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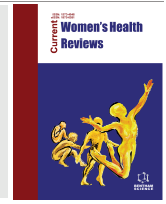

The Impact of Maternal Voice on the Fetus: A Systematic Review

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Abstract: ***Background***: Studies have shown pre-natal memory underlining the ability of newborns to discriminate maternal *vs.* other voices and to recognize linguistic stimuli presented prenatally by the mother. The fetus reacts to maternal voice at the end of gestation but it is important to clarify the indicators and conditions of these responses.

Objective: To understand the state of the art concerning: 1) indicators of fetal reactions to maternal voice *vs.* other voices; 2) conditions of maternal voice required to obtain fetal response, 3) neonatal recognition of maternal voice and of linguistic material presented prenatally and 4) obstetric and behavioral maternal conditions compromising fetal ability to discriminate between maternal and other female voices.

Method: Systematic review using EBSCO, WEBSCIENCE and MEDLINE. Eligibility: studies with maternal voice delivered before birth as stimulus and with fetal or neonatal behavior as responses.

Results: Fetal responses to maternal voice are observed through fetal cardiac, motor (fetal yawning decrease, mouth opening, fetal body movements) and brain responses (activation of the lower bank of the left temporal lobe). Newborns' head orientation and non-nutritive sucking are shown as being neonatal indicators.

Conclusion: Gestational age, baseline measures (fetal state, acoustic conditions and pre-stimulus time) and obstetrical conditions may enable or compromise fetal discrimination between maternal and other voices. The role of maternal voice for prenatal human bonding needs to be discussed according to different maternity conditions such as surrogate mothers. A new paradigm is suggested; the focus of research should be on maternal-fetal interaction under the presence of maternal voice.

Keywords: Prenatal maternal voice, fetal responses, neonatal behavior, fetal cardiac response, fetal motor response, fetal brain response, obstetric conditions.

1. INTRODUCTION

The role of maternal voice at the beginning of human communication has been the focus of theoretical and empirical research for decades. The empirical studies finding that newborns prefer their mothers' voices [1] lend support to the existence of a prenatal memory. This stimulated the quest for empirical evidence of fetal responses to maternal voice towards the end of gestation [2-5]. Since the 1980s, several empirical studies have been conducted on auditory fetal competencies in relation to a variety of sound stimuli [6-12]. Between 36 and 41 weeks of gestation, fetuses submitted to extra-uterine acoustic stimuli (92-95dB) show the ability to discriminate low-frequency sounds (250Hz-500Hz) and specifically between two different musical sounds [6]. It also happens that the fetus discriminates contents related to the human voice and human language such as it is required for the discrimination between different linguistic units such as: a) consonants, vowels, phonemes [7, 9] and b) sequences of phonemes with vowels (a / i) presented in reversed order – "ba / bi" *vs.* "bi / ba" [8] and c) bisyllabic phonemes like "baba" *vs.* "bibi" [9]. The comparison between spoken language and music was also investigated. No significant differences were detected in the fetal reaction to nursery rhymes recited by a female voice and to a musical stimulus recorded with guitar [11]. Later, other studies [12] showed the fetal ability to discriminate spectral and temporal-specific charac-

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teristics of linguistic stimuli (a sentence spoken in Icelandic delivered to a French sample) and of musical stimuli (piano ascending *vs.* descending melodic contour). Therefore, it can be concluded that the fetus is sensitive to temporal duration in linguistic or in musical stimuli. Near-term, the fetus can discriminate between female and male voices [13, 14].

Two different mechanisms of proto-cognitive processing appear to operate during prenatal stages: habituation and discrimination. The starting point for the study of fetal discrimination of acoustic stimuli was the protocol of Clarkson and Berg [15]. Faced with the repetition of a stimulus the fetus habituates and stops reacting, whereas when faced with a variation of the stimulus, it starts reacting again. However, it is not yet clear how those two processes operate during pre-natal life. The vast majority of the studies used the paradigm of habituation-novelty in order to study fetal discrimination of maternal voice compared to other voices or of various linguistic stimuli or even of linguistic and non-linguistic stimuli. Currently, there is evidence regarding the relationship between fetal cardiac activity and "fetal proto-cognition". This evidence is provided by discrimination, habituation and learning of acoustic stimuli [16], already supported by pioneering studies [6, 8, 9, 12-14]. When fetal habituation becomes faster due to the repetition of the stimuli, it is also possible to talk about fetal memory [16]. This hypothesis concerning prenatal memory was already suggested by DeCasper and Fifer [1] as well as by the Casper and his team [4].

2. OBJECTIVES

The focus of this systematic review is the state of the art of research concerning the impact of prenatal maternal voice on the fetus. This will be done through four different parameters: 1) indicators of fetal response to maternal voice *vs.* other voices or of maternal voice *vs.* other maternal stimuli; 2) conditions of maternal voice required to obtain fetal responses; 3) indicators of neonatal response to linguistic stimuli previously delivered prenatally by the mother and 4) obstetric and maternal behavioral conditions which may compromise the fetal discrimination between maternal voice *vs.* another female voice.

Our main source of investigation consists of studies using fetal observation in the presence of maternal voice. However, we also included studies using prenatal maternal voice and neonatal behavioral observations because they suggest the existence of an enduring prenatal impact of maternal voice. As a secondary aim, we sought to identify maternal, fetal, neonatal and acoustic experimental conditions as well as the indicators of fetal responses and neonatal behavior used in the relevant scientific literature. Although, the existence of studies about the relationship between maternal voice and fetal behavior, it was not possible to find any published review on this matter.

