Do children laugh like their parents? Conversational laughter mimicry occurrence and acoustic alignment in middle childhood

Supplementary Material

1 Formula

1.1 Mimicry calculation

The following describes our method of identifying Mimicking and Non-Mimicking laughs, where A_i and B_j are the i^{th} and j^{th} laughs produced by interlocutors A and B, respectively, T_{start} and T_{stop} are the start and stop times, respectively, and ΔT is set to 1 second. In order for laugh B_j to mimic laugh A_i, B_j must occur after the *start* time of A_i (1) with an onset before the *stop* time of A_i with a margin ΔT. To avoid duplication, B_i must stop before the start time of laugh A_{i+1} (2). If these criteria are met then A_i can be considered a Non-Mimicking laugh that initiated Mimicking laugh B_i, henceforth an *Initiating* laugh. However, if the difference between A_i and B_j is greater than ΔT, then Non-Mimicking laugh A_i is considered *Isolated*. Note, for the current analysis the amount of overlap between *Initiating* and *Mimicking* laughs is not taken into account.

(1) $T_{start}(A_i) < T_{start}(B_j)$

(2) $T_{start}(B_j) < min\{T_{stop}(A_i) + \Delta T, T_{start}(A_{(i+1)})\}$

1.2 Transitional Property

Equation 1 describes the Transitional Property (TP) of participant B, where M is the total number of laughter mimicry produced by B and L is the total number of laughs produced by their partner A.

$$\mathrm{TP}(B) = \frac{\sum_{m=0}^{M} B_m}{\sum_{l=0}^{L} A_l} \tag{1}$$

1.3 Modulation Power Spectrum

As in previous work (Elliott & Theunissen, 2009; Singh & Theunissen, 2003; Thoret, Caramiaux, Depalle, & Mcadams, 2021) MPS is derived from a two-dimensional Fourier transform of the time-frequency representation of an audio signal. Equation 2 below provides the formal definition of the MPS, where s and r are spectral and temporal modulations, respectively, and $Y(t, f)$ is the amplitude extracted from the Fourier transform:

$$\mathrm{MPS}(s, r) = \int \int |Y(t, f)| e^{-2\pi i s f} e^{-2\pi i r t} df dt \tag{2}$$

To obtain the MPS of laughs in our dataset, similar procedures described in Marczyk, O'Brien, Tremblay, Woisard, and Ghio (2022) and Mazzocconi, O'Brien, and Chaminade (2023) were developed and applied. All

processing was done in MATLAB 2021a (MathWorks Inc, USA) and based on adaptations to scripts described in Flinker, Doyle, Mehta, Devinsky, and Poeppel (2019). Recordings were down-sampled to 16 kHz. Time-frequency representations were obtained using a gammatone filter bank summation method (128 full-width half-maximum Gaussians with center frequencies logarithmically spanning the frequency domain). Hilbert transforms were then used to extract the analytical amplitudes from these filter outputs. The *fft2* MATLAB function transformed the time-frequency representations into the modulation domain, whereupon negative and positive modulations were averaged.

1.4 Generalized Additive Mixed Models

The following describes the design of GAMMs used for the current study. The R-package $mgcv$ was used, which relies on thin plate regression *splines* to smooth the non-linear variation present in the data (s in Formulas 3 and 4). The R-package $itsadug$ (van Rij, Wieling, Baayen, & van Rijn, 2015) was used to estimate an AR-1 correlation parameter ρ and pairwise differences between the non-linear smooths of the factor levels.

