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Review

Fetal Memory: The Effects of Prenatal Auditory Experience on Human Development

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Abstract

The paper presents evidence that the intrauterine auditory environment plays a key role in shaping later auditory development. The acoustic environment in *utero* begins to shape the auditory system much earlier than sensory systems that are not exposed to input until after birth. The effects of prenatal auditory experience can be observed both among fetus through different paradigms and in the new-borns within few hours or days after birth. This manuscript collects a comprehensive snapshot of the work in this research area presenting evidence of a consistent number of papers published in this topic of study. Furthermore, the potential function of learning prenatally is explored in terms of its relevance for perinatal development. So, we describe growing evidence that externally generated sounds and music influence the developing foetus, and argue that such prenatal auditory experience may also set the trajectory for the development.

Key words: Fetal Memory; Auditory Learning; Prenatal Experience; Plasticity

Introduction

Learning is the basis of adaptive and intelligent behaviour; it is established on variations in neural assemblies and revealed by the modulation of electric brain responses. The evidence that auditory experience effects central nervous system maturation is both convincing and challenging. In infancy, long-term memory traces are formed by auditory learning, improving discrimination skills, in particular those relevant for speech perception and understanding. The early influence of social enrichment is relevant for psychological development whereas investigations in humans and primate showed that social deprivation has long-term effects on emotional and social behaviour. In addition, there is an effect of visual and tactile stimulation in the development of perceptual responsiveness in chicks. So, it is essential to analyse the role of environmental stimulation on the developmental pattern of various brain area related to learning and memory. Several studies confirm that the auditory system in chicks becomes functional before birth and, thus, they can perceive external sounds in the prenatal period. Many observations have shown that the auditory pathway of chick is plastic and undergoes changes as a consequence of prenatal sound stimulation [1]. Possible functions of fetal memory are practice, recognition of and attachment to the mother, promotion of breast feeding, and language acquisition. A challenge for the study of plasticity understands how environmentally-induced alterations to central auditory function correlate with variations to auditory perception. It was showed direct neural evidence that also human neural memory traces are shaped by auditory learning prior to the birth suggesting that prenatal experiences have an extraordinary impact on the brain's auditory discrimination accuracy, which may support, for example, early auditory development and potentially compensate for difficulties of genetic nature, such as language impairment or dyslexia [2].

Brain Plasticity and Sounds

During fetal period brain undergoes extensive developmental changes as new synapses are formed [3] and axonal connections between neurons are myelinated [4], enabling efficient recognition and analysis of complex information. There is evidence indicating that enriched environment in the form of auditory stimulation can have an essential role in plasticity modulation during the prenatal period. The present paper focuses on the emerging role of prenatal auditory experiences, and particularly on the effect of music in the development of higher brain function such learning and memory in humans. The functional maturation of the developing nervous system is driven by external input, which is demonstrated, for instance, by the rapid reorganization of the auditory cortex via external stimuli occurring in humans typically by the Gestational Age (GA) of 27 wk. [5]. Human hearing develops gradually by the last trimester of gestation and there is increase in fetal cortical brain activity in response to species typical sound. By 35 weeks of GA, cochlear biomechanics and frequency selectivity are mature [6]. Near-term characteristics of fetal cardiac responses to airborne sounds demonstrate that fetuses can discriminate intensity, frequency and spectra [7, 8] and can also process some fast and slow amplitude temporal variations in auditory streams [9]. Fetal MEG studies, using the Mismatch Negativity paradigm with tone bursts [2], confirmed that detection of frequency changes arises in utero very early in development, at 28 weeks GA, therefore only 2-3 weeks after the onset of cochlear function [9, 10]. Such plastic changes in neural assemblies during early development point out that humans have some learning capability even before

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birth. Brain plasticity serves in a wide range of vital functions assisting in adaptation behaviour to the surroundings, in learning new strategies for optimizing a certain reward-seeking policy for survival or in adjusting motor activity through sensory feedback. However, this learning capability may be grounded predominantly on the discrimination of low-pitched sounds that can penetrate the intrauterine walls. This low-pitch information may play a chief role in early speech discrimination of new-borns [11]. For airborne sounds recorded within the amniotic fluid in the gestating ewe, power-spectrum analyses show that most components over 60 dB SPL (Sound Pressure Level, re: 20 μPa) in the mothers near field environment are conducted with little distortion into the uterus and, in general, are not masked by internal sounds, music is attenuated <10 dB SPL in the gestating ewe, in contrast, the maternal voice itself suffers no or little decrease in the womb.

