoting and sustaining sleep and the second designed to support auditory development.

The composition of Smarter Sleep soundtracks begins with the creation of background envelopes in genres consistent with soothing auditory soundscapes often used to encourage sleep (classical music, lullabies, nature sounds and womb/heartbeat sounds) and able to mask noise that might otherwise disturb sleep. More specifically, the rhythm of each of Smarter Sleep's background envelopes is governed by the principle of entrainment – whereby brainwaves synchronize with the rhythm of the sounds - to induce the alpha and delta oscillations that induce and maintain sleep. The principles employed are similar to those used in meditation to promote an increase in alpha waves (DeLosAngeles et al. 2016), thus allowing natural body rhythms and eventually slower theta and delta waves to emerge. Additionally, Smarter Sleep soundtracks are composed to include more soothing lower frequency sounds and a more complex layered mix of sounds than is generally found in traditional sound machines to optimize their ability to serve as a better sleep environment.

Once a soothing background envelope is created, a second, structured "events" track consisting of non-speech but linguistically relevant acoustic cues or "events" that support auditory development is embedded into the background envelope (Figure 6).

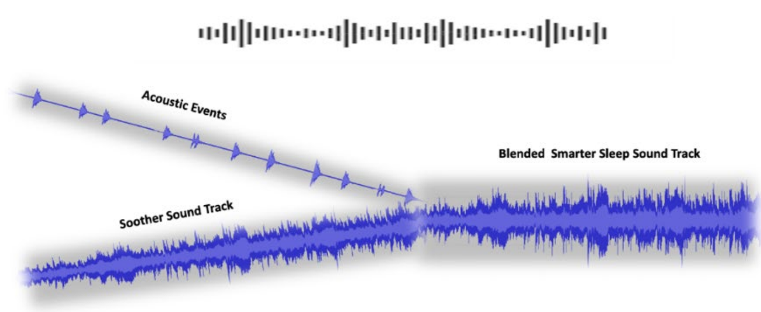

FIGURE 6: SMARTER SLEEP SOUNDTRACK COMPOSITION. Source: RAPT Ventures, Inc.

These sounds engage the parts of the brain that should be active in language processing, including the frontal, parietal, superior temporal and somatosensory cortices which are all involved in processing acoustic information and linking sounds to meaning (Friederici 2015; Telkemeyer et al. 2011), without disturbing the ability of the background envelope to support sleep. These types of acoustic events have also been observed to modulate brain areas that have been shown to preferentially respond to syllables (Binder et al. 2000; Cogan et al. 2014; Forgács et al. 2022) as well as to spectrotemporally modulated sounds that contain similar very rapid acoustic cues (Benasich et al. 2002; Cantiani et al. 2016; Ortiz-Mantilla et al. 2022). More specifically, the events are spectrotemporally organized in the 10s of millisecond range to provide exposure to the pre-linguistic early acoustic cues that the developing brain is listening for; these transitional cues signal that language might be present and thus they are preferentially parsed and processed. Further, they are presented in an "odd-ball" fashion that engages the parts of the brain that discriminate and perform statistical analysis of these types of sounds. A typical oddball paradigm has sounds that are presented as a repeating *standard* (a frequently presented sound) with a more rarely presented *novel* sound or sounds.

This odd-ball paradigm alerts the brain to pay attention and to figure out how the sounds differ from one another. Event streams such as these have been used for many years in infant and child research because they are easily discriminated and processed by the infant brain during both wake and sleep (Frederici et al. 2022; Gilley et al. 2017; Otte et al. 2013) and generate a robust response in awake or sleeping babies whether measured by EEG or fMRI (Hämäläinen et al. 2019; Kostilainen et al. 2020; Koyama et al. 2017). When the structured events are blended into each soundtrack, special care is taken to ensure that the merged track continues to be soothing. Each track's events have been designed to blend with that particular track, and the variation and volume of the event as well as the type of sound is matched to the harmonics of that particular soundtrack.

Infants hearing Smarter Sleep's soundtracks demonstrate the targeted responses.

As described above, Smarter Sleep's soundtracks are designed to activate brain activity conducive to the development of language networks. To understand how the responses generated in infants hearing Smarter Sleep soundtracks relate to that objective requires some understanding of brain anatomy. The picture below (Figure 7) displays the location of major brain regions including the frontal, temporal, parietal and occipital lobes which are important to the activity Smarter Sleep is designed to support. The central area, which is right on the top of the head, is not shown. While this view is of the left side of the brain, the general anatomy of the brain is about the same on both the left and right, although there are functional and some anatomical differences between the left and right hemispheres.