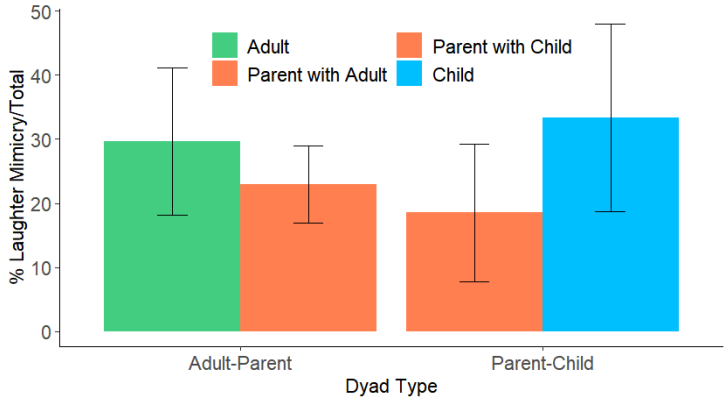
Formula 3 describes the general GAMM used to evaluate the effects of Laughter Type (Mimicking, Initiating, Isolated) across Participant Types (Adult, Parent interacting with Adult, Child, Parent interacting with Child). Amplitudes A (in dB) corresponding to modulations v were used as dependent variables, where the unit for v is Hz for TM and c/o for SM. The term T represents the interaction between laughter l and interlocutor type (12 levels). A non-linear random factor of interlocutor p was added to the models. The ρ-value described in Formula 3 was estimated from the data and included to control for auto-correlation in the time series (ρ_{TM} = 0.74; ρ_{SM} = 0.83). As proposed in Ludusan and Wagner (2020), each model was first tested against a base model not containing the fixed factor via the $compareML$ function.

$$\text{bam}(A \sim T + \text{s}(v, \text{by} = T) + \text{s}(v, p, \text{by} = l, \text{bs} = \text{"fs"}), rho = \rho) \tag{3}$$

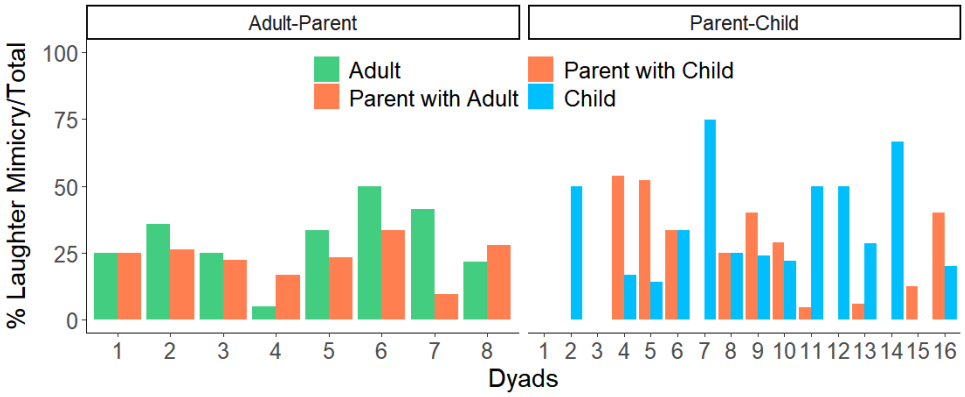
To further explore the results from the first analysis comparing Laughter Types (Isolated, Initiating, Mimicking) separate GAMMs were used to evaluate whether arousal levels (Low, Medium, High) lead to any of the observed effects. Amplitudes A' corresponding to modulations v' were used as dependent variables, where v' is bounded by the lower and upper modulations identified as significantly different between different laughter types fitted class models for each interlocutor type. The term T' represents the interaction between Laughter Type l (Isolated, Initiating, Mimicking) and Arousal levels (Low, Medium, and High), for a total of 12 levels. A non-linear random factor of interlocutor p' was added to the models for interlocutor type. Formula 4 describes the general GAMM developed for each interlocutor type.

$$\text{bam}(A' \sim T' + \text{s}(v', \text{by} = T') + \text{s}(v', p', \text{by} = l, \text{bs} = \text{"fs"}), rho = \rho) \tag{4}$$