3. METHOD

3.1. Literature Search Strategy

This review was based on references retrieved before the 19 May 2017 *via* three databases, EBSCO, WEBSCIENCE and MEDLINE and follows guidelines provided by PRISMA [17]. The first two authors proceeded independently in the detection, collection and comparison of data using the databases selected for the period between January 1980 and May 2017. Keywords linked prenatal maternal voice, fetal behavior and neonatal behavior: a) fetal behavior & maternal voice; b) fetal behavior & mother's voice; c) prenatal & maternal voice; d) prenatal & mother's voice and e) prenatal maternal voice & neonatal behavior. A checklist was created with items related to: a) participants' characteristics (N, with or without obstetric risk, nationality), b) maternal voice conditions (live speech, live reading, recorded speech, recorded reading, live singing, acoustic conditions), c) control conditions (unfamiliar female voice, paternal voice, other maternal stimuli), d) fetal conditions (gestational weeks, heart rate, behavioral state), e) fetal outcome measures (heart rate, breathing movements, motor activity, brain activity) and f) newborns' outcome measures (head orientation and non-nutritive sucking).

3.2. Eligibility Criteria

Inclusion criteria were: maternal voice delivered to the fetus and the observation of fetal response. Studies reporting results on newborns' responses were also included provided that maternal voice was delivered prenatally. We excluded multimodal studies where the maternal voice is delivered to the fetus simultaneously with other stimuli (the voice of the music-therapist, the sound of musical instruments, *etc*.). Also, excluded were studies with maternal voice stimulation but without the observation of fetal or neonatal behavior.

4. RESULTS

In total, 130 references (Fig. **1**) were obtained using the aforementioned keywords. A further 39 papers were added to this review using other sources. After the removal of duplicates, 99 references were taken into account. Screening these references, 22 papers were excluded on account of their content. Of the remaining 77 papers, 59 references were excluded based on eligibility criteria. Finally, we identified 18 papers (Tables **1** and **2**) presenting 22 empirical studies on maternal voice delivered during gestation and fetal responses or neonatal behavior. Fourteen of these were with populations without risk and 4 with risk. Fifteen papers were exclusively on fetal responses to maternal voice. Only 1 paper used maternal voice delivered to the fetus during gestation and the newborn's behavior after birth. Two papers were on both fetal responses and neonatal behavior. All of the studies included some baseline assessment before the delivery of stimuli to the fetuses.

4.1. Outcome Measures

As can be seen in Table **3**, among the 15 papers dedicated exclusively to fetal responses, 5 used exclusively cardiac activity, 3 used only motor responses, 4 used cardiac and motor responses, 2 used cardiac activity and motor activity as well as breathing movements and another used fetal brain activity. Among the papers using fetal and neonatal responses, 1 used fetal cardiac activity, motor and breathing movements and newborns' head orientation and 1 used fetal cardiac activity and motor responses and newborns' head orientation. Only 1 paper was selected that used the observa-

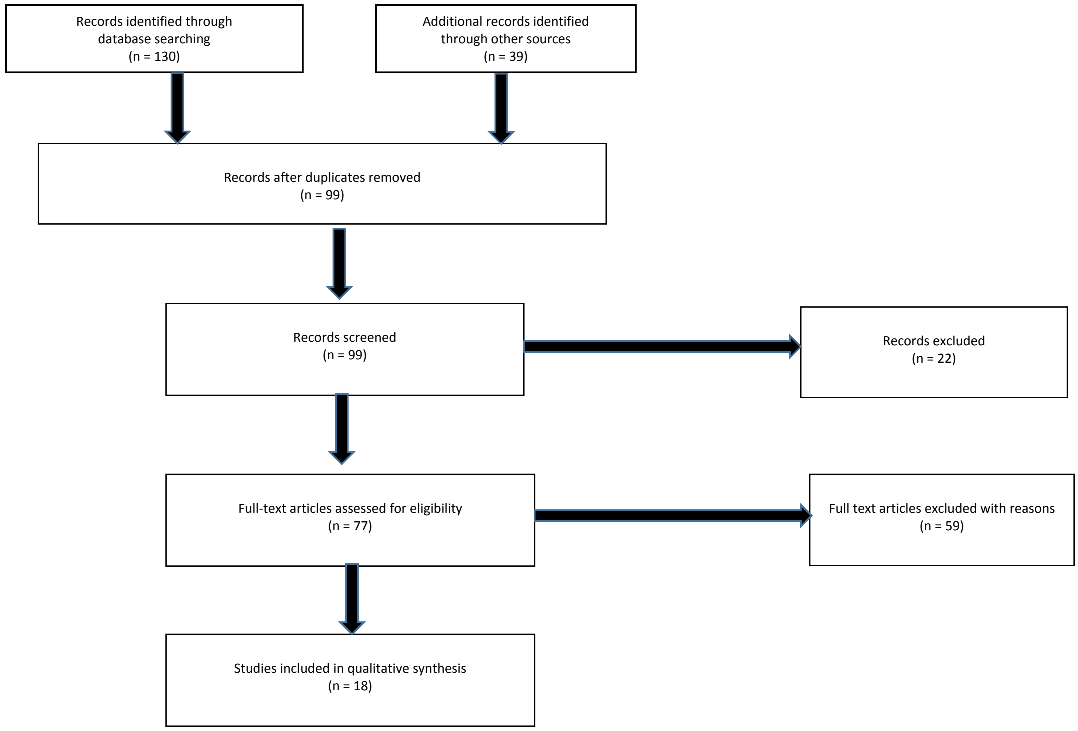

Fig. (1). Flow diagram of the database search.

tion of neonatal non-nutritive sucking after a training period with maternal voice during gestation.

