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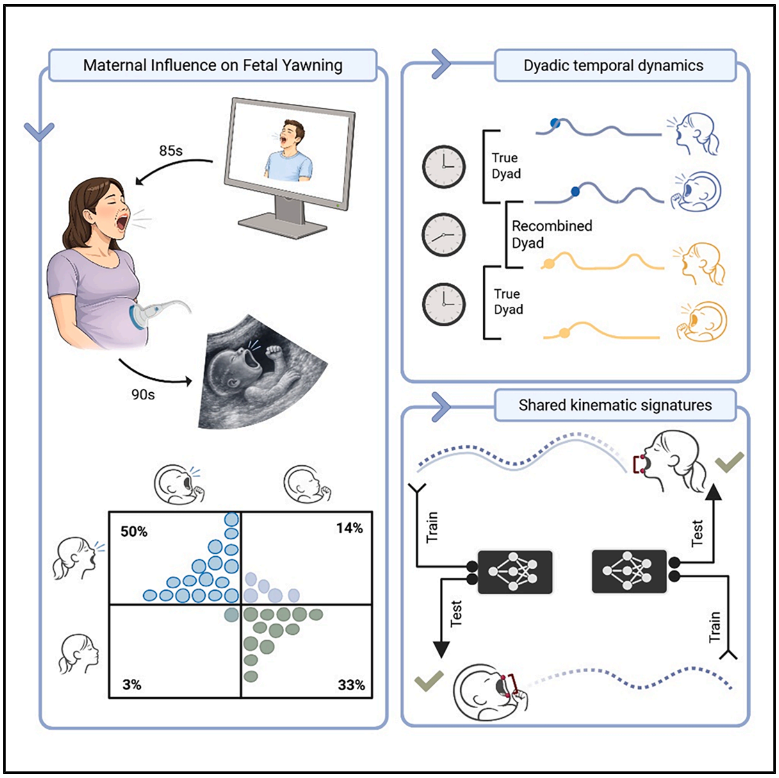
Prenatal behavioral contagion through maternal yawning and fetal resonance

Graphical abstract



Highlights

- Maternal yawning selectively increases fetal yawning during contagion
- Fetal yawns follow maternal yawns with nonrandom dyadic timing
- Cross-domain models identify common yawning kinematics across ages

Authors

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In brief

D'Adamo et al. report that fetal yawning increases selectively when mothers yawn, suggesting a possible prenatal form of contagion. True mother-fetus pairs exhibit stronger temporal coherence than recombined dyads, and kinematic analyses reveal a highly conserved motor pattern, highlighting a remarkable continuity of this behavior across developmental stages.

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Report

Prenatal behavioral contagion through maternal yawning and fetal resonance

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SUMMARY

Yawning is a phylogenetically preserved and highly stereotyped behavior observed across vertebrates.[1] In humans, it emerges early in development, as it is already present prenatally.[2,3] Qualitative studies show that fetal yawns display a structured motor pattern closely resembling adult yawns, suggesting a role in early sensorimotor organization,[4,5] and they have been proposed to support the maturation of brainstem central pattern generators and early synaptic development.[6,7] Due to its early emergence in development, prenatal yawning has largely been interpreted as driven by endogenous programs, whereas in postnatal life, yawning can also be shaped by the social context through contagion, a phenomenon linked to sensorimotor mirroring and affective attunement.[8,9] Here, we tested whether prenatal yawning may also be modulated by maternal behavior. Using ultrasound recordings of fetal facial activity combined with controlled elicitation of maternal yawning, we show that fetal yawning selectively increases following maternal yawns but not during non-contagious control conditions. Temporal analyses reveal structured coordination between maternal and fetal yawning, and machine-learning classification identifies shared kinematic signatures across maternal and fetal yawns. These findings suggest that fetal yawning might also be embedded within a dyadic sensorimotor context in which maternal behavior shapes fetal expression, suggesting that forms of behavioral resonance and embodied alignment precede birth and contribute to the early foundations of social attunement.

RESULTS

Building on the dual motor and social nature of yawning, this study examined whether prenatal yawning may be sensitive to maternal behavior. Thirty-eight pregnant women (28 + 0/32 + 0 weeks) first underwent a single 1-min baseline recording and then viewed three 6-min video conditions: yawning (contagion stimulus), open/close (non-contagious mouth-movement imitation), and still-face (static facial control), presented in a counterbalanced order. Maternal and fetal facial movements were captured via video and two-dimensional ultrasound recordings, respectively, and were then annotated by three independent coders and subjected to a frame-by-frame lip-aperture tracking to derive temporal and kinematic parameters.

Maternal influence on fetal yawning

Our primary aim was to determine whether fetal yawning is modulated in response to maternal yawns.

As a first step, we verified that yawning, the target behavior, occurred more frequently in the yawn condition than in all other conditions, thereby demonstrating the reliability and specificity of the contagion effect (Figures 1A and 1B; a parallel control analysis on mouth movements is provided in Figure S1; Table S1). In both mothers (χ^2 = 80.76, p < 0.001, ε^2 = 0.57) and fetuses (χ^2 = 24.17, p < 0.001, ε^2 = 0.17), yawning occurred significantly more frequently in the yawn condition compared with all control contexts. In the control conditions, yawning incidence remained near zero and showed no meaningful variation (mothers, all mean [M] < 0.1, median [Med] < 0.1, standard error [SE] ≈ 0; fetuses, baseline, M = 0.06, Med < 0.1, SE = 0.04; still, M = 0.33, Med < 0.1, SE = 0.14; OpCl, M = 0.28, Med < 0.1, SE = 0.11). During the yawn condition, 63.9% of mothers yawned at least once, with an average of 2.6 yawns (Med = 1, SE = 0.51; all p_{adj} < 0.001). In the same condition, 52.8% of fetuses exhibited yawning, with a mean incidence of 0.81 yawns (Med = 1, SE = 0.16; all p_{adj} < 0.01).