2 Distribution Analysis

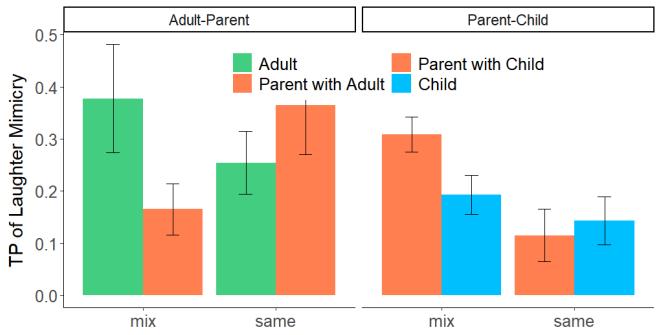


(a) Mean by Dyad Type

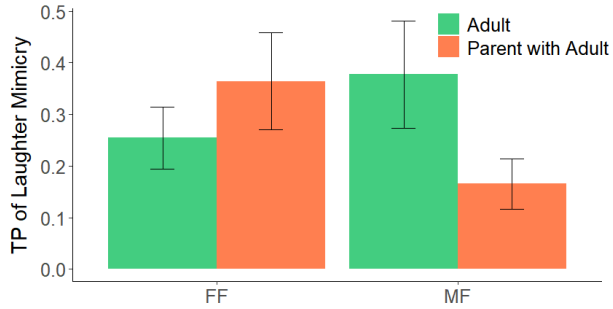


(b) Individual

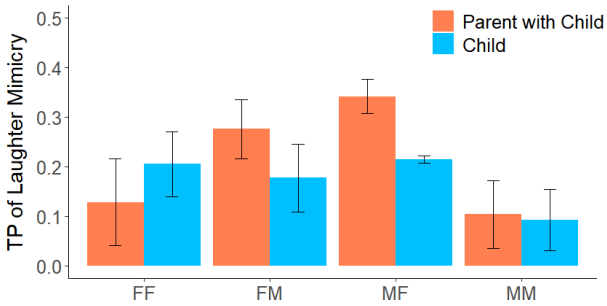
Figure 1: Percentage of Laughter Mimicry over total laughter produced.



(a) TP Mean and sd by Gender composition of Dyads (Mix = Male-Female or Female-Male; Same = Female-Female or Male-Male) and Dyad Type (Adult-Parent and Parent-Child)



(b) Adult-Parent by Gender



(c) Parent-Child by Gender

Figure 2: Transitional Probability of laughter mimicry according to the Gender composition of the dyads (F = Female, M = Male).

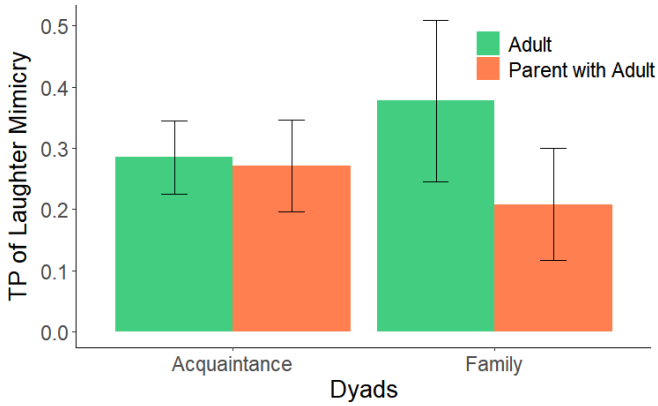


Figure 3: Transitional Probability of laughter mimicry according to Familiarity in adult dyads.

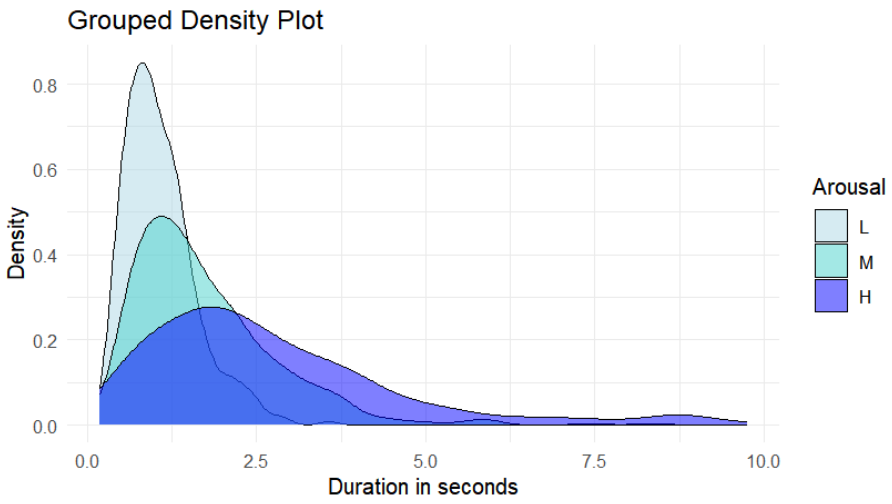


Figure 4: Laughter Mimicry Transitional Probabilities according to the degree of familiarity in Adult-Parent dyads