4.2. Fetal and Maternal Voice Conditions

Most of the studies described fetal and maternal voice conditions during stimuli presentation. Concerning fetal conditions (Table **4**), fetal heart rate is mentioned once as a single controlled condition [4] and it is also mentioned once as a condition controlled together with fetal movements [18]. Fetal behavioral state [19] in all its parameters was never considered. Yet gestational age is always taken into account. The lower bounds of gestational age are nearly equally distributed across three different time categories of gestational age (21-29 weeks, 30-35 weeks, 36-37 weeks, Table **4**). A high proportion of papers (n = 11) was concerned with the upper bounds of gestational age measured in weeks, *e.g.*, with fetuses older than 35 gestational weeks. Most of these studies were observing samples of fetuses where gestational age varied widely. This leads to difficulty interpreting the data given that, by the end of gestation, fetal neurological maturation evolves notoriously quickly from one week to the next.

Concerning prenatal maternal voice parameters (Table **5**), the acoustic intensity of the stimuli was controlled in the majority of the papers (n = 10) and was usually between 94 and 95 Decibels. However, sound frequencies were never considered. The maternal live voice was used in 3 studies. Most of the studies (Table **1**) with exposition to maternal voice and other voices used recordings (20 studies) of sentences, stories or nursery rhymes read aloud. A majority (n = 11) of studies (Table **1**) on the discrimination between voices used maternal voice *vs.* an unfamiliar female voice while 2 studies used maternal voice *vs.* paternal voice. Other studies (n = 9) used maternal voice as the only voice stimulus: a) 2 studies used maternal voice *vs.* other maternal stimuli (maternal touch or maternal mouth movements), b) 2 studies used live maternal voice *vs.* recorded maternal voice, c) only 1 study used maternal voice after a silent baseline *vs.* a baseline where the mother talked to the researcher, d) another study used maternal voice at different gestational ages, e) one study used maternal voice *vs.* a silent baseline, f) one study used maternal voice of diabetic pregnant women and maternal voice of overweight pregnant women and g) another study used maternal voice of smoking and non-smoking pregnant women.

4.3. Studies on Maternal Voice and Fetal Cardiac Activity

Several papers suggested that the fetus is able to discriminate between maternal voice and an unfamiliar female voice [20, 21]. When the maternal voice is presented in an audio recording, an increase in cardiac rate is detected [20, 21]. On the other hand, a cardiac deceleration was found when the fetus was exposed to the mother's voice in a live condition [22]. The cardiac acceleration observed when the fetus is submitted to a familiar stimulus (the mother's voice) in an unfamiliar manner (the recorded maternal voice) may be considered a reaction to novelty. This suggests that the fetus is surprised by the unusual way in which maternal voice is presented. When comparing fetal reaction to live *vs.* recorded maternal voice, a minimal deceleration is obtained in the first condition (the most familiar condition for the fetus) while an acceleration is detected in the second condition which is the less familiar one [18]. Few studies focused on the father's voice. Interestingly, after birth, newborns prefer their mothers' voices as opposed to their fathers' voices [22]. Another relevant finding is that fetal reactivity to maternal voice is dependent on the fetal neurological maturation

Table 1. Studies according to research parameters.

Studies	Voice Presentation	dB	Stimuli	Population	Prenatal or Post-natal Age
DeCasper, & Spence [2] (1986)	RR	70	Maternal voice in utero and unfamiliar female voice after birth	Without risk N= 33	M = 55.8hl SD = 10hl
Hepper, Scott, & Shahidullah [28] (1993) study 2a	RS	NM	Maternal voice *vs.* unfamiliar female voice	Without risk N= 10	36gw
Hepper, Scott, & Shahidullah [28] (1993) study 2b	RS *vs.* LS	NM	Maternal voice	Without risk N= 10	36gw
DeCasper *et al.* [4] (1994)	RR	80-82	Maternal voice (training) and unfamiliar female voice (test)	Without risk N= 28	37gw
Kisilevsky *et al.* [20] (2003)	RR	95	Maternal voice *vs.* unfamiliar female voice	Without risk N= 60	M = 38.4gw SD = 1.1gw
Lee *et al.* [16] (2007)	RR	95	Maternal voice *vs.* unfamiliar female voice	Hypertensive pregnant women (n= 20) *vs.* normotensive (n= 20)	33-41gw
Cowperthwaite, Hains, & Kisilewsky [17] (2007)	RR	92-95	Maternal voice	Smoking pregnant women (n = 18) *vs.* non-smoking pregnant women (n = 20)	34-40gw
Smith *et al*. [34] (2007)	RR	88-95	Maternal voice *vs.* unfamiliar female voice	Without risk N= 84	M = 38.1gw SD = .7gw
Kisilevsky *et al.* [21] (2009) study 1	RR	95	Maternal voice and unfamiliar female voice	Without risk N= 24	33-41gw
Kisilevsky *et al.* [21] (2009) study 2	RR	95	Maternal voice and unfamiliar female voice	Without risk N= 40	33-41gw
Kisilevsky *et al.* [21] (2009) study 3	RR	95	Maternal voice and paternal voice	Without risk N= 20	33-41gw
Kisilevsky *et al.* [21] (2009) study 4	RR	95	Maternal voice (English), unfamiliar female voice (English) and unfamiliar female voice (Mandarin)	Without risk N= 20	33-41gw
Kisilevsky & Hains *et al.* [23] (2011)	RR	95	Maternal voice at different gestational ages	Without risk N= 143	29-40gw
Jardri *et al.* [32] (2012)	RR	100	Maternal voice *vs.* unfamiliar female voice	Without risk N= 6	33-34gw
Kisilevsky *et al.* [36] (2012)	RR	94	Maternal voice	Pregnant diabetic women (n= 14) *vs.* pregnant overweighted women (n= 32)	35-37gw
Kisilevky *et al.* [37] (2014) study 1	RR	95	Maternal voice *vs.* unfamiliar female voice	Intrauterine growth restriction N= 167	28-41gw
Voegtline *et al.* [25] (2013)	RR	NM	Maternal voice	Without risk N= 69	36gw
Lee & Kisilevsky [22] (2014)	RR	95	Maternal *vs.* paternal voice	Without risk N= 43	≥ 37gw
Marx & Nagy [29] (2015)	LR	NM	Maternal voice *vs.* maternal touch	Without risk N= 23	21-33gw
Krueger *et al.* [18] (2015)	RR *vs.* LR	71-81	Maternal voice	Without risk N= 21	28-34gw
Ferrari *et al.* [31] (2016)	LSI	NM	Maternal voice *vs.* other maternal mouth stimuli	Without risk N= 29	25gw
Kisilevsky & Brown [27] (2016)	RR	95	Maternal voice	Without risk N= 39	M = 37.8gw SD = .7gw