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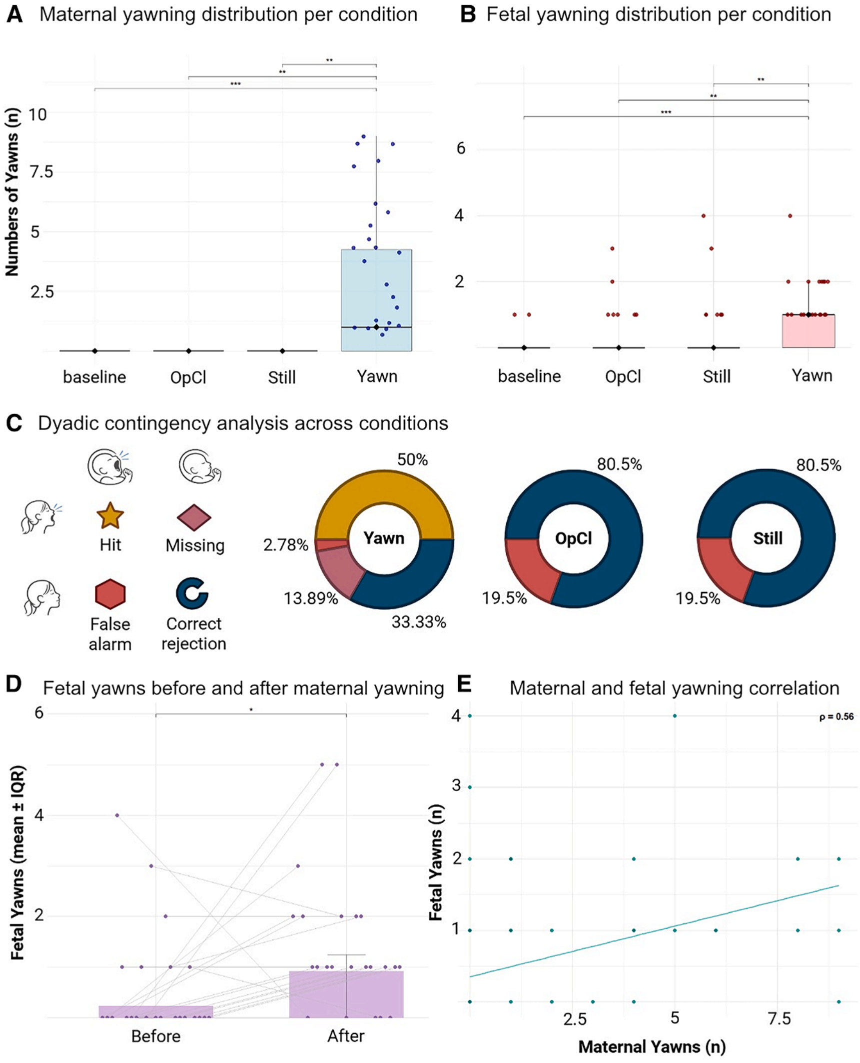

Figure 1. Distribution of yawning across experimental conditions

(A and B) (A) Maternal yawning distribution per condition and (B) fetal yawning distribution per condition. Each point represents an individual observation, and the vertical whiskers indicate the interquartile range (IQR), with the central line representing the median. Statistical comparisons between conditions are indicated above the plots (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Baseline; OpCl, open/close condition; still, still-face condition.

(C) Dyadic contingency analysis across conditions showing the percentages of hits, misses, false alarms, and correct rejections for mother-fetus yawning events.

(D) Fetal yawning frequency before and after maternal yawning. Points and connecting lines represent individual changes, while bars indicate the IQR (*$p < 0.05$).

(E) Correlation between maternal and fetal yawning frequencies across dyads. Each point represents a dyad, and the regression line illustrates the positive association between maternal and fetal yawns (Spearman's $\rho = 0.56$).

See also Figure S1 and Table S1.

Dyadic contingency analysis revealed specific mother-fetus coupling in yawning (Figures 1C and 2). Calculated on the entire sample, hits (both yawned) accounted for 50% and correct rejections (neither yawned) for 33.33%, markedly outnumbering misses (maternal-only yawns; 13.89%) and false alarms (fetal-only yawns; 2.78%) ($d' = 2.21$; Fisher's $p < 0.001$; odds ratio [OR] = 37.49). By contrast, no coupling emerged in the control conditions, which showed no hits and higher false-alarm rates. Analyses further indicated that fetal yawning was not randomly distributed across the experimental sequence but increased systematically following maternal yawns (Wilcoxon signed-rank test [V] = 27, $p = 0.016$). Fetal yawns were markedly more frequent after ($M = 0.94$, Med = 1, SE = 0.17) a maternal yawn than before ($M = 0.23$, Med < 0.1, SE = 0.08) (Figure 1D), highlighting a temporal sensitivity of the fetal response to maternal behavior. This pattern was reinforced at the dyadic level: mothers who yawned more also tended to have fetuses that yawned more ($\rho = 0.56$, $p < 0.001$), revealing a robust positive association between maternal and fetal yawning frequencies (Figure 1E).

Together, these findings underscore a clear relational linkage in the expression of yawning, suggesting that fetal behavior is modulated in systematic relation to maternal cues.

Temporal dynamics of maternal and fetal yawning

Beyond our primary aim, we also examined whether maternal and fetal yawns exhibit directional dyadic temporal alignment.

With respect to the onset of the experimental condition, maternal yawns occurred significantly earlier (maternal latency [Lat_m]: M = 84.81 s, Med = 45.01, SE = 21.8) than fetal yawns (fetal latency [Lat_f]: M = 175.19 s, Med = 155.95 s, SE = 28.4) ($V = 18$, $p = 0.033$). However, Lat_m did not differ from the relative latency between mother and fetus (Lat_{fm}: M = 90.37 s, Med = 77.9 s, SE = 36.7) ($V = 46$, $p = 0.706$), suggesting that the fetal response delay to maternal stimulation (yawn) is equivalent to the maternal response to contagious video stimulation (Figure 3A).

To explore dyadic latency alignment, Lat_{fm} values obtained in the true dyads were compared with a reference distribution generated from random pairings (Figure 3B). The observed latency in the true dyads was significantly greater than expected by chance, and no random recombination produced a comparable value (permutation-derived null distribution: M = −14.39 s, Med = 3.5 s, SE = 7.6; 95% CI [−50.37, 19.44]; empirical one-sided $p_{10,000} < 0.0001$). This pattern suggests that maternal and fetal yawns are temporally coupled rather than randomly coordinated.