Evidence for Fetal Auditory Learning and Memory

Learning is defined as a change in behaviour that occurs as a result of experience. The retention of a change in behaviour from experience (i.e. learning) is what we identify as memory. It is clear that the fetus can learn by means of habituation, classical conditioning and exposure learning. These types of learning will be discussed in relation to exposure in the womb and the memory of learned material after birth. But is the effect of prenatal exposure to stimuli retained and can the fetus learn? This question is not just of speculative curiosity, but is relevant to the controversial issue of whether fetal neurodevelopment can be enhanced. The argument of fetal learning has been observed in three developing psychobiological domains [12]:

1. State or fetal motility;

2. Cardiac autonomic responses;

3. Associative learning.

Habituation is an example of non-associative learning in which there is a progressive decrease of behavioural response with repetition of a stimulus. There is a first response to a stimulus and then the frequency and/or strength of the subsequent responses diminish with repeated stimulation. The state modifications investigated in the fetus were variation from a non-active to an active state, habituation rate of gross body movements, changes in behavioural state and state transitions. In the neonate, state changes include the passage into a quiet-alert state, orientation and attention to the stimulus. The occurrence of a stimulus elicited cardiac deceleration or the cardiac orienting response was used to assess learning and memory. The conventional interpretation of a stimulus-elicited heart-rate deceleration is that it represents the cardiac component of the orienting response. Current theoretical interpretations of the fetal cardiac response to speech vary. Further, another body of literature would interpret their findings as attention and perception. The associative learning involved classical conditioning of movements in the fetus and operant learning in the new born. These responses vary for their grade of reflexivity, sensory-motor integration, accuracy of the motor behaviour engaged and auditory processing essential to resolve the stimulus (stimulus complexity).

Respect to prenatal studies, habituation of fetal gross body movements and heart rate responses to loud airborne noises and tones, or vibro-acoustic stimuli placed against the mother's abdomen [13, 14, 15] have been extensively evaluated mostly for clinical aims showing a relationship between speed of habituation and developmental scores in infancy. Fetal heart rate sign suggests that during the third trimester fetuses discriminate the speech of their mother from that of a stranger and speech of their native language from a non-native language.

Habituation is the decline of attention or response following repetitive stimulation with the same stimulus. Habituation is thought to represent a basic form of learning, needing possibly an intact central nervous system (CNS) [16]. Prenatal memory has been mostly investigated by comparing habituation and re-habituation rates of gross movements. The majority of the studies of fetal learning have used some form of acoustic stimulation. Detection of a sustained heart rate deceleration began to emerge by 34 weeks GA and was statistically evident at 38 weeks GA. Thus, fetuses begin to show evidence of learning by 34 weeks GA and, without any further exposure to it, are capable of remembering until just prior to birth [2].

However, there are wide methodological variations in the acoustic frequency and volume of the stimulus used in the exposure protocols and whether the sound source was applied directly to the maternal abdomen or in the environment. All these variables can influence the amount and quality of the sound reaching the fetus and thus its effects. Vibro-acoustic studies show a savings in the number of trials to re-habituation after a 10 min delay in fetuses of 30 weeks GA, after a 24 hours' delay and a 4-week interval with first habituation at 34 weeks GA. Thus, it was confirmed that fetuses are able to learn: they have a short-term memory of at least 10 min, and a long-term memory of at least 24 h. It was also established that fetal learning depends on fetal age [17]. It should be noted that vibro-acoustic stimuli provide tactile and auditory stimulations to the mother and auditory, tactile, proprioceptive and vestibular stimulations to the fetus. Most stimulators have a wide frequency band with fundamental frequencies and first overtones ranging from 75 to 300 Hz. They have a medium-high SPL in air (70-80 dB) but they are extremely amplified inside the amniotic fluid, e.g., >110 dB intra-uterine level in the gestating ewe [18]. In addition to learning based habituation involving latero-basal amygdala, fetus react differently to native/non-native vowels or familiar/non-familiar melodic contour decrementing between vowels of native language. These data showing a fine-tuned auditory processing and discrimination indicate that memory traces lasting for several days in the auditory cortex are a result of fetal learning [2]. Recently maternal relaxation (US) and music (CS) have been reported to produce fetal conditioning after more than 20 prenatal exposures. In the new born, the CS induced quiet awake state in conditioned fetuses [19].

Studies with External Auditory Stimuli Exposition in Utero and New-Borns Recognition

Fewer studies have examined the effect of recurrent exposition to complex auditory streams within the fetal age. Musical stimuli are reported to elicit intensification in movements [13] or in mean

Heart Rate (HR) and Heart Rate Variability (HRV) in familiarized fetuses compared to control fetuses [20]. Research examining prenatal auditory memory when mothers declaimed a specific speech passage aloud each day, between the 35-38 weeks GA [21] or from 28-34 weeks GA [22] indicated that the target story elicited a brief cardiac deceleration while the control story did not.