RR- recorded reading, RS- recorded speech, LS- live speech, LR- live reading, LSI- live singing, NM- not mentioned.

Table 2. Studies according to outcome measures and results.

Studies	Outcome Measures	Results
DeCasper, & Spence [2] (1986)	Non-nutritive sucking	The interruption of newborns' pattern of non-nutritive sucking during the presentation of familiar stories (after a period of training with maternal voice) changes even when the voice belongs to a female strange.
Hepper, Scott, & Shahidullah [28] (1993) study 2a	Fetal movements (number of upper body, arms or head movements)	There were no significant differences between fetal gross body movements in response to recorded maternal *vs.* unfamiliar female voice.
Hepper, Scott, & Shahidullah [28] (1993) study 2b	Fetal movements (number of upper body, arms or head movements)	Fetal gross body movements do emerge when maternal voice is delivered live *vs.* recorded maternal voice.
DeCasper *et al.* [4] (1994)	Fetal heart rate	A decrease of fetal heart rate was observed during the presentation of familiar rhymes (recorded with an unfamiliar female voice) after a period of training by maternal voice.
Kisilevsky *et al.* [20] (2003)	Fetal heart rate and fetal movements	Fetal heart rate increased when listening to mothers' voices and decreased in response to the voice of a strange. There were no significant differences in fetal movements.
Lee *et al.* [16] (2007)	Fetal heart rate and fetal movements	A fetal cardiac acceleration in normotensive dyads was observed during maternal voice presentation while in hypertensive dyads the acceleration was only observed after the offset of the maternal voice. This discrimination was not followed by fetal movements.
Cowperthwaite, Hains & Kisilewsky [17] (2007)	Fetal heart rate, body movements, breathing movements	Before 37 weeks of gestational age, fetuses of smoking pregnant women did not present the increase of heart rate presented by fetuses of non-smoking pregnant women after the offset of maternal voice.
Smith *et al*. [34] (2007)	Fetal heart rate	It is only when fetal vagal tone is high that differential responses of the fetal heart rate to familiar and unfamiliar voice recordings can be observed during a two minutes post stimulus period.
Kisilevsky *et al.* [21] (2009) study 1	Fetal heart rate	When shifting from strange to maternal voice there is no increase of the fetal heart rate. When shifting from maternal to strange voice there is no decrease of the fetal heart rate. A higher heart rate is observed for fetuses who listened first to their own mothers' voices when compared to fetuses who started by listening to the unfamiliar female voice.
Kisilevsky *et al.* [21] (2009) study 2	Fetal heart rate	Fetuses listening first to maternal voice, during the presentation of unfamiliar female voice present an initial fetal heart rate decrease followed by a linear increase. This is not observed in fetuses listening first to the unfamiliar female voice.
Kisilevsky *et al.* [21] (2009) study 3	Fetal heart rate	During voice presentation, there are no significant differences in fetal heart rate responses to maternal and paternal voice. During the post-voice period of the paternal voice, after a short deceleration, fetal heart rate increases linearly followed by a new deceleration.
Kisilevsky *et al.* [21] (2009) study 4	Fetal heart rate	In dyads of English native language, a fetal cardiac increase is detected when, after a familiarization with English voice (maternal or strange) and a delay of 15 minutes, fetuses are exposed to an unfamiliar female Mandarin voice. This is not detected when after the 15m delay fetuses are exposed to English voice (maternal or strange).
Kisilevsky & Hains *et al.* [23] (2011)	Fetal heart rate	The onset of fetal cardiac responses to voice presentation emerges between 32 and 34 gestational weeks. From 32 to 37 an initial cardiac deceleration followed by a cardiac acceleration is observed. By the end of pregnancy the initial response is an accelerative one. At the beginning of the third trimester 46% of fetuses respond to stimulation while at the end of gestation the proportion rises to 83%.
Jardri *et al.* [32] (2012)	Fetal brain response	A higher activation of the left temporal cortex is detected during the presentation to voices *vs.* pure tones, at 33 gestational weeks. A specific sensitivity to speech of the upper bank of the left temporal lobe was observed at 34 gestational weeks. The lower bank of the left temporal lobe presents a significantly higher activation to maternal voice than to an unfamiliar female voice also at 34 gestational weeks.
Kisilevsky *et al.* [36] (2012)	Fetal heart rate, fetal movements and fetal breathing	Fetuses of overweighed mothers presented a heart rate increase during maternal voice presentation which could not be found in fetuses of diabetic mothers. After the offset of maternal voice, fetal heart rate in the overweighed group decreases while fetal heart rate in the diabetic group increases.

(Table 2) contd….