By a cross-recurrence quantification analysis, we extended this real-versus-random-dyad comparison to the entire lip-aperture time series recorded during the entire yawn condition (Figure 3C). True dyads showed higher values of both recurrence rate (RR; M = 89.8%, SE = 1.39) and longest diagonal line (Lmax; M = 1,102.5, SE = 149.0) compared with the null model, with

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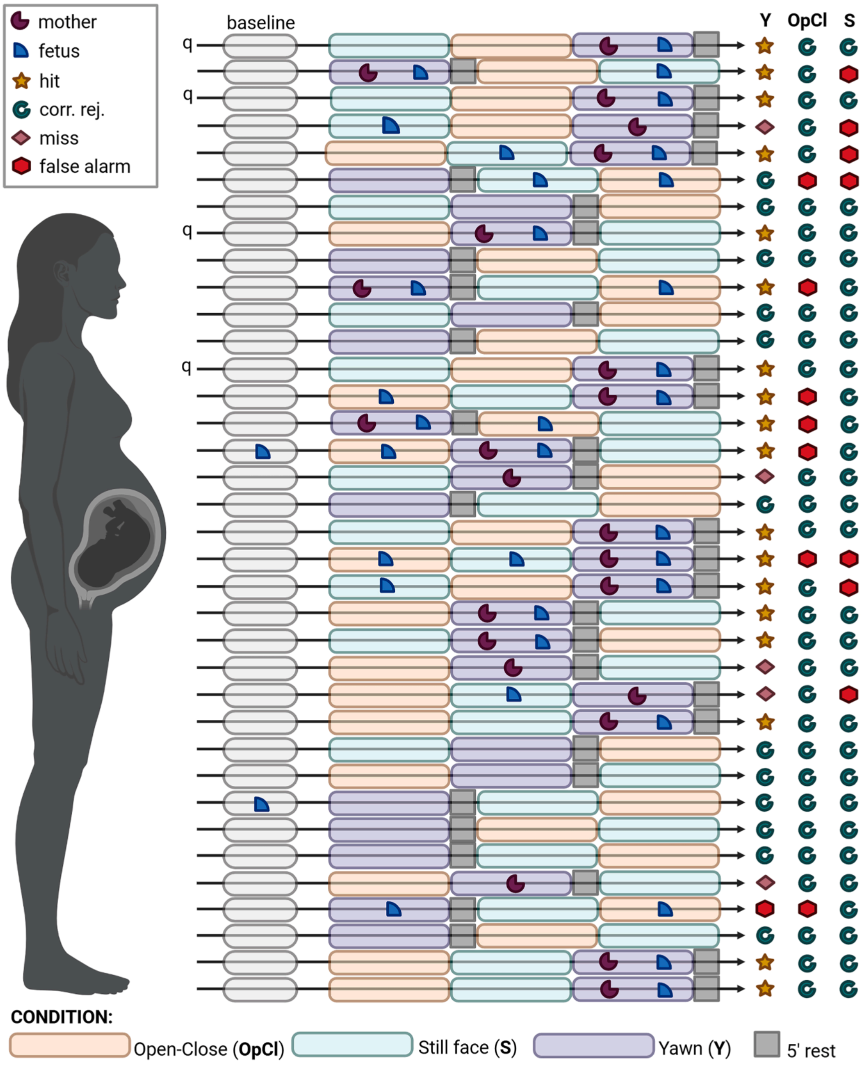

Figure 2. Dyadic yawning contingency

Each row represents a pair of participants. The presence of at least one yawn produced by the mother and/or the fetus is indicated by the corresponding symbol. Based on the distribution of these events, each condition is classified for every participant pair as a hit, correct rejection, miss, or false alarm. The letter "q" denotes pairs for which only qualitative evaluations are available.

none of the 10,000 bootstrap samples reaching the observed means (permutation-derived null distribution; RR, M = 85.6%, SE = 0.01; Lmax, M = 672.6, SE = 0.33, both $p < 0.0001$). This indicates that the full temporal dynamics of the movement also carry a dyad-specific structure, unlikely to occur by chance.

Taken together, analyses of timing and full temporal profiles converge on a dyad-specific coupling between maternal and fetal behaviors.

Shared kinematic signatures of maternal and fetal yawning

As a final line of inquiry, we evaluated whether yawning in mothers and fetuses shares a common kinematic organization.

The cross-prediction model trained on maternal lip-aperture data and tested on fetal sequences achieved a precision of 0.60, a recall of 1, and an F1 score of 0.75 in identifying fetal yawns (Figure 4A). The model trained on fetal data and tested on maternal yawns yielded a precision of 1, a recall of 0.71, and an F1 score of 0.84 (Figure 4B). Despite differences in precision and recall, both models reliably retrieved true yawns (maternal data to fetuses = 67.3%; fetal data to mothers = 85.1%), even when applied to individuals they were not trained on.

The ability of each model to identify yawns in the other group, despite having been trained on a different population, points to the presence of shared spatiotemporal and motor features in how yawns are expressed in both groups.

DISCUSSION

This study shows how fetal yawning is responsive to the maternal physiological environment during contagious stimulation, suggesting that prenatal motor patterns can be entrained by dyadic states. This finding suggests a greater continuity between pre- and postnatal behavioral organization than is typically assumed. Specifically, it indicates that even a highly stereotyped fetal motor pattern, commonly regarded as largely endogenously driven, could be embedded within a dyadic context sensitive to maternal physiological changes. More broadly, these findings support the view that the prenatal period should not be considered solely as a stage of internally programmed maturation but also as a relational context in which shared physiological dynamics shape fetal expression in systematic ways.[10–13]

Recent work suggests that pregnant women may be especially susceptible to yawn contagion, possibly as a consequence of hormonal and neurobiological changes associated with pregnancy.[14–16] Consistent with this literature, nearly two-thirds of the mothers in our sample yawned during the contagion condition, a proportion that appears higher than the rates typically reported in the general population (40%–60%).[8,17,18] To evaluate whether maternal and fetal yawns are coherently related, we applied complementary analyses that considered both when and how often yawns occur within and across dyads. Our analyses revealed a consistent dyadic pattern. Yawning occurred selectively in the contagion condition for both mothers and fetuses, and joint mother-fetus yawning was observed more often than expected by chance. Moreover, fetal yawns tended to follow maternal yawns with a structured delay, and yawning frequency was positively associated within dyads. Overall, these findings suggest how this phenomenon might reflect a form of prenatal behavioral contingency that may operate alongside