Prenatal auditory learning studies in the new-borns involved numerous versions of the maternal voice, speech, language and musical stimuli as reinforcers in operant learning tasks. Operant choice procedures (differential reinforcement and stimulus discrimination procedures) with new-borns can tell us whether and which features of a sound can affect its power to reinforce behaviour and are informative since they directly compare the reinforcing effect of prenatal sounds with that of control sounds. Synthetically, these studies revealed that new-borns chose or prefer reacting differently: their mother's voice vs. stranger's female voice [23], a low pass filtered version of the mother's voice, vs. the airborne version, a specific speech passage [24], familiar and unfamiliar melodic contours [9, 25], and their mother recited or sang only while pregnant over novel speech passage/melody of their mother's language over a dissimilar language they never heard before [26]. Sentences from both languages of bilingual women were established to be more rewarding for their infants than a non-maternal language [27]. These neural memory traces are a prerequisite for effective recognition, categorization, and understanding of speech, enabling new-borns to produce precise learned behaviours, such as crying at birth with the neonates' native language prosody [28]. The neural basis of fetal learning was also investigated presenting variants of words to fetuses. Data indicated that unlike infants with no response to these stimuli, the exposed fetuses demonstrated enhanced brain activity (mismatch responses) as a consequence of pitch changes for the trained variants after birth. A direct positive correlation emerged between the amount of prenatal exposition and brain activity [2].

Synchronization with Complex Auditory Stimulus: The Case of Music

Rat studies have suggested the positive effect of the exposure to structured sounds environments, such as music, in terms of cortical organization and long-term cognitive capabilities. Several studies confirm that the auditory system in chick becomes functional before birth and thus they can perceive external sounds in the prenatal age. For example, prenatal auditory stimulation in the form of species-specific sound or music increases the size of neurons and volume of the brainstem auditory nuclei as well as mediorostral nidopallium hyperpallium ventral in chick [1]. It is proposed that listening to music facilitates hippocampal neurogenesis, the generation and repair of nerves by adjusting the secretion of steroid hormones, ultimately leading to cerebral plasticity [29].

The effects of instrumental music and maternal sounds have not been directly compared. It is challenging to infer answers from prior work due to the diversity of stimuli (i.e., mother's, recorded singing joint with uterine sounds, multimodal stimulation) as well as dependent measures. A musical stimulus perceived before birth can alter behavioural states [20] or trigger attention reaction in new-borns. Hepper [30] reported that new-borns went quickly into a quiet-alert attentive state upon hearing the jingle from a TV soap opera that their mothers watched daily throughout their pregnancy.

Thus, prenatal memory is present very early and that near-term fetuses record some of the spectral and temporal features of repeated complex stimuli, e.g., prosody, melodic contour of speech, language and music. Music has been revealed to have positive influence on premature infant behaviour. From 31 weeks GA, premature infant measures (i.e. heart rate, state-of-arousal, face expressions of pain) returned to baseline more quickly when Brahms' Lullaby was played [31] and premature infants become agitated (increased heart rate) or calmed (decreased heart rate) with different music pieces.

Kisilevsky and colleagues [32] chose Brahms' Lullaby since the tempo approximated the rate of the maternal heartbeat, 65-80 beats per minute, and Van Leeuwen and colleagues [33] discovered unknown phase synchronization between the heartbeats of mother and fetus, perhaps facilitated by acoustic characteristics of maternal heartbeat and vessel pulsation perceived by the fetal auditory system. Because the heartbeat is the first regular and periodic stimulus a fetus hears, it could, in theory, effect subsequent preferences for other periodic auditory stimuli. These stimuli may act as an external rhythm to entrain the fetal heartbeat to that of the mother. This finding confirmed a change in perception and processing of complex sounds at around 33 weeks GA nevertheless music was delivered through a loudspeaker at about 20 cm above the maternal abdomen and average sound levels were measured in-air. This study improves to the small body of knowledge concerning fetal maturational changes of the peripheral auditory system and physiological development showing that near-term fetuses are able to distinguish and respond differentially to a complex auditory stimulus.

Fetal memories can affect several psychobiological domains, from gross body movements, to orienting responses, to operant discrimination learning in new-borns, but prenatal memory effects beyond this period have been observed in a few cases. It was claimed [34] that fetal learning lasts for months and perhaps years. Nevertheless, no methodological details of the study were reported. Only a study [8] assessed memory for a melodic sequence administered in uterus after a 6-week retention interval, when new-borns were 1-month old. Fetuses were exposed to the melody twice daily between their 35th and 38th week of gestation. When 1-month old (44 weeks GA), they and a control group were stimulated one time, in quiet sleep, with the descending melody or ascending control melody. The effect of prenatal exposition to the descending melody was evaluated by examining the direction and magnitude of the cardiac response elicited by the two melodies in both exposed and naive infants. Data showed that 3-weeks prenatal exposure influence infants auditory processing or perception, i.e., impacts the autonomic nervous system. This finding extends the retention interval over which a prenatally acquired memory of a specific sound stream can be observed from 3-4 days to six weeks. The long-term memory for the descending melody was considered in terms of enduring neuro-physiological tuning and its implication for the developmental psychobiology of attention and perception, as well as for the early speech perception (see Figure 1).