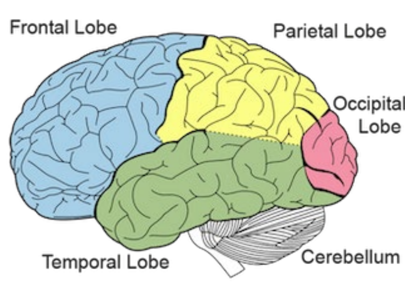

FIGURE 7: BRAIN ANATOMY.

This brain anatomy provides context for reviewing test results from infants hearing Smarter Sleep soundtracks while wearing soft EEG caps that measure the electrical pulses that are generated by the brain and create brain waves.

Figure 8a displays the results of the electrical activity (measured by EEG) generated in a sleeping infant listening to a Smarter Sleep classical soundtrack, in one case listening to the blended track (classical music envelope plus embedded events) that is one of the Smarter Sleep sound machine selections and, in the other case, listening to the classical music envelope by itself, without events. Results are displayed using an EEG spectrogram that depicts spectral power, the intensity of a time-varying signal that is distributed in the frequency domain – essentially a measure of the strength and intensity of brain activity within a particular frequency.

Smarter Sleep Classical Music Soundtrack Results: 4-Month-Old Infant
Dense Array sEEG - Stage 2/3 NREM Sleep
With and Without Acoustic Events

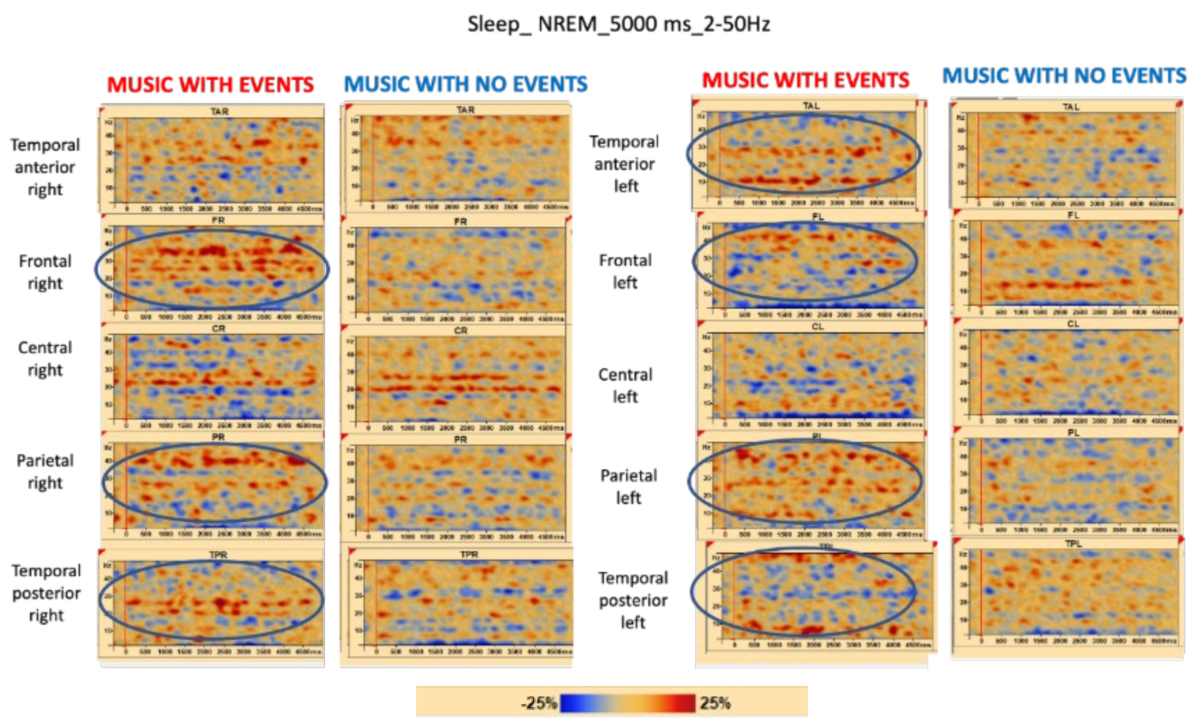

FIGURE 8a: Sleep Soundtrack Spectrogram Results. Source: RAPT Ventures, Inc.