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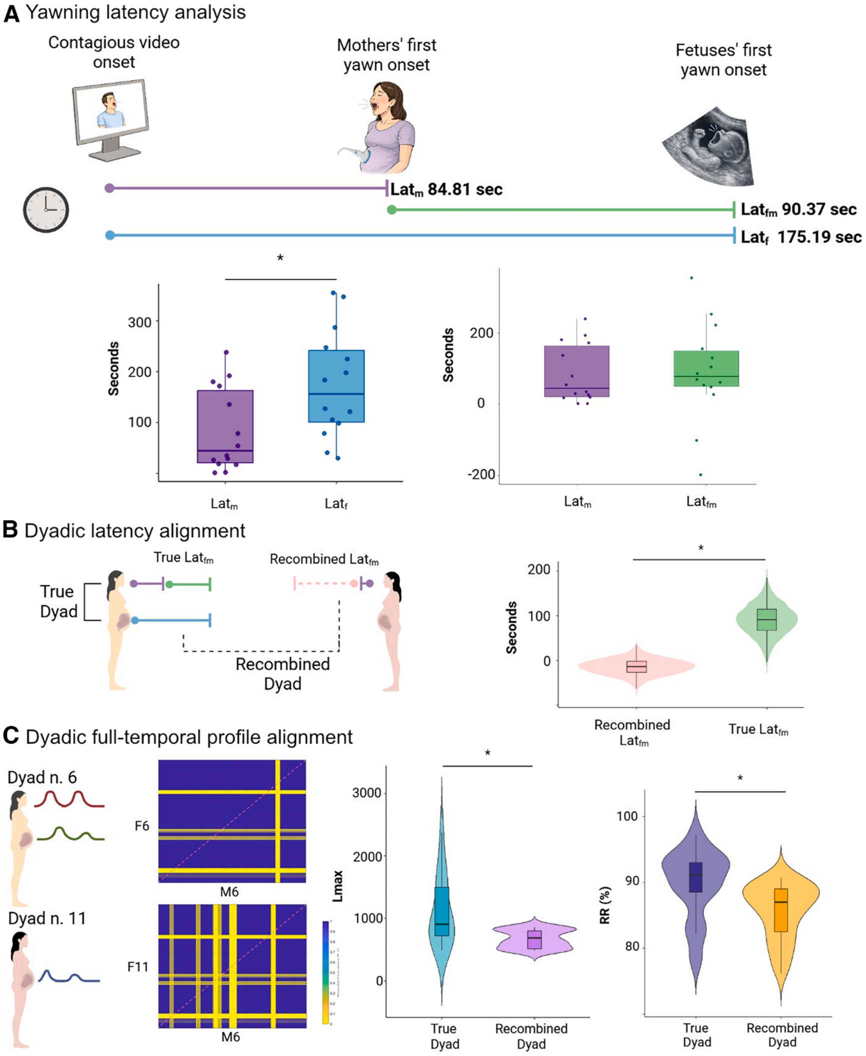

Figure 3. Dyadic temporal dynamics

(A) Top: schematic representation of the mean latency from video onset to the first maternal yawn (Lat$_m$; in purple), the first fetal yawn (Lat$_f$; in light blue), and the mother-fetus latency between the two events (Lat$_{fm}$; in green). Bottom: the left boxplot shows the significant comparison between Lat$_m$ and Lat$_f$, whereas the right boxplot illustrates the non-significant comparison between Lat$_m$ and Lat$_{fm}$. Points represent individual dyads, boxplots show the median, and bars indicate IQR. *$p < 0.05$.

(B) On the left, the analytical procedure used to generate the reference distribution through random mother-fetus pair recombination, iterated 10,000 times. On the right, violin plots comparing the distribution of true Lat$_{fm}$ values, computed within dyads, with the reference distribution obtained from random pairings. In each violin plot, the shaded kernel density contour represents the full distribution of values, while the central line and enclosed box indicate the median and IQR, respectively. *$p < 0.05$.

(C) On the left, an illustrative representation of the analytical procedure, showing example cross-recurrence plots. The first plot corresponds to a true mother-fetus dyad (mother 6 with fetus 6), whereas the second displays the corresponding plot for a random-dyad pairing (mother 6 with fetus 11). The right panel presents violin plots comparing the longest diagonal line (Lmax) and the RR between true dyads and all possible recombined pairings. In each violin plot, the shaded kernel density contour represents the full distribution of values, and the central line and enclosed box indicate the median and IQR, respectively. *$p < 0.05$.

other physiological mechanisms shaping fetal yawning, rather than reflecting a purely autonomous account of fetal motor activity.[19,20]

These findings are consistent with postnatal human and animal evidence showing that yawning is shaped not only by physiological variables but also by social context, most notably through contagious yawning.[9] Our results extend this broader framework to the prenatal period by showing that fetal yawning is part of a shared dyadic response. Of course, the present findings cannot be interpreted as evidence of behavioral contagion mediated by perceptual mirroring. Rather, they are more consistent with a form of intrauterine physiological contagion, likely grounded in the bodily and interoceptive consequences of maternal actions. Indeed, this physiological resonance may be mediated by a combination of mechanical and hormonal signals: potentially, the biomechanical pressure changes induced by maternal yawning may provide proprioceptive cues to the fetus,[21–23] while a shared neuroendocrine milieu[24,25] further aligns fetal responsivity to maternal states, creating a multimodal physiological signal capable of entraining fetal resonance. In this perspective, contagious yawning may be understood as the socially recruited expression of a motor pattern that is already robust and available early in development. Considered longitudinally across pre- and postnatal life, the developmental trajectory of yawn contagion is therefore unlikely to reflect the emergence of the motor template itself. Instead, it may reflect the gradual maturation of the attentional, social, and regulatory systems that govern when and how that template becomes behaviorally expressed in response to others.