3 Acoustic Analysis

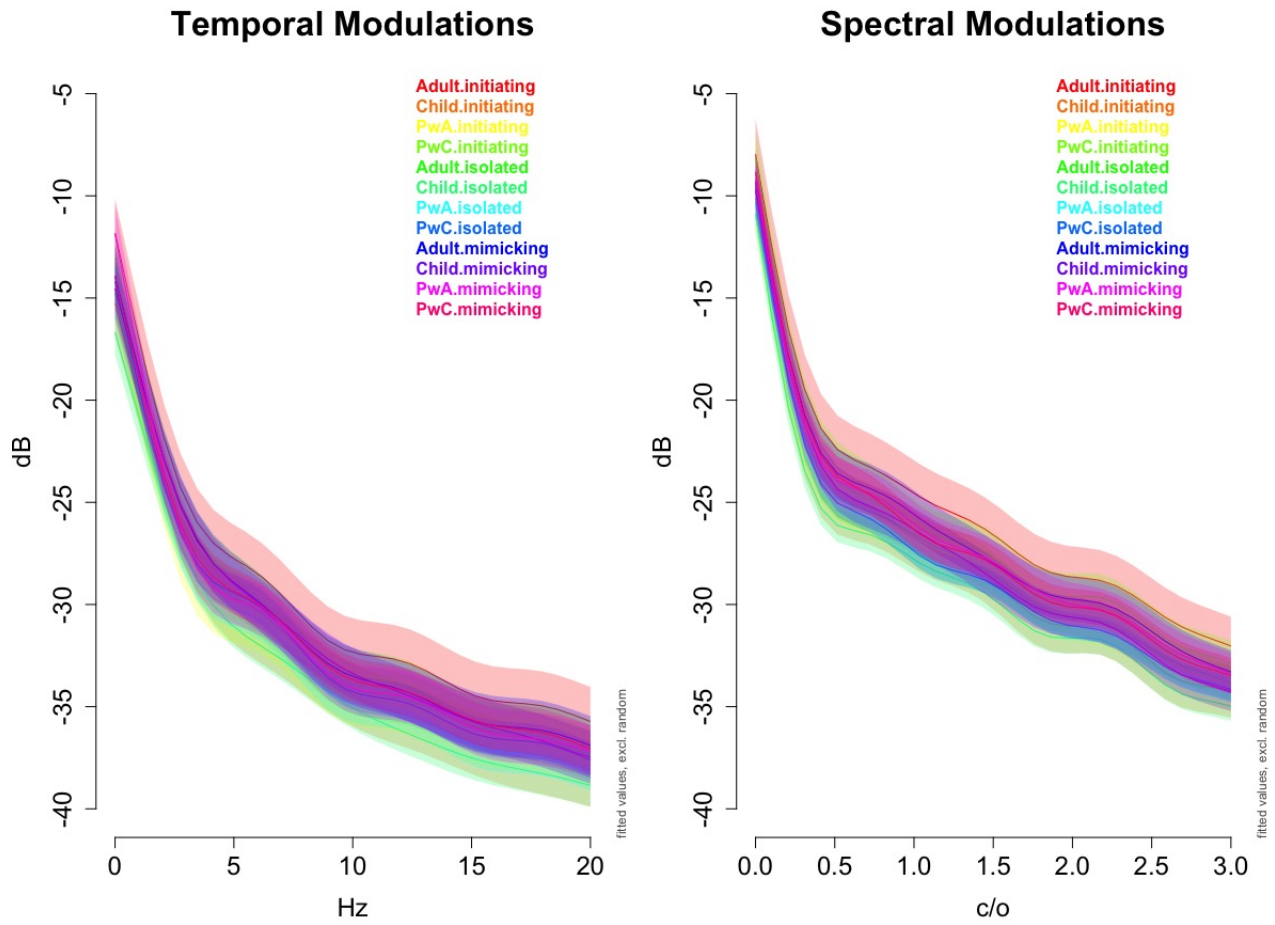


Figure 5: Fitted class models for temporal (Left) and spectral (Right) modulations across interlocutor (Adult; PwA; PwC; Child) and laughter type (initiating; isolated; mimicking) interactions.