Characteristics of the Figure 8a graphs are as follows:

- Results are shown separately for the combined track (music with events) and for the music envelope soundtrack alone (music without events).
- Spectral power is measured in Hz on the Y axis for frequencies from delta (1-3.99 Hz) at the bottom of each graph, up through gamma (30-50 Hz) at the top of each graph.
- The x-axis shows time in milliseconds (ms).
- The color scale at the bottom of 8a shows changes in the intensity of spectral power over this time period ranging from a 25% increase in power to a 25% decrease (desynchronization or inhibition) in power.
- Both right and left hemispheres are shown separately for 5 brain areas: temporal anterior, temporal posterior as well as frontal, central (in the middle of the head), and parietal areas.

Given the purpose for which Smarter Sleep was designed, there are two questions that can be answered by these results.

First, do the acoustic events embedded in the soundtrack differentially modulate the brain over and above the activation induced by the soundtrack alone? Figure 8a is a snapshot from a larger data set, but as the circles on the plots indicate, there are large increases in spectral power for music with events when compared with music alone (no events). During music with events, higher spectral power (dark red areas) is seen in both the right and left hemispheres. In the right hemisphere, higher power can be seen when music with events is presented in the gamma range (30-50 Hz) in both frontal and parietal regions while increases in power are seen in the beta range (13-30 Hz) in the temporal posterior right area as compared to music alone with no events. In the left hemisphere, higher theta power (4-6 Hz) is seen in the temporal anterior and temporal posterior parts of the brain and more gamma power (30-50Hz) is seen in frontal and parietal regions with less prominent activation in the temporal anterior and left temporal posterior than during music without events. The entire pattern of activation (red) and inhibition (blue) gives us important information about how the brain is responding to both music with events and music without events. But the answer is "yes", the sleeping infant brain responds differentially with more activation and a more extensive pattern of connectivity when subtle acoustic events are added to soothing soundtracks.

Second, are the areas that are responding more actively to the Smarter Sleep acoustic events during sleep the expected anatomical regions that research has shown are engaged in setting up language networks? The brain areas involved in processing acoustic information and linking sounds to meaning include the frontal, parietal, superior temporal and somatosensory regions, which include parts of the parietal and central areas (Friederici 2015; Telkemeyer et al. 2011; Weiss-Croft and Baldeweg 2015). Moreover, these same areas are active in processing acoustic events including syllables (Binder et al. 2000; Cogan et al. 2014; Forgács et al. 2022) as well as spectrotemporally modulated non-speech sounds that contain very rapid, successive acoustic cues, like the events in the Smarter Sleep soundtracks (Benasich et al. 2002; Cantiani et al. 2016; Ortiz-Mantilla et al. 2022). Thus, not only does the infant brain respond more strongly to a soundtrack with added acoustic events, the increases in spectral power and changes in the pattern of activation and inhibition are manifested in the cortical areas which are part of the developing language network.

Figure 8b also shows spectral power; however, this graph is a topoplot which displays the results from clusters of electrodes from a dense array EEG and the response pattern (here in a single frequency range) on the scalp generated by a sleeping infant listening to a Smarter Sleep nature soundtrack, again shown with and without embedded events.

Characteristics of this figure are as follows:

- The topoplot shows the infant's head from the top, with the front of the head and nose on the top of the circle and the back of the head on the bottom; left is left and right is right.
- The right side of the figure shows the response to the nature soundtrack alone (without events) while the left side shows the brain response when acoustic events are present (and embedded in the nature soundtrack).

- Spectral power is shown on a similar scale as in Figure 8a with higher spectral power shown in the red range and lower power, or desynchronization, shown in the blue range. Both types of responses are important as the overall pattern illustrates how networks are interacting. Note: scales on the two topoplots vary for display purposes given there is much more spectral power overall in Nature with Events.
- These plots are "baseline corrected," meaning that the brain activity that is normally present at any time in an infant brain is subtracted out so that the topoplot shows only the **incremental** brain activity created when a nature soundtrack is played (on the right side), and, on the left, when a blended soundtrack (the nature envelope with embedded acoustic events) is played.
- Brain responses in these baseline-corrected plots are shown for the Theta range (4 to 7 Hz). The Theta range is particularly relevant because it is highly involved in processing syllables as well as non-speech that has transitions that are language-like in their spatiotemporal structure. Information about how the syllable is encoded and then discriminated is processed within the 4 to 7 Hz theta range (Ding and Simon 2014; Jin et al. 2014; Ortiz-Mantilla et al. 2022; Peelle et al. 2013).