The analyses of temporal dynamics and shared kinematic features of maternal and fetal yawning further support this interpretation. Machine-learning models trained on maternal yawns were able to identify fetal yawns, and models trained on fetal yawns worked similarly with maternal yawns. This cross-prediction performance indicates that the spatiotemporal organization of yawning is sufficiently conserved to generalize across developmental stages. These findings are consistent with the view that yawning is a highly stereotyped and evolutionarily preserved motor pattern, likely supported by early maturing brainstem circuitry and largely independent of voluntary control.[26,27] In this respect, our cross-prediction analysis provides initial computational evidence that yawning is characterized by a conserved motor signature spanning fetal life and adulthood.

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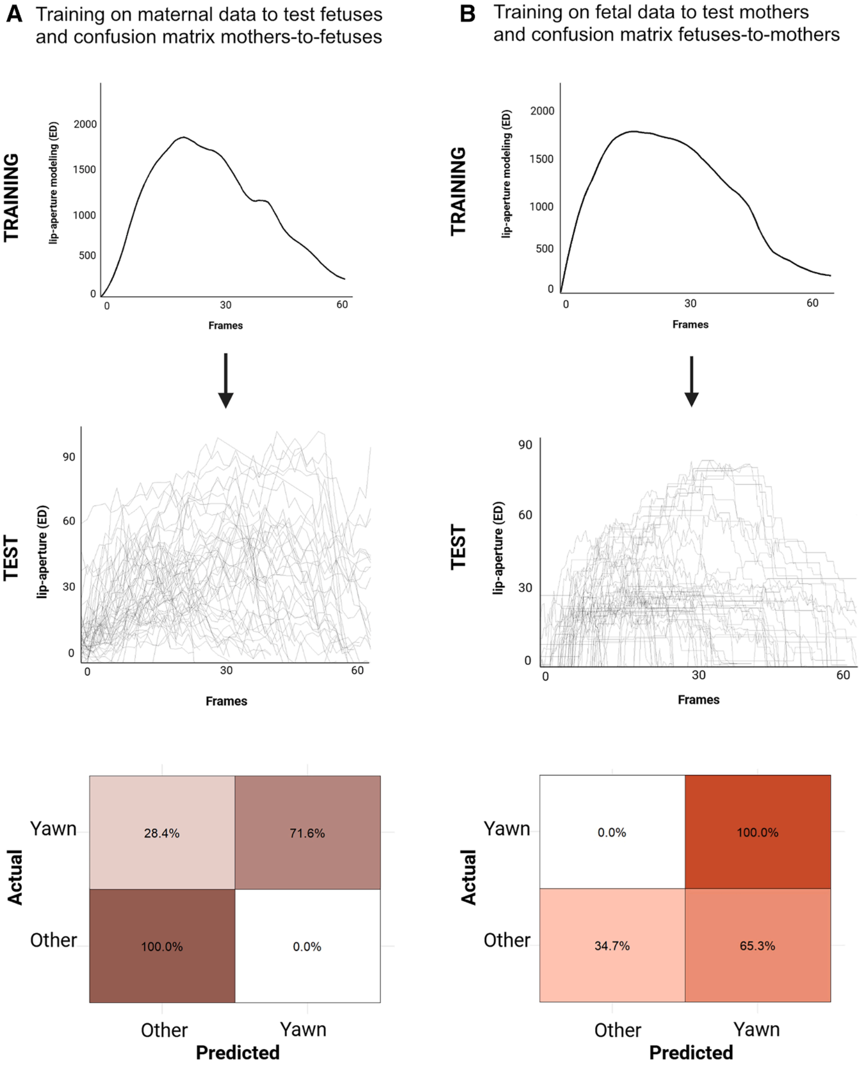

A Training on maternal data to test fetuses and confusion matrix mothers-to-fetuses

B Training on fetal data to test mothers and confusion matrix fetuses-to-mothers

Figure 4. Cross-prediction models

(A) Performance evaluation and confusion matrix of the LSTM model trained on maternal data for classifying fetal facial movements.

(B) Performance evaluation and confusion matrix of the LSTM model trained on fetal data for classifying maternal facial movements. ED, Euclidean distance.

A preserved motor functional architecture may constitute a necessary, but not sufficient, substrate to account for contagious expression. Examining the temporal organization of yawning within the mother-fetus dyad provides a complementary perspective on how this conserved motor pattern may become embedded in interactive dynamics. Latency analyses are, indeed, consistent with a selective mother-fetus temporal linkage. Maternal and fetal yawns were not randomly distributed in time, and the delay between maternal and fetal yawning resembled the delay between the onset of the contagion stimulus and maternal yawning. Although this pattern does not imply intentional coordination, it suggests a structured temporal contingency within the dyad. More generally, it is compatible with the possibility that shared physiological rhythms contribute to the alignment of maternal and fetal behavior.

Postnatal yawn contagion can be elicited by multiple classes of cues, including visual, auditory, and semantic signals, and when present, it typically unfolds within the first few minutes after stimulus exposure.[8,17,28–30] Against this background, the inconsistent expression of contagious yawning in infants and preschool children observed in standard experimental paradigms, even when the model is socially salient,[31] does not necessarily indicate the absence of contagion or of the motor mechanisms that support it. Rather, it likely reflects the ongoing maturation of the neural and perceptual systems that allow different social cues to effectively recruit a conserved motor pattern. This interpretation is consistent with evidence that contagious yawning may emerge earlier in naturalistic social settings than in decontextualized tasks[32,33] and more broadly with models of social development emphasizing the gradual integration and specialization of increasingly complex social signals across infancy and childhood.[34,35] From this perspective, future work could adopt longitudinal, pre- to postnatal, and multimodal designs to track how early forms of dyadic resonance develop into foundational components of social cognition.

Several limitations of this study should be acknowledged. First, the sample size constrains generalizability and limits the analysis of interindividual variability. Second, the study focused on a relatively narrow gestational window (28–32 weeks), making it unclear when this form of mother-fetus coupling first emerges and whether its temporal or kinematic features change across pregnancy, particularly closer to term. Third, although the present design demonstrates behavioral contingency, it does not identify the physiological pathway through which maternal yawning influences fetal behavior. Future studies should therefore examine larger and more diverse samples, test broader gestational ranges, and directly assess potential moderating and mediating factors, including gestational age, parity, and maternal physiological state. It will be important to integrate explicit and physiological indices of maternal stress, combining self-report measures such as the perceived stress scale[36] with biological markers including maternal cortisol levels and fetal heart rate variability, to better map the neurophysiological foundations of this dyadic alignment.