Table 1: Model overview for Temporal modulations across interlocutor (Adult; PwA: Parent interacting with Adult; PwC: Parent interacting with Child; Child) and Laughter Type (Initiating; Isolated; Mimicking) interactions.

Intercept	*estimates*	*SE*	*t*	*p*
Intercept	-34.47	0.20	-175.8	***
Child.initiating	1.72	0.75	2.31	0.02 *
PwA.initiating	-0.79	0.71	-1.11	0.27
PwC.initiating	-0.40	0.53	-0.76	0.45
Adult.isolated	0.57	0.52	1.11	0.27
Child.isolated	-0.04	0.57	-0.07	0.94
PwA.isolated	-1.37	0.48	-2.87	0.01 **
PwC.isolated	-0.64	0.41	-1.58	0.12
Adult.mimicking	-0.20	0.39	-0.52	0.61
Child.mimicking	0.54	0.62	0.87	0.38
PwA.mimicking	0.21	0.55	0.38	0.71
PwC.mimicking	0.18	0.47	0.38	0.71
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v):Adult.initiating	10.33	10.91	266.83	2^{-16} ***
s(v):Child.initiating	10.38	10.92	321.06	2^{-16} ***
s(v):PwA.initiating	10.65	10.97	318.67	2^{-16} ***
s(v):PwC.initiating	10.52	10.95	375.55	2^{-16} ***
s(v):Adult.isolated	10.70	10.98	305.83	2^{-16} ***
s(v):Child.isolated	10.56	10.96	365.52	2^{-16} ***
s(v):PwA.isolated	10.79	10.99	433.98	2^{-16} ***
s(v):PwC.isolated	10.89	11.00	708.23	2^{-16} ***
s(v):Adult.mimicking	10.32	10.90	152.48	2^{-16} ***
s(v):Child.mimicking	10.20	10.87	185.92	2^{-16} ***
s(v):PwA.mimicking	10.57	10.96	187.17	2^{-16} ***
s(v):PwC.mimicking	10.63	10.97	216.28	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v,p):initiating	57.24	378.00	3.02	2^{-16} ***
s(v,p):isolated	88.68	438.00	2.57	2^{-16} ***
s(v,p):mimicking	79.16	391.00	2.22	2^{-16} ***

Table 2: Overview of GAMMs fitted with temporal modulation responses associated with Mimicking laughter (Mim), Initiating laughter (Init), and Isolated (Iso) laughter across interlocutors (Child; PwC: Parents interacting with Child; Child; PwA: Parents interacting with Adult; Adult).

Role	**Comparison**	p	**Range (Hz)**	**Difference (dB)**
Child	Mim > Iso	***	0-17	+3
	Mim ≈ Init	n.s		
	Init ≈ Iso	n.s		
PwC	Mim ≈ Iso	n.s		
	Mim ≈ Init	n.s		
	Init ≈ Iso	n.s		
PwA	Mim ≈ Iso	n.s		
	Mim ≈ Init	n.s		
	Init ≈ Iso	n.s		
Adult	Mim ≈ Iso	n.s		
	Mim ≈ Init	n.s		
	Init > Iso	***	0-3	+3

Table 3: Model overview for Spectral modulations across interlocutor (Adult; PwA: Parent interacting with Adult; PwC: Parent interacting with Child; Child) and Laughter Type (initiating; isolated; mimicking) interactions