Studies	Outcome Measures	Results
Kisilevky *et al.* [37] (2014)	Fetal heart rate, fetal movements, fetal breathing and head orientation of the newborn	During maternal voice presentation, fetuses without growth restriction presented an increase of heart rate and this response was sustained during the period of offset. Fetuses with growth restriction, during maternal voice presentation, presented an initial decrease of the heart rate followed by an increase which did not last after the first minute.
Voegtline *et al.* [25] (2013)	Fetal heart rate and fetal movements	During the presentation of maternal voice a fetal cardiac deceleration and a motor decrease is observed after a baseline where the mother was awake and talking. A fetal cardiac acceleration and a spike of fetal movements is observed after a baseline where the mother was in rest and silence.
Lee & Kisilevsky [22] (2014)	Fetal heart rate and fetal movements and head orientation of the newborn	During the presentation to maternal recorded voice an increase of fetal cardiac frequency is observed and a deceleration is observed during the presentation of maternal non-recorded voice. Fetuses responded with an increase of cardiac frequency to the mothers' as well as to the fathers' voices. The number and the duration of fetal body movements do not show significant differences if recorded maternal voice is compared to paternal recorded voice.
Marx & Nagy [29] (2015)	Fetal movements	By the third trimester the cross of the fetal arms is more frequent in response to voice than to touch condition or during a period without stimuli. During the voice condition a decrease of yawning is detected from the second to the third trimester.
Krueger *et al.* [18] (2015)	Fetal heart rate and fetal movements	A minimal fetal cardiac deceleration to live maternal voice and a fetal cardiac acceleration to recorded voice were observed. There were no significant differences in fetal movements.
Ferrari *et al.* [31] (2016)	Fetal movements	There is no change of the fetal general activity when, after a silent baseline, the fetus is exposed to the experimental condition. A significant increase of the fetal mouth opening is detected when the mother sings the LA syllable.
Kisilevsky & Brown [27] (2016)	Fetal heart rate and maternal heart rate	During a baseline where mothers are at rest and silent for 20 minutes, correlations between maternal and fetal heart rate are moderate to high for 77% of the dyads. During the presentation of maternal voice correlations are moderate to high for 95% of the dyads.

Table 3. Indicators of fetal and neonatal responses.

Fetal Responses					Fetal & Neonatal Responses		Neonatal Responses
FHR	FM	FHR & FM	FHR, FM & FBM	FBR	FHR, FM, FBM & NHO	FHR, FM & NHO	NNS
5	3	4	2	1	1	1	1

FHR- fetal heart rate, FM- fetal movements, FBM- fetal breathing movements, FBR- fetal brain response, NHO- newborn's head orientation, NNS- non-nutritive sucking.

Table 4. Fetal conditions controlled during stimuli presentation.

GW								FHR	FM & FHR
Lower Bound				Upper Bound					
21-29	30-35	36-37	NM	25-30	31-34	35-41	NM		
5	5	6	3	1	3	11	4	1	1

GW- gestational weeks; FHR- fetal heart rate; FM & FHR- fetal movements and fetal heart rate; NM- not mentioned.

Table 5. Voice conditions controlled during stimuli presentation.

Acoustic Conditions					Maternal Voice Presentation					Other Voices and Stimuli		
dB				Hz	LS	LR	RS	RR	LSi	UFV	PV	OMS
(70-82) 3	(88-95) 10	(100) 1	(NM) 4	0	1	1	1	15	1	5	1	2

dB- Decibels; Hz- Hertz; LS- live speech; LR- live reading; RS- recorded speech; RR- recorded reading; LSi- live singing; UFV- unfamiliar female voice; PV- paternal voice; OMS- other maternal stimuli; NM- not mentioned.

which evolves according to gestational age [23]. However, as other authors have pointed out [22], these results were difficult to interpret for various reasons. One of these is that there was no control condition for sound stimuli other than maternal voice. It is also important to note that the statistical analysis performed in the paper by Kisilewsky and Hains [23] has been heavily criticized by DeCasper and his team [24].

The inclusion of a baseline condition is also a very important methodological aspect for studying fetal reaction to maternal voice. A cardiac acceleration was observed after a silent and quiet baseline period while a cardiac deceleration was detected after a baseline period where the mother is talking [25]. The fetal vagal tone was also observed before the delivery of the stimulus [26].

Kisilevsky and Brown observed interesting correlations between fetal cardiac frequency and maternal cardiac frequency before and during maternal voice presentation [27]. When mothers are at rest and silent during a baseline condition, correlations vary between moderate to high for as many as 77% of dyads. After that, when recordings of the mothers' voices are delivered to the fetuses, correlations vary also from moderate to high but its incidence increases to 95% of the dyads.

4.4. Studies on Maternal Voice and Fetal Motor Behavior

In contrast to fetal cardiac indicators, fetal body movements do not seem to be discriminative relatively to recorded maternal voice [18, 20, 22, 28]. However, a significant decrease in body movements was observed when the maternal voice was delivered live but not with recorded maternal voice [18, 28]. These studies seem to suggest that changes in fetal body movements are only observable when the mother's voice is delivered in a live condition. The number and the duration of fetal body movements also vary significantly between recorded maternal and paternal voice [22].

Baseline acoustic conditions also seem to influence fetal movements during exposition to live maternal voice. A spike of movements is observed after a period of rest and silence while a decrease in motor activity is detected after a period during which the mother is awake and talking [25].