In conclusion, this study provides the first empirical evidence that fetal yawning can resonate with maternal behavior. These findings challenge the view of fetal behavior as purely reflexive or entirely self-contained and instead support a picture of the fetus as an organism whose behavioral expression is already integrated into a shared biological context. More broadly, the

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study suggests that examining maternal behavior and its impact on fetal action may help clarify the earliest foundations of co-regulation and embodied development, which later support motor and social competencies after birth.[10,13,37,38]

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Giulia D'Adamo (giulia.dadamo@unipr.it).

Materials availability

This study did not generate any new materials.

Data and code availability

- All anonymized datasets and analysis code from this study have been deposited in the OSF "Prenatal Behavioral Contagion" project repository (10.17605/OSF.IO/U2VR9) and are publicly available as of the date of publication.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

G.D., M.A., T.G., and V.G. contributed to the study design and conceptualization. G.D., G.A., V.M., A.D., S.S., M.C., and P.D. were involved in data collection. A.D. was responsible for the ultrasound acquisitions. G.D., M.A., and F.F. conceived and defined the statistical analysis plan. G.D. and V.M. conducted the data analysis. D.O.I. and C.F. implemented the neural network and its analysis. The manuscript was written by G.D., V.M., and M.A. and revised by G.A., F.F., A.D., S.S., M.C., P.D., T.G., and V.G. M.A., T.G., and V.G. were responsible for project administration.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Datasets, scripts & code	This paper	10.17605/OSF.IO/U2VR9
Software and algorithms		
MATLAB	MathWorks	RRID: SCR_001622
R v.4.2.3	R	RRID: SCR_000432

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

This prospective monocentric study was conducted at a tertiary maternity hospital (Unit of Obstetrics and Gynecology, Department of Medicine and Surgery, University of Parma). The study protocol was approved by the local Ethics Committee (protocol no. 4852 592/2022/SPER/UNIPR) and was carried out following the Declaration of Helsinki (1964 and subsequent amendments). All participants provided written informed consent prior to inclusion in the study.

Thirty-eight pregnant women with uncomplicated singleton pregnancies were recruited. Inclusion criteria were: maternal age between 18 and 45 years, gestational age between 28+0 and 32+0 weeks, and a non-anomalous fetus confirmed by second-trimester screening anomaly ultrasound scan. Exclusion criteria included: maternal history of chronic illness, multiple pregnancy, and any suspected fetal genetic syndrome or fetal anomaly identified at ultrasound assessment. Gestational age was calculated based on first-trimester crown-rump length (CRL) measurement. Additionally, participants completed the Perceived Stress Scale (PSS[36]) to obtain a self-reported measure of perceived stress, which was used as a control to account for potential individual differences in maternal stress levels. Two participants were excluded entirely due to suboptimal ultrasound recordings that did not allow reliable coding.

See the demographic characteristics table of the analyzed sample.

Characteristics (*n* = 36)	Value
Maternal age	32.7 ± 3.6
Education (years)	18.8 ± 3.6
Maternal pre-pregnancy BMI (kg/m2)	23.0 ± 3.1
Nulliparous	26/36 (72.2%)
GA at ultrasound exam	(30+5) ± (1+2)
EFW percentile	74° ± 19
PSS	15 ± 6.7

Demographic and ultrasound characteristics table of cohort of study participants (*n* = 36). Data are given as mean ± SD or *n*(%). BMI, body mass index; GA, gestational age; EFW, estimated fetal weight; PSS, Perceived Stress Scale.

METHOD DETAILS

Ultrasound observations were conducted in the early afternoon in a quiet room with controlled lighting (30 lux), with participants in a semi-supine position. An EPIQ ELITE ultrasound system (Philips Healthcare, Bothell, WA, USA) equipped with a volumetric multifrequency transabdominal probe (4–8 MHz) was used. Real-time 2D ultrasound acquisitions were performed by a single experienced operator (A.D.) by insonating the fetal nose and lips on the same coronal plane as recommended by ISUOG guidelines[39] for the screening of facial anomalies such as cleft lip. The ultrasound screen was positioned so that it could not be visualized by participants. A video camera was positioned to record maternal facial behavior; markers were applied around the mother's mouth to facilitate off-line tracking. Prior to the experimental session, fetal position, adequate visualization of mouth movements, and fetal wakefulness were confirmed via ultrasound. The session commenced only once the fetus was confirmed to be awake (e.g. frequent body movements, eye movements, and variability in the heart rate pattern).

The session began with a 1-minute baseline recording rest period, during which participants viewed videos of neutral natural landscapes. This was followed by three experimental conditions, presented in a counterbalanced and randomized order across participants: Yawning, 6-minute videos depicting individuals yawning (contagious behavior stimulus); mouth

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Open/Close (OpCl), 6-minute videos depicting individuals opening and closing their mouths (non-contagious control behavior); Still-Face, 6-minute videos depicting individuals with a neutral facial expression (static control behavior). Each experimental condition comprised three distinct 2-minute videos. Each video consisted of 20 gender-balanced, black-and-white clips of actors, interspersed with a 500 ms fixation cross. A 5-minute rest period was implemented following the Yawning condition block, consistent with the typical latency of yawn responses.[8] Fetal facial kinematics (via ultrasound – 10fps, focusing on isolated mouth movements in a coronal view including the nose and lips) and maternal facial behavior (via video camera – 30fps) were recorded in real-time throughout the entire duration of each video presentation (baseline and experimental conditions). The entire experimental session lasted approximately 30 minutes per participant, with the precise duration depending on the degree of fetal compliance during the recording. An example of the experimental setting and procedure is illustrated in Figure S3.

QUANTIFICATION AND STATISTICAL ANALYSIS

Data Coding and Reliability

Offline coding of fetal ultrasound and maternal video recordings was conducted under blind conditions, with coders unaware of the experimental condition corresponding to each recording segment and the identities of the participants. To minimize observational bias, ultrasound and maternal video data were coded separately. All videos were analyzed frame-by-frame independently by three trained coders (two inexperienced with ultrasounds, previously trained to reliability criteria, and one experienced gynecologist). Coders identified the occurrence and precise timing of fetal and maternal yawns and other mouth-movements.