Smarter Sleep Nature Soundtrack Results: 4-Month-Old Infant
Dense Array sEEG - Stage 2/3 NREM Sleep
Nature Track With and Without Acoustic Events

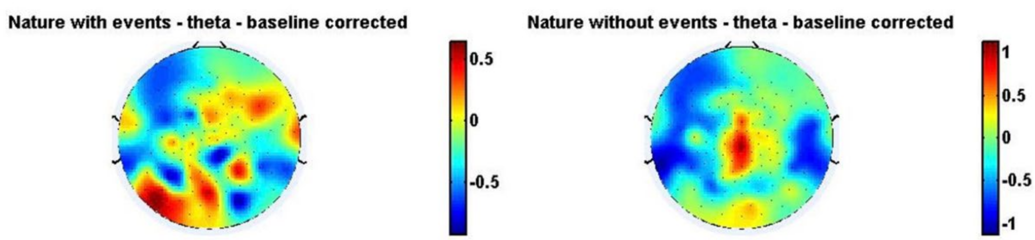

FIGURE 8b: SMARTER SLEEP SOUNDTRACK TOPOPLOT RESULTS. Source: RAPT Ventures, Inc.

On the right, the plot displays additional activity (shown in bright red) in the central region of the infant brain, midway between the top (frontal region) and the occipital region at the back of the head. This region is part of a band of areas that process somatosensory (relating to touch) input including secondary analysis of more complex sound patterns (Hamilton et al. 2021; Weiss-Croft and Baldeweg 2015). Given that this nature soundtrack includes rain, wind and bird noises, that activity is not surprising. The plot also shows less power (inhibition) in left and right parietal and left frontal areas (in dark blue), but as this plot has the baseline brain activity removed, we don't see a large increase in processing (as would be indicated if these areas were displayed in red). However, on the left plot, which shows the activity when the acoustic events are added to the track (that is, the combined track which is one of the Smarter Sleep track selections), we see increased spectral power in areas similar to the spectrograms for the Smarter Sleep blended classical music soundtrack in 8a. As this is a theta power (4-6 Hz) plot, the expected increased spectral power appears in the anterior temporal areas, on either side of the head about where the ears would be (in bright yellow and red), as well as over most of the cortex, excluding the most central areas, but specifically in the right temporal and left tempo-parietal-occipital areas (in dark red), indicating a marked difference in power when embedded acoustic events are present.

As was demonstrated in the spectrograms in Figure 8a, these topoplots show that the sleeping infant brain responds differentially with increases in spectral power and thus more active processing to a soundtrack with added acoustic events, and that the increases in spectral power and changes in the pattern of activation (red) and inhibition (blue) are in the cortical areas which are part of the developing language network.

V. RESULTS SUMMARY

Because the Smarter Sleep acoustic events have been structured to be "language-like" although not language, it was expected that the brain areas that process these types of acoustic cues would respond to these events, even during sleep. Overall, Figures 8a and 8b indicate that the baby's brain is registering the tens of millisecond changes within the events when they are added to their respective base soundtracks. These responses are not only seen in acoustic (temporal) cortex, but also in the additional brain areas that process and make sense of these sounds (e.g., frontal, parietal and somatosensory cortex). These particular brain areas have been shown to exhibit robust sensory-motor neural responses during both perception and production of language (Cogan at al. 2014). As noted, comparing the response for the background soundtrack alone against the response from the same track with the embedded acoustic events shows that the infant brain responds more strongly, as evidenced by the changes in the pattern of activation when the events are present. Thus, as shown in these tests, the events are indeed stimulating brain areas that process speech and speech-like sounds, an activity that is essential to the development of language networks and an outcome strongly supported in the research described above.

Smarter Sleep and the Adult Brain

The importance of appropriately structured sound on the organization and functioning of the auditory cortex has been emphasized, both for the still maturing cortex of the child and for the mature cortex of the adult (e.g., Bidelman et al. 2019; Eggermont 2008; Miguel et al. 2019). In the adult acoustic cortex, one would expect the effects of top-down modulatory and regulatory processes on these highly learned and behaviorally relevant sounds to dominate (Kral and Eggermont 2007).

However, there is evidence that difficulty hearing speech in noise as we age may include the effects of diminished or over-extended/merged acoustic maps as well as changes in global connectivity patterns (Bidelman et al. 2019; Erb et al., 2020; Presacco et al. 2016). As a result, in older adults, the engaging events incorporated in Smarter Sleep soundtracks may reduce the loss of temporal specificity and acoustic tuning which decreases the ability to decode speech , particularly in noise, which is characteristic of aging brains.

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