Marx and Nagy [29] hypothesized that the fetus is able to produce attentional-orientation responses resembling those of newborn babies during the presentation of maternal voice. The authors observed a decrease in yawning behavior which may be regarded as a new indicator of fetal attentional response to maternal voice. Fetal yawning is spontaneous and highly frequent during the third trimester and it is viewed as an indicator of well-being and maturation of the brainstem [30]. In a recent study [31], fetal mouth movements, namely opening, have been shown to be a possible indicator of discrimination between different forms of maternal singing (LA syllable *vs.* LU syllable) and also between maternal singing of the LA syllable and other maternal stimuli such as opening of the mouth, chewing a wafer or a biscuit or simulated yawning. There is also a question about the experimental condition where the mother chews material with glycoses; this possibly changes the physiological condition of the fetus. It is important to examine critically the interpretation of fetal responses to maternal voice when fetuses are only at the 25th week of gestation. In the future, this research should be undertaken again with fetuses with more advanced gestational ages.

4.5. Studies on Maternal Voice and Fetal Brain Activity

The study of Jardri, Houfflin-Debarge, Delion, Pruvo, Thomas and Pins [32] offers interesting insights into a specific location for the fetal processing of the maternal voice. This was done with fMRI technology using fetal hemodynamic responses based at blood-oxygen-level-dependent-signal and neurovascular coupling [33]. Comparing responses to different voices (mother voice or unfamiliar female voice) with responses to pure tones at the 33rd gestational week, the activation of the left temporal cortex was significantly greater in the voice conditions than in the pure tones condition. A specific response to maternal voice compared to the response to the new female voice was registered at the 34th gestational week. This study also shows that the lower bank of the left temporal lobe presents a significantly higher activation with the mother's voice than with the unfamiliar female voice. Rousseau, Studholme, Jardri and Thomason [33] underlined that in Jardri and colleagues' work [32], the upper bank region of the left temporal lobe was activated in response to an unfamiliar female voice.

4.6. Studies on Maternal and Obstetric Conditions and Fetal Response to Maternal Voice

Studies on the impact of obstetric conditions on fetal neurological maturation reveal atypical fetal reactions in the auditory processing of maternal voice and also in the discrimination between maternal voice and unfamiliar female voice. Lee, Brown, Hains and Kisilevsky [34] aimed to observe the processing of fetal audition stimulated by a recorded story read aloud by mothers compared to recorded unfamiliar female voices; in this study, the voices were captured from pregnant women with and without hypertension in pregnancy. It seems that hypertension in pregnancy induces an atypical fetal cardiac response to maternal voice. Moreover, fetuses of pregnant smoking women below 37 gestational weeks fail to present the cardiac response to the offset of maternal voice that is observed in fetuses of non-smoking pregnant women [35]. It also appears that diabetes in gestation is an obstetric condition able to change the fetal cardiac response to maternal voice [36]. In this study, during maternal voice presentation, it was observed that fetuses of overweight mothers present a heart rate increase which was not found in fetuses of diabetic mothers. Fetal growth restriction is an obstetric condition that seems to compromise the processing of the discrimination between maternal voice and unfamiliar female voice. This underlines a fetal difficulty with adaptation to novelty and most of all difficulty in sustaining fetal attention relative to the change of stimuli [37]. The characteristics of the responses of fetuses without growth restriction are close to what has been described in other studies conducted by the same research team [20, 23]. The role played by intrauterine growth retardation in fetal auditory development is underlined by transnatal studies pointing to newborns' vulnerabilities relative to the discrimination between maternal voice and other voices [37].

5. DISCUSSION

The study of fetal cardiac reactivity to human speech has developed rapidly in the scientific literature since 1980 [*e.g.,* 2, 4]. But, it is only recently that researchers have begun to search for scientific evidence of fetal response to maternal voice [18, 20, 23, 25, 29, 31, 32] and it is not yet clear when and how the fetus differentiates the mother's voice from other human voices. Although these methodologies are promising, the unique characteristics of maternal voice raise problems with regard to the control of the variability of the stimulus. The only study that compares live maternal voice and recorded maternal voice [18] is also difficult to interpret. It uses a training period which comprises live maternal voice but not recorded maternal voice; the fetal acceleration observed after exposure to the recorded maternal voice may be due not only to the unfamiliar condition in which the stimulus is delivered but also to the absence of previous training with recorded maternal voice. Cardiac, motor (yawning decrease, mouth opening and body movements) and fetal brain responses to maternal voice (activation of the lower bank of the left temporal lobe) are highlighted in the scientific literature. Studies using maternal voice *vs.* unfamiliar female voice were conducted using samples with and mostly without risk factors between 28 and 41 gestational weeks. A recorded reading of linguistic stimuli was delivered to the fetuses (80-100 Db) and to the newborn (70 Db). With regard to outcome measures, the majority of the studies used fetal heart rate while others used fetal movements, brain response and non-nutritive sucking. Results suggest that an increase of fetal heart rate occurs during maternal voice in dyads without risk. A decrease in fetal heart rate is observed during the presentation by an unfamiliar female voice of a familiar stimulus previously presented by maternal voice [4] evidencing the existence of a prenatal memory relative to linguistic contents even when the training was made with maternal voice and the testing was performed with an unfamiliar female voice. The decrease of fetal heart rate during the stimulation by the recording of an unfamiliar female voice observed by Kisilevsky and her team [20] is particularly difficult to interpret since in the baseline these fetuses presented motor and cardiac characteristics notably different from the fetuses that were stimulated by the recording of the maternal voice. The fetal response seems to be influenced by the sequence "maternal voice - unfamiliar female voice" and also by exposure to "native language *vs.* non-native language". As Kisilevsky and team [21] suggested, fetal cardiac acceleration seems to be associated with a response of surprise or novelty independent of the source (maternal voice or unfamiliar female voice). In these authors' study 1, no fetal heart rate increase is detected when shifting from strange to maternal voice. Also, decrease of fetal heart rate when shifting from maternal to unfamiliar female voice is not detected. An increase of fetal heart rate was found for fetuses listening first to maternal voice *vs.* fetuses listening first to an unfamiliar female voice. In study 2, an initial fetal heart rate decrease followed by a linear increase was found during unfamiliar female voice in fetuses first exposed to maternal voice; this was not observed in fetuses listening first to the unfamiliar female voice. In study 4, a fetal cardiac increase is observed in dyads of English native language when fetuses are exposed to an unfamiliar female Mandarin voice after familiarization with an English voice (maternal or unfamiliar female) and a delay of 15 minutes. This is not detected when after the 15m delay fetuses are exposed to a native English-speaking voice (whether of the mother or of another woman). So, it appears that the fetus is already able to discriminate between linguistic stimuli of his/her native language *vs.* non-native language independently of the source being maternal or non-maternal in origin. Thus, it seems that fetal cognitive functioning is not only sensitive to the acoustic characteristics of maternal voice but also to other aspects such as linguistic content and also to the stimuli sequence presentation (*e.g.,* maternal voice *vs.* unfamiliar female voice; native language *vs.* non-native language).