Behavioral labels were assigned at the clip level based on established ethological criteria distinguishing yawning (Yawn) from simple mouth opening (OpCl). While both behaviors involve oral opening, yawns were defined by their characteristic temporal structure and kinematic profile: the mouth remains open for 2 to 8 seconds before shutting fast.[2,40,41] Differently, isolated opening–closing movements lacking the full yawn pattern and lasting less than 2 seconds were labeled as OpCl. These distinctions were applied consistently during manual annotation and preserved in the subsequent automated analyses.

Inter-rater reliability for fetal yawning had an intraclass correlation coefficient (ICC) of 0.94 for both consistency and agreement (95% CI: 0.909–0.971), indicating high coherence among the three coders. Inter-rater reliability for maternal yawning had an intraclass correlation coefficient (ICC) of 0.98 for both consistency and agreement (95% CI: 0. 972–0. 991), indicating, again, high coherence among the three coders. Overall, 23 out of 36 mothers yawned at least once during the Yawn condition (63.9% of the sample). Among these cases, a maternal-fetal correspondence in yawning was identified in 18 dyads, corresponding to 50% of the entire sample and 78.3% of yawning mothers.

In addition to qualitative coding, a quantitative extraction of facial kinematics was performed to generate datasets suitable both for latency computation, cross-recurrence quantification analysis (CRQA) and neural network classification. For latency and CRQA analyses, the entire sequences of maternal video recordings and fetal ultrasound during the yawning condition were tracked to capture the full temporal dynamics. Differently, for the neural network, only frames corresponding to yawns and to other facial movements were used.

Facial landmarks were identified and tracked frame by frame using DeepLabCut (DLC),[42] a deep learning–based toolbox for motion tracking. To align temporal sampling, mother videos (originally at 30 fps) are down sampled to match the fetal frame rate (10 fps).

The selected landmarks included: left and right lips, top and bottom mid inner lips, and nose. To obtain lip-aperture measure, the upper and lower inner lips were used as reliable reference of the mouth's opening and closing trajectory, which is critical for capturing the spatio-temporal profile of mouth movements. For each frame, the software extracted two-dimensional coordinates (x, y), resulting in time-series data that described the dynamic trajectories of the lip-aperture over time. To ensure comparability across participants and recording modalities, the coordinate values were subsequentially normalized to a common scale within the range [–1, +1], thereby minimizing inter-individual variability, reducing potential biases due to differences in recording resolution, and enhancing the stability and efficiency of subsequent analyses. To calculate the mouth opening dynamics, the Euclidean distance between the standardized two-dimensional coordinates was computed frame by frame (lip-aperture time series).

For each dyad, maternal latency (Lat_m) and fetal latency (Lat_f) were computed in seconds by converting into temporal units the video frame identified as the onset of the first yawning event, based on the corresponding frame rate of the recording. The onset of a yawn was operationally defined as the first frame of an event coded as yawn in which the lip-aperture exceeded zero, thereby marking the beginning of the mouth-opening trajectory. Lat_m was defined as the interval between the onset of the experimental condition and the onset frame of the mother's first yawn; Lat_f was calculated analogously for the fetus. To evaluate whether maternal and fetal yawns exhibited comparable temporal delays relative to their own stimulation onset, a relative latency index ($Lat_{fm} = Lat_f - Lat_m$) was derived for each dyad.

To provide a characterization of the global recurrence structure of mouth-movement across time in both members of the dyad during the entire yawn condition, we computed CRQA measures on maternal and fetal lip-aperture time series independently. CRQA [embedding = 3, delay = 1, radius = 0.27] was applied to every pairwise pairing of mothers with one another and fetuses with fetuses in the dataset. CRQA[43] allows quantification of the properties in the temporal evolution of a dynamic system, such as stability, complexity, and the occurrence of epochs of chaos vs. order. Here, we extract for each pair the recurrence rate (RR) and the length of the longest diagonal line (Lmax), each reflecting different aspects of temporal organization and behavioral alignment. Specifically, the RR shows how frequently matching states occur between two systems. Stronger overall coordination is indicated by a higher

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RR. On the other hand, the length of the longest continuous match in state development, which relates to how similarly the systems evolve, is captured by the Lmax.

A Long Short-Term Memory (LSTM) network models the temporal dynamics of lip-aperture time series, leveraging packed sequences to respect each clip's true length. Input sequences are constructed from clips grouped by (test, frame, label) identifiers and padded or truncated to 60 frames. Each clip is assigned one label from the configured class list and we therefore run both binary (yawn vs other, OpCl vs other). The dataset size therefore depends on the source split (all, mother-only, fetus-only, or cross-domain variants); sample counts vary and are not fixed to 407 blocks. DeepLabCut is used only for pose extraction: for each clip, DLC outputs CSV files of frame-level coordinates for five facial landmarks, which are aggregated into the sequences described above. The LSTM architecture and training hyperparameters were optimized for each experiment category. For Yawn detection, hidden units and layer counts were tuned across categories: fetus (32 units, 3 layers, 0.45 dropout), mother (256 units, 3 layers, 0.04 dropout), combined "all" dataset (256 units, 2 layers, 0.10 dropout), and cross-domain variants (mother vs fetus: 64 units, 2 layers, 0.20 dropout; fetus vs mother: 64 units, 3 layers, 0.27 dropout). Similarly, for the mouth opening-closing (OpCl) problem, configurations varied: fetus (64 units, 3 layers, 0.44 dropout), mother (256 units, 2 layers, 0.29 dropout), "all" (512 units, 2 layers, 0.44 dropout), and cross-domain (mother vs fetus: 128 units, 3 layers, 0.30 dropout; fetus vs mother: 512 units, 3 layers, 0.39 dropout).