Intercept	*estimates*	*SE*	*t*	*p*
Intercept	-28.95	0.16	-178.87	2^{-16} ***
Child.initiating	1.79	0.65	2.76	0.01 **
PwA.initiating	-0.53	0.61	-0.88	0.38
PwC.initiating	-0.33	0.48	-0.70	0.49
Adult.isolated	0.82	0.46	1.77	0.08
Child.isolated	-0.25	0.39	-0.64	0.52
PwA.isolated	-1.38	0.34	-4.09	5^{-5} ***
PwC.isolated	-0.42	0.32	-1.34	0.19
Adult.mimicking	-0.57	0.28	-2.03	0.04 *
Child.mimicking	0.59	0.47	1.26	0.21
PwA.mimicking	-0.32	0.42	-0.76	0.45
PwC.mimicking	0.35	0.40	0.86	0.39
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v):Adult.initiating	10.79	10.99	232.03	2^{-16} ***
s(v):Child.initiating	10.93	11.00	439.90	2^{-16} ***
s(v):PwA.initiating	10.87	11.00	334.36	2^{-16} ***
s(v):PwC.initiating	10.89	11.00	402.98	2^{-16} ***
s(v):Adult.isolated	10.93	11.00	501.53	2^{-16} ***
s(v):Child.isolated	10.96	11.00	721.68	2^{-16} ***
s(v):PwA.isolated	10.91	11.00	561.89	2^{-16} ***
s(v):PwC.isolated	10.97	11.00	1134.79	2^{-16} ***
s(v):Adult.mimicking	10.86	11.00	301.60	2^{-16} ***
s(v):Child.mimicking	10.84	11.00	343.96	2^{-16} ***
s(v):PwA.mimicking	10.84	10.99	289.38	2^{-16} ***
s(v):PwC.mimicking	10.92	11.00	459.35	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v,p):initiating	50.35	379.00	1.29	2^{-16} ***
s(v,p):isolated	74.26	440.00	1.00	2^{-16} ***
s(v,p):mimicking	49.54	391.00	0.71	2^{-16} ***

Table 4: Overview of GAMMs fitted with spectral modulation responses associated with Mimicking laughter (Mim), Initiating laughter (Init), and Isolated (Iso) laughter across interlocutors (Child; PwC: Parents interacting with Child; Child; PwA: Parents interacting with Adult; Adult).

Role	**Comparison**	*p*	**Range (c/o)**	**Difference (dB)**
Child	Mim ≈ Iso	***	0-1.2	+2
	Mim > Init	n.s		
	Init ≈ Iso	n.s		
PwC	Mim ≈ Iso	n.s		
	Mim ≈ Init	n.s		
	Init ≈ Iso	n.s		
PwA	Mim ≈ Iso	n.s		
	Mim ≈ Init	n.s		
	Init ≈ Iso	***	0-3	+3
Adult	Mim ≈ Iso	n.s		
	Mim ≈ Init	n.s		
	Init > Iso	***	0-3	+3

Table 5: Arousal model overview for Child Temporal modulations across Arousal (Low; Medium; High) and Laughter Type (Mimicking; Isolated) interactions.

Intercept	*estimates*	*SE*	*t*	*p*
(Intercept)	-32.72	0.44	-74.37	2^{-16} ***
low.isolated	1.46	0.49	2.99	0.01 **
medium.isolated	-2.35	0.45	-5.17	2^{-7} ***
high.mimicking	0.10	0.45	0.22	0.82
low.mimicking	2.75	0.47	5.85	5^{-9} ***
medium.mimicking	-2.39	0.52	-4.60	4^{-6} ***
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v'):high.isolated	8.16	9.66	79.16	2^{-16} ***
s(v'):low.isolated	8.43	9.89	208.80	2^{-16} ***
s(v'):medium.isolated	9.02	10.31	184.89	2^{-16} ***
s(v'):high.mimicking	7.60	9.11	165.43	2^{-16} ***
s(v'):low.mimicking	5.82	7.30	102.95	2^{-16} ***
s(v'):medium.mimicking	8.44	9.87	225.88	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v',p'):isolated	22.43	155.00	1.54	2^{-16} ***
s(v',p'):mimicking	13.50	131.00	2.65	2^{-16} ***

Table 6: Arousal model overview for Child Spectral modulations across Arousal (Low; Medium; High) and Laughter Type (Mimicking; Isolated) interactions.