Differential responses of fetal heart rate to familiar and unfamiliar voice recordings are only observed when fetal vagal tone is high [26]. This reinforces the need to control fetal baseline characteristics in order to ensure that fetal responses are in fact the result of the discrimination between maternal and non-maternal voices.

The fetal lower bank of the left temporal lobe presents a significantly higher activation by maternal voice than by an unfamiliar female voice at 34 gestational weeks [32] being important to replicate this study with a larger sample. But, as Rousseau, Studholme, Jardri and Thomason [33] mentioned the fMRI observation of the fetal brain functioning raises methodological problems on account of fetal head movements; these movements are sporadic, difficult to predict and are possibly contaminated by maternal breathing. When the fetal head moves the fMRI data are submitted to distortion; for that reason, fMRI data of the fetal brain are only valid when fetal head motion is minimal.

5.1. Limitations

Conclusions concerning fetal competencies in this domain should be treated with caution given that several studies present some methodological limitations, especially in terms of the criteria used for the control of important variables. Several issues restrict the interpretation of the results published in the selected papers. An initial question arises from the diversity of methodologies used by different researchers. Secondly, it is hard to be completely satisfied with the idea of fetal responsiveness when it is recognized that a fetal psychophysics does not yet exist [38]. More than that, the maternal voice phenomenon captured by the fetus is an extremely complex multisensory reality; besides the fact that maternal voice varies from subject to subject, it is always associated with other sounds, movements (mostly diaphragmatic) and biochemical productions that have an impact on the intrauterine environment. Another aspect of maternal voice that is not taken into account is its emotional quality. Indeed one may question whether a mother can be absolutely neutral when researchers ask her to read a story or a nursery rhyme. Several studies attempted to standardize the stimuli contents offered to the fetus. However, each participant produces a unique prosody making absolute control of the stimuli impossible. Finally, neuronal plasticity is an ongoing process involving very important changes at the level of fetal neurological maturation. Due to this fact, it is problematic to associate observations made at the end of pregnancy and at the beginning of post-natal life. In order to obtain scientific evidence about the fetal reaction to maternal voice, it is important to further current understanding of the indicators of fetal responsiveness. It is also important to control better the variables that determine fetal response to maternal voice. None of the studies included in this review took into account all the features of fetal state in a baseline condition. Future studies should control for the fetal behavioral state given that an F1 state [19] is probably the most adequate one for the baseline condition. Regarding gestational age, although all studies reported on this important variable, the range of fetal ages is sometimes so broad that the interpretation of results becomes difficult because of the implications for the impact of neurological maturation on fetal response.

Whereas the confrontation of maternal voice with an unfamiliar female voice is widely used, only a very few studies confronted maternal with paternal voice. In the future, studies using paternal voice should also control the extent to which fathers are used to speak to the fetus before the experimental protocol. In line with the study by DeCasper and Prescott [39] on newborns' discrimination between paternal voices and other male voices, it would be interesting to compare paternal voice with unfamiliar male voices presented to the fetus.

Most studies on exposure to maternal voice and other voices used recordings of sentences, stories or nursery rhymes read aloud by mothers. Very few studies used live maternal voice. This raises questions about the absence of specific motherese elements when researchers use tape-recordings. It also should be noted that when a mother is asked to speak to the fetus prosodic variations are likely to occur. These variations have not yet been studied. Studies that use only maternal voice delivered in different conditions (live *vs.* recorded; silent baseline *vs.* active baseline) with healthy populations are scarce and are affected by methodological issues. The discrimination between live and recorded maternal voice should be replicated using a training period with both conditions for maternal voice.

Little attention has been given to other variables involved in maternal voice. In this sense, we deem it important to select the vocal material more rigorously, avoiding the emotional evocations that the material (a story, a poem or a song) may elicit in each maternal participant. Some studies in this area [12] tried to prevent mothers from listening to the stimuli delivered to the fetus. Headphones delivering other auditory stimuli being placed on the mothers. Yet despite this measure one may wonder whether it triggers some kind of maternal emotional response that may influence the fetal response *via* physiological interactions. In future studies, it would be interesting to question mothers directly about their individual sensibility to specific audio stimuli. Also, in the observation of fetal responses, the impact of live singing maternal voice has been less studied and this possibility should be addressed by future studies. A final issue regarding research into maternal voice is the simulation of maternal voice by another woman. This would allow one to observe whether the fetus is able to discriminate the real maternal voice against the simulation of it. In this way, one could understand whether the fetus only discriminates structural aspects of maternal voice or whether fetal discrimination encompasses emotional aspects specific of each voice.