Training utilized the Adam optimizer with tuned learning rates (ranging from 1.0e-5 to 1.0e-2) and batch sizes (8, 16, or 32) for a maximum of 200 epochs, with early stopping (patience 25) monitoring validation loss. Class imbalance can be mitigated via SMOTE-driven oversampling or random undersampling before the DataLoader, depending on the experiment configuration; no on-the-fly geometric augmentations are applied. Single-fold runs are supported through stratified splits, and cross-domain variants use one domain for training and the other for testing. For standard splits (all, mother-only, fetus-only), data are stratified into 80%training and 20% test, with the test split used as validation during training for early stopping; for cross-domain experiments (fetus→mother, mother→fetus), the entire source domain is used for training and the entire target domain is held out for testing with no overlap. During evaluation, confusion matrices and scikit-learn classification reports are generated for each experiment (or fold), yielding per-class precision, recall, F1, and aggregate accuracy or macro-F1 scores. Binary experiments additionally log ROC-style probabilities for the positive class. Results, including metrics, confusion matrices (absolute and percentage), training logs, and model weights, are written under output/<experiment_name>/.

Statistical analysis

We structured the analyses around three focused levels of investigation: first, to test whether fetal yawning frequency is modulated by maternal yawns; second, to quantify the latency structure of maternal–fetal yawning to assess directional temporal alignment; and third, to examine whether maternal and fetal yawning share a common kinematic organization. The distribution of all variables related to yawning frequency was assessed using the Shapiro–Wilk test to verify compliance with the assumption of normality. As the distributions significantly deviated from normality (all $p_s < 0.001$), non-parametric methods were adopted for the main statistical analyses.

Maternal influence on fetal yawning

To investigate whether yawning behavior varied across the different experimental conditions (Baseline, Still-face, OpCl, Yawn), non-parametric Kruskal–Wallis rank-sum tests were employed separately for maternal and fetal data on the number of mouth movements coded as Yawn. Post-hoc comparisons were conducted using Dunn's test, with *p-value*s adjusted via the Benjamini–Hochberg procedure to control the false discovery rate due to multiple testing. As a control analysis, the same behavioral pipeline was applied to open–close mouth movements category, separately for maternal and fetal data. This parallel analysis allowed us to determine whether the observed condition effects were selective for yawning or extended to non-yawn mouth movements (see Figure S2; Table S1).

To quantify the dyadic association between maternal and fetal yawning, we additionally applied a signal detection framework. For each condition, dyads were classified into four categories: hits (maternal yawn accompanied by fetal yawn), correct rejections (absence of yawning in both), misses (maternal yawn without fetal yawn) and false alarms (fetal yawn without maternal yawn). From these counts we computed hit rates and false-alarm rates and derived a sensitivity index (d′) using standard signal detection theory. Association between maternal and fetal yawning, whenever possible, was further tested using Fisher's exact test, and effect sizes were expressed as odds ratios.

To explore whether maternal yawning exerted a specific influence on fetal behavior, a within-subject design was applied to the subset of dyads in which mothers yawned ($N = 23$). Given the randomized presentation of experimental conditions, fetal yawns were categorized as occurring either before or after the maternal yawning event, depending on their position in the sequence. The total number of fetal yawns was then compared across these two temporal phases using the non-parametric Wilcoxon signed-rank test, suitable for analyzing dependent observations from the same dyad. Furthermore, to assess the dyadic association in yawning behavior, a Spearman correlation was computed between the total number of maternal and fetal yawns across these dyads.

To complement human coding, an automated method for fetal and maternal mouth-behavior classification was developed using deep learning, implemented in PyTorch 2.3.1, we applied a Long Short-Term Memory (LSTM) neural network to classify yawns from facial kinematic data. Three separate models were trained, respectively based on fetal movements, maternal movements, and a combined dataset including both. Model performance was quantified using precision, recall, and F1-score. Classifier validity was

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evaluated also for the discrimination of open–close mouth movements. Standard experiments confusion matrices and detailed precision, recall, and F1-score values are reported for both behavioral classes in supplemental information (Figure S2; Table S2).

Temporal dynamics of maternal and fetal yawning

Wilcoxon signed-rank tests were performed to compare Latency values (i.e., L_m, L_f, L_{fm}). Dyadic latency alignment was assessed with a permutation test comparing real mother–fetus pairings against randomly recombined pairs. L_m and L_f onset times were crossed to generate all possible pairings, excluding the true mother–fetus dyads, and latency was defined as the difference between fetal and maternal onset. This surrogate distribution provided an estimate of the Lat_{fm} values expected under the assumption of no dyadic specificity. Pairings preserving the original mother–fetus match ($n = 14$) were treated as the observed data, whereas all mismatched combinations formed the reference pool. To obtain a conservative null model, analyses were restricted to the lower 50% of the latency distribution from the mismatched pairs. A null distribution was estimated over 10,000 iterations by sampling 14 mismatched pairs without replacement and computing their mean latency. The observed mean was evaluated against this distribution, and a one-sided empirical *p-value* was calculated as the proportion of sampled means equal to or exceeding the observed value.

To provide a descriptive characterization of the overall temporal structure of maternal and fetal mouth-movement dynamics across the full time series, we compared CRQA indices (RR and Lmax) for each true dyad against an empirical reference distribution derived from non-dyadic pairings. This comparison was aimed to contextualize the magnitude of recurrence observed in biological dyads relative to the level of similarity expected from randomly paired maternal and fetal time series with comparable base-rate structure. To establish a consistent and conservative baseline, we first defined a reference subset of non-dyads whose values fell at or below the median of the overall distribution for each CRQA metric. This subset served as the pool from which the reference model was generated. For each CRQA index, we then constructed an empirical distribution using a bootstrap sampling procedure. At each of 10,000 iterations, we randomly sampled non-dyadic pairs from this reference subset (without replacement) and computed the corresponding mean. The resulting distribution of 10,000 means represented the expected range of coupling levels under the null hypothesis that true dyads do not differ from non-dyadic pairings. Cross-recurrence plots used for visualization were generated in MATLAB (RRID:SCR_001622; http://www.mathworks.com/products/matlab/).

Shared kinematic signatures of maternal and fetal yawning

To explore developmental similarities in yawning kinematics a cross-prediction procedure was implemented: maternal-trained models were tested on fetal data, and fetal-trained models on maternal data. As done before, using deep learning implemented in PyTorch 2.3.1, we applied a Long Short-Term Memory (LSTM) neural network to classify yawns from facial kinematic data. Model performance was quantified using precision, recall, and F1-score. This approach enabled us to assess whether spatiotemporal features defining maternal yawns were sufficiently preserved in fetal behavior to allow accurate classification across domains, and viceversa.

All statistical analyses were performed using R (RRID:SCR_000432; https://www.r-project.org/about.html).