Intercept	*estimates*	*SE*	*t*	*p*
(Intercept)	-26.84	0.36	-75.35	2^{-16} ***
low.isolated	1.26	0.45	2.81	0.01 **
medium.isolated	-1.83	0.37	-4.94	8^{-7} ***
high.mimicking	0.13	0.38	0.344	0.73
low.mimicking	2.17	0.45	4.81	1^{-6} ***
medium.mimicking	-2.09	0.43	-4.68	3^{-6} ***
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′):high.isolated	10.37	10.88	127.19	2^{-16} ***
s(v′):low..isolated	10.79	10.96	319.07	2^{-16} ***
s(v′):medium.isolated	10.73	10.96	242.85	2^{-16} ***
s(v′):high.mimicking	9.89	10.78	178.13	2^{-16} ***
s(v′):low.mimicking	9.84	10.76	168.94	2^{-16} ***
s(v′):medium.mimicking	10.34	10.92	299.39	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′,p′):isolated	53.05	154.00	1.67	2^{-16} ***
s(v′,p′):mimicking	11.74	131.00	0.58	2^{-16} ***

Table 7: Arousal model overview for Parent interacting with Child (PwC) Spectral modulations across Arousal (Low; Medium; High) and Laughter Type (Initiating; Isolated) interactions.

Intercept	*estimates*	*SE*	*t*	*p*
(Intercept)	-28.88	0.28	-103.06	2^{-16} ***
low.initiating	2.02	0.34	5.96	2^{-9} ***
medium.initiating	-1.87	0.39	-4.80	2^{-6} ***
high.isolated	0.20	0.34	0.61	0.54
low.isolated	2.13	0.31	6.84	9^{-12} ***
medium.isolated	-2.26	0.30	-7.58	4^{-14} ***
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′):high.initiating	10.69	10.98	155.349	2^{-16} ***
s(v′):low.initiating	10.43	10.94	117.775	2^{-16} ***
s(v′):medium.initiating	10.74	10.99	178.039	2^{-16} ***
s(v′):high.isolated	10.77	10.99	479.430	2^{-16} ***
s(v′):low.isolated	10.92	11.00	838.026	2^{-16} ***
s(v′):medium.isolated	10.94	11.00	970.503	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′,p′):initiating	20.68	155.00	0.96	2^{-16} ***
s(v′,p′):isolated	22.75	190.00	0.47	2^{-16} ***

Table 8: Arousal model overview for Adult Temporal modulations across Arousal (Low; Medium; High) and Laughter Type (Initiating; Isolated) interactions.

Intercept	*estimates*	*SE*	*t*	*p*
(Intercept)	-21.72	0.29	-75.86	2^{-16} ***
low.initiating	2.05	0.488	4.21	3^{-5} ***
medium.initiating	-1.09	0.51	-2.14	0.03 *
high.isolated	1.43	0.46	3.121	0.01 **
low.isolated	-0.11	0.51	-0.23	0.82
medium.isolated	-2.05	0.40	-5.08	5^{-7} ***
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′):high.initiating	2.62	3.32	26.96	2^{-16} ***
s(v′):low.initiating	2.02	2.52	41.31	2^{-16} ***
s(v′):medium.initiating	2.88	3.627	26.00	2^{-16} ***
s(v′):high.isolated	3.19	4.03	17.72	2^{-16} ***
s(v′):low.isolated	2.63	3.21	34.42	2^{-16} ***
s(v′):medium.isolated	3.30	4.10	29.63	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′,p′):initiating	5.08	89.00	0.19	0.01 **
s(v′,p′):isolated	12.24	90.00	0.45	4^{-6} ***

Table 9: Arousal model overview for Adult Spectral modulations across Arousal (Low; Medium; High) and Laughter Type (Initiating; Isolated) interactions.