Studies performed with pregnant women with obstetric risk showed atypical responses of the fetuses when stimulated by maternal voice. Some authors justify these atypical fetal responses as a consequence of fetal neurological immaturity. Nevertheless, it is also possible that the fetal response in the context of obstetric conditions is influenced by maternal psychological aspects; specifically, it is possible that an at-risk pregnancy induces a defensive adaptation in order to control emotional life [40]. This defensive adaptation may have consequences upon the quality of maternal voice (vitality, intonation, pitch) and may reduce the amount of speech directed to the infant. This research field is also important for the identification of fetal response in the context of prenatal diagnostics. It is also possible that these studies will help to increase the psychobiological fundamentals with regard to the possible benefits and risks of the stimulation of maternal voice upon the development of fetal behavior and upon mother-fetus interaction. Maternal anxiety during gestation is another vulnerability factor that seems to compromise auditory processing after birth. Emotional states in pregnancy are possibly influential in the development of fetal discrimination between maternal and unfamiliar female voices. Harvison, Molfese, Woodruff-Borden and Weigel [41] observed that post-natal auditory discrimination becomes atypical because of the maternal level of anxiety during pregnancy.

5.2. Implications

Fetal reactivity to maternal voice does not depend only on factors related to fetal competence but also on factors related to maternal experience and condition and to maternal-fetal relationship. The observation of fetal behavior as a manifestation of a separate organism reacting to maternal stimulation raises complex issues. Specifically, it questions whether the fetus constitutes a psychobiologic entity separated from the maternal organism. In analogy to the placenta's function, it is supposed that maternal voice delivered prenatally is able to play a mediator role in the maternal-fetal interaction with positive implications for human bonding after birth. However, one may question what happens when newborns have to deal with a maternal voice that is different from the maternal voice listened during gestation; this is the case with surrogate pregnant women. Special conditions such as this need to be submitted to specific research.

These issues may indeed call into question the current methodological paradigm. A promising new paradigm could be the observation of maternal-fetal interaction activated by the presence of contingent live maternal speech or singing. Research related to this new paradigm will imply observations made at the end of pregnancy requiring a level of neural maturation that goes near term. Fetal cardiac variability is the most common indicator in studies of fetal auditory abilities. In this field, one of the most interesting contributions was the identification of short epochs of cardiac synchronization between the mother and the fetus in non-controlled conditions [42]. It was later shown that the epochs of maternal-fetal cardiac synchronization depend on maternal respiratory activity [43]; in fact when the mother breaths with a higher respiratory rate her cardiac frequency becomes closer to that of the fetus. Ivanov, Ma and Bartsch [44] propose that the mediator mechanism for maternal-fetal cardiac synchronization may be understood in two different ways. The first is that maternal breathing affects both the fetal and maternal cardiac systems. The second one is that the maternal cardiac system has a detuning effect upon the heart rate of the fetus. This hypothesis may be explained by the possibility that maternal-fetal synchronization is mediated by fetal perception of acoustic stimuli such as maternal heartbeat and maternal pulse. Di Pietro, Irizarry, Costigan and Gurewitsch [45] noticed that significant correlations between maternal and fetal heart rate could only be observed from the 32nd gestational week on. Moreover, fetal movements and maternal cardiac activity were significantly associated. In the future, it would be interesting to explore the use of Doppler examination as a possible measure of observation of maternal-fetal hemodynamic interaction before and after maternal voice exposure to the fetus. Maternal cardiac frequency and fetal cardiac frequency present very interesting correlations before and during maternal voice. Although a baseline condition of rest and silence seems to favor an interesting maternal-fetal cardiac correlation this can even be improved when the fetus is exposed to recorded maternal voice [27]. This study underlines and expands the importance of maternal-fetal cardiac synchronization in the domain of fetal reactions to maternal voice. Having in mind the hypothesis that mother-fetus cardiac synchronization can be influenced by maternal respiratory rate [43] and knowing that vocalizations do change the respiratory rate it would be interesting to investigate the mother-fetus cardiac synchronization during exposition to maternal singing. It is also important to clarify, empirically, how the experience of prenatal sound stimulation, particularly contingent maternal speech and singing, may prove to be an important factor for contingent maternal-fetal interaction and for the epigenetic development of human communication. Expanding on the findings involving mouth movements as responses to maternal voice, other studies [46] on the lateralization of fetal mouth movements suggest another important hypothesis. Specifically, the lateralization of mouth movements may indicate different ways of responding to maternal voice, especially when confronting maternal singing, speech and motherese directed to the fetus. Surprisingly movements of the fetus' eyes do not appear to have been studied within this research field. However, fetal pupil dilation reacting to vibroacoustic stimulation has been suggested as an indicator of fetal attention [47]. It would be interesting to use this indicator in the future as a measure of fetal attention reacting to maternal voice. It would be very interesting to investigate whether fetal brain processing would occur at different locations in different conditions: a) live maternal voice; b) maternal voice in motherese to the fetus and c) maternal singing.

The impact of hearing the mother's voice before birth may constitute an important and expanding though still incipient field of research leading to the links between the psychological and physiological nature of the maternal-fetus interaction. In the future, an important goal for researchers should be to deepen our knowledge about the importance of maternal voice on fetal ontogenetic development as well as on mother-fetus interaction and on precursors of human communication.

CONCLUSION

This review revealed difficulties relatively to conclusions because of the methodological diversity and the lack of control for important variables. Nevertheless, the available data suggest that the human fetus is a competent being from the auditory point of view. This is a particularly important indicator of the prenatal development of a precursor of human communication. This review also reveals the existence of an important field of research that needs to be further clarified in future studies. One of the questions concerns the still incipient knowledge about the fetal psychophysics making it difficult to know the indicators of fetal response and behavior when the fetus is exposed to maternal voice. Another issue concerns the clarification of maternal and maternal-fetal variables that may compromise or facilitate the fetal response relatively to maternal voice.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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