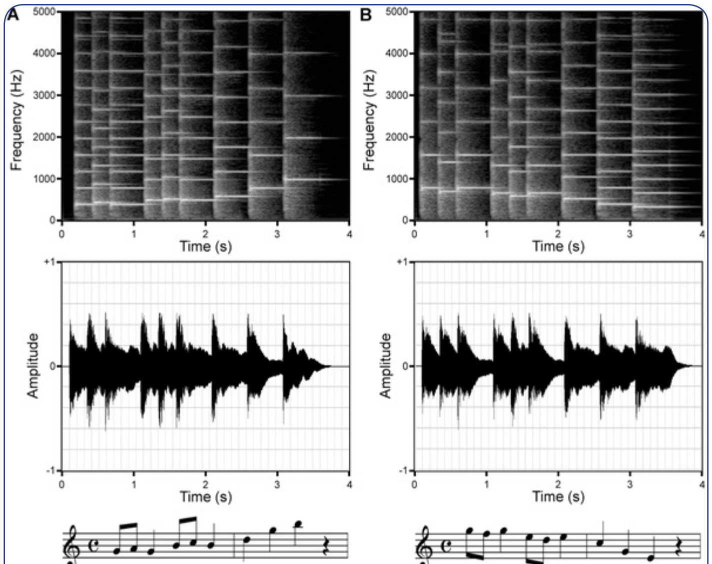

Figure 1: Spectrogram (top), envelope (middle) and score (bottom) for ascending melody (A, Control) and descending melody (B, Experimental) (From: Granier-Deferre, Bassereau, Ribeiro, Jacquet, & De Casper, 2011)

Prenatal exposure to the sounds of language influences infants' preferences for language, as described above, but this exposure might also generalize to preferences for music. Although no studies directly examine whether exposure to internal sounds such as the heartbeat can give rise to new-born musical preferences, some evidence is consistent with this possibility. Musical tempo, defined as the number of beats per minute (BPM), is used by composers to manipulate the subjective speed and mood of a piece of music. Tempo can influence adults' and children's musical preferences and emotional responses to music, often taking priority over other musical elements such as instrumentation, vocal vibrato, and genre. Listeners generally prefer a tempo of 100 bpm and this 600 ms interval is often termed the "indifference interval" that is neither "too slow" nor "too fast" [35].

Factors Involved in Fetal Learning

This finding and the antecedent research indicated that recurring auditory experience during human prenatal development of the auditory system can affect multiple psychobiological systems. It produces quantitative differences in the behaviour (amount of reinforce value in new-borns or degree of HR decelerations). These changes in behaviour suggest that a mutual effect of repeated prenatal experience with sounds is an enriched subsequent perceptual sensitivity to the sound. One possibility is that the cardiac deceleration denotes a correlate, mediated by the autonomic nervous system, of tuning of the auditory system [36].

The increased sensitivity to various characteristics of a sound repeatedly experienced before birth could be explained by the same underlying neuro-physiological adaptive mechanism. Partanen and colleagues' study [2] established direct neural correlates of human fetal learning of speech-like acoustic stimuli; giving variants of words to fetuses, they concluded that unlike infants with no experience to these stimuli, the exposed fetuses showed enhanced brain activity in response to pitch changes for the trained variants after birth (see Figure 2).

Figure 2: Excerpt of the experimental stimuli (From: Partanen, Kujala, Tervaniemi & Huotilainen, 2013).

However, other evidence suggests that new-borns preferences can generalize to novel sounds that share structural features with sounds heard *in utero*, such as novel speakers uttering familiar passages. Furthermore, a significant correlation emerged between the extent of prenatal exposure and brain activity, with greater activity being associated with a higher amount of prenatal speech exposition. Moreover, the learning effect was generalized to other types of similar speech sounds not included in the training stimuli. Consequently, their results suggested a neural involvement precisely tuned to the speech features heard before birth and their memory representations.

Conclusions

Thus, it appears likely that hearing a great deal of speech before birth may have positive effects, preparing the neural apparatus for the accurate analysis and discrimination of the fine acoustic features of speech. These early experiences may, then, affect the individual's future capabilities of speech perception and language acquisition. Although further research is needed, the above findings implicate a maturational process of auditory development that begins *in utero* and is dependent on the acoustic environment and the listening experience, both pre- and post-natal. The advanced technology in the last few years permits a detailed account of facial and body movements making potentially possible identifying emotions prenatally. So, this will offer to us a larger picture of fetal memory and factors implied in its development.

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