Intercept	*estimates*	*SE*	*t*	*p*
(Intercept)	-27.61	0.3195	-86.41	2^{-16} ***
low.initiating	2.07	0.4666	4.43	9^{-6} ***
medium.initiating	-0.68	0.40	-1.71	0.09
high.isolated	0.67	0.41	1.65	0.1
low.isolated	0.99	0.45	2.24	0.03 *
medium.isolated	-2.31	0.34	-6.72	2^{-11} ***
Fixed smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′):high.initiating	10.31	10.92	142.40	2^{-16} ***
s(v′):low.initiating	10.63	10.98	292.91	2^{-16} ***
s(v′):medium.initiating	10.50	10.95	241.26	2^{-16} ***
s(v′):high.isolated	10.28	10.91	169.07	2^{-16} ***
s(v′):low.isolated	10.91	11.00	622.42	2^{-16} ***
s(v′):medium.isolated	10.83	10.99	500.54	2^{-16} ***
Random smooth terms	*edf*	*ref.df*	*F*	*p*
s(v′,p′):initiating	9.01	94.00	0.46	2^{-16} ***
s(v′,p′):isolated	10.00	94.00	0.42	9^{-7} ***

Table 10: Overview of GAMMs per interlocutor (Adult; PwC: Parents interacting with Child; Child) models for fitted temporal and spectral modulation responses across Mimicking laughter (Mim), Initiating laughter (Init), and Isolated laughter, where arousals levels (High: H; Medium: M; Low: L) were held constant

Temporal Modulations						
Participant	R^2	Arousal	Comparison	p	Range (Hz)	Diff (dB)
Child	0.87	H	Mim ≈ Iso	n.s		
		M	Mim ≈ Iso	n.s		
		L	Mim ≈ Iso	n.s		
Adult	0.70	H	Init > Iso	***	0-2	+2
		M	Init ≈ Iso	n.s		
		L	Init ≈ Iso	n.s		
Spectral Modulations						
Participant	R^2	Arousal	Comparison	p	Range (c/o)	Diff (dB)
Child	0.91	H	Mim ≈ Iso	n.s		
		M	Mim ≈ Iso	n.s		
		L	Mim ≈ Iso	n.s		
PwC	0.93	H	Init ≈ Iso	n.s		
		M	Init ≈ Iso	n.s		
		L	Init ≈ Iso	n.s		
Adult	0.92	H	Init ≈ Iso	n.s		
		M	Init ≈ Iso	n.s		
		L	Init > Iso	***	0-2	+2

References

Elliott, T. M., & Theunissen, F. E. (2009, 03). The modulation transfer function for speech intelligibility. *PLOS Computational Biology*, *5*(3), 1-14. Retrieved from `https://doi.org/10.1371/journal.pcbi.1000302` doi: 10.1371/journal.pcbi.1000302

Flinker, A., Doyle, W., Mehta, A., Devinsky, O., & Poeppel, D. (2019, 04). Spectrotemporal modulation provides a unifying framework for auditory cortical asymmetries. *Nature Human Behaviour*, *3*. doi: 10.1038/s41562-019-0548-z

Ludusan, B., & Wagner, P. (2020). Speech, laughter and everything in between: A modulation spectrum-based analysis. In *10th international conference on speech prosody 2020.*

Marczyk, A., O'Brien, B., Tremblay, P., Woisard, V., & Ghio, A. (2022). Correlates of vowel clarity in the spectrotemporal modulation domain: Application to speech impairment evaluation. *The Journal of the Acoustical Society of America*, *152*, 2675-2691. doi: 10.1121/10.0015024

Mazzocconi, C., O'Brien, B., & Chaminade, T. (2023). How do you laugh in an fmri scanner? laughter distribution, mimicry and acoustic analysis. In *Disfluency in spontaneous speech (diss) workshop 2023* (pp. 43–47). doi: 10.21437/DiSS.2023-9

Singh, N. C., & Theunissen, F. E. (2003). Modulation spectra of natural sounds and ethological theories of auditory processing. *The Journal of the Acoustical Society of America*, *114*(6), 3394-3411. doi: 10.1121/1.1624067

Thoret, E., Caramiaux, B., Depalle, P., & Mcadams, S. (2021, 03). Learning metrics on spectrotemporal modulations reveals the perception of musical instrument timbre. *Nature Human Behaviour*, *5*. doi: 10.1038/s41562-020-00987-5

van Rij, J., Wieling, M., Baayen, R. H., & van Rijn, D. H. (2015). itsadug: Interpreting time series and autocorrelated data using gamms..