Needing to shout to be heard? Affective dysregulation, caregiver under-responsivity, and disconnection between vocal signalling and autonomic arousal in infants from chaotic households

Wass, S.V.(*)(1), Goupil, L.(1), Smith, C.S.(2), Greenwood, E.M.G.(1)

1 – Department of Psychology, University of East London

2 – Institute of Psychiatry, Psychology & Neuroscience, King's College London, UK

Corresponding author: Dr Sam Wass ORCID ID 0000-0002-7421-3493. Address: University of East London, London E15 4LZ. Telephone: +44(0)7725369189. Email: s.v.wass@uel.ac.uk

This research was funded by ESRC grant number ES/N017560/1, by ERC grant number ONACSA 853251, by Project Grant RPG-2018-281 from the Leverhulme Trust and by an ERC Marie Curie Fellowship JDIL 845859. Thanks to Kaili Clackson and Farhan Mirza for help with data collection; to Caitlin Gibbs, Emma Bruce-Gardyne, Florian Andrey-Csolm, Joan Eitzenberger, Leanne Barnes, Louise Stubbs, Deborah Scatlebury and Anne Hepworth for help with data coding. Thanks to members of the UEL BabyDev Lab for comments and discussions on earlier drafts of this manuscript, and to all participating children and caregivers.

Data sharing: Due to the personally identifiable data of the data contained in this manuscript (microphone recordings of infants), access to the data is only available through direct request to the first author.

Abstract

Higher levels of household chaos have been related to increased child affect dysregulation during later development. To understand why this relationship emerges, we used miniature wearable microphones and autonomic monitors to obtain day-long recordings in home settings from a cohort of N=74 12-month-old infants and their caregivers from the South-East of the UK. Our findings suggest a disconnect between what infants communicate and their physiological arousal levels, that are likely to reflect what they experience. Specifically, in households which families self-reported as being more chaotic, infants were more likely to produce negative affect vocalisations such as cries at lower levels of arousal. This disconnection between signalling and autonomic arousal was also present in a lab still face procedure, where infants from more chaotic households showed reduced change in facial affect and slower physiological recovery despite equivalent change in arousal during the still face episode. Finally, we found that this disconnect between what infants communicate and their physiological arousal levels may influence the likelihood of a caregiver responding. Implications for understanding the mechanisms underlying the relationship between household chaos, emotion dysregulation and caregiver under-responsivity are discussed.

Keywords: emotion regulation, self-regulation, arousal regulation, caregiver sensitivity, household chaos

Introduction

A lack of family and weekly routines, high noise levels, disorganisation and crowding are all part of household chaos (Evans & Wachs, 2010; Matheny Jr. et al., 1995). Higher levels of household chaos have been related to worse child outcomes across a range of areas including cognitive and academic development (Shamama-tus-Sabah et al., 2011), language (Martin et al., 2011) and mental and physical health outcomes (Coldwell et al., 2006; Marsh et al., 2020; Mills-Koonce et al., 2016). One finding in particular that has attracted attention is the well-replicated relationship found between household chaos and affect dysregulation, evaluated using a variety of measures including response to challenge (Vernon-Feagans et al., 2016), delayed gratification (Martin et al., 2011), caregiver-reported emotion regulation (Miller et al., 2017) and caregiver- and clinician-rated behaviour problems (Bobbitt & Gershoff, 2016; Coldwell et al., 2006; Deater-Deckard et al., 2009) (see (Marsh et al., 2020) for a review).

How and why chaos impacts on affect dysregulation remains unclear, but research suggests that this is mediated by an impact on caregiver responsiveness. Higher levels of household chaos are known to relate to less responsive and more intrusive caregiving styles (Andeweg et al., 2020; Deater-Deckard et al., 2012; Dumas et al., 2005; Geeraerts et al., 2021). Vernon-Feagans and colleagues examined the relationship between household chaos, early executive function and behavioural regulation, and caregiver responsiveness in a longitudinal study of 1145 infants. Household chaos and caregiver responsiveness were rated by trained researchers at each of the 5 home visits, and executive function tests were administered at older ages. Results suggested that the relationship between household chaos and executive function was

mediated by caregiver responsivity (Vernon-Feagans et al., 2016) (see also (Geeraerts et al., 2020; Song et al., 2018)).

The key to appreciating how caregiver under-responsivity leads to child affect dysregulation is likely to lie in understanding the dynamic bi-directional influences between children and the caregivers. Infants are thought to learn self-regulation by experiencing repeated cycles of co-regulation with their caregiver; over time, the infant internalises the expectation of the caregiver's soothing response and through this learns self-regulation (Bronfenbrenner, 1977; Ham & Tronick, 2009a; Kopp, 1982; Olson & Lunkenheimer, 2009). In home settings, for example, caregivers respond to their infants' distress by upregulating their own arousal state to match their child's, leading to short-term increases in arousal synchrony; greater caregiver responsivity to infant stress associates with faster infant quieting (Wass et al., 2019, 2021). In lab settings, studies have similarly shown that the recovery period of the infant following a 'still face' procedure is dependent on the response of the caregiver during the 'reunion' phase (Enlow et al., 2014; Feldman, Gordon, et al., 2010; Provenzi et al., 2015a).

These studies have, however, concentrated on understanding how caregiver under-responsivity is driven by caregiver adapting (or not) to their child. Less research has investigated bi-directional links, examining simultaneously the role of the child as a sender in these exchanges, as well as how the caregiver responds to the child. From birth, infants typically express signs of heightened arousal and distress through cries and facial expressions. It is thought that initially, infants mostly express these communicative displays automatically - that is, directly as a function of autonomic arousal and physiological responses to their environment (Craig, 1992; Zeskind, 2013). This predicts that, early on, physiological states of arousal and facial and vocal displays of stress/distress should typically

align; e.g., in the absence of dysregulation, infants should mostly cry when they are aroused, and not otherwise (Zeskind, 2013). Over time, infants develop the ability to use displays flexibly and intentionally (Feldman, 2007a; Matthews, 2020), according to specific display rules that are culture-specific. The onset of such intentional communication can for instance be seen in gaze-coordinated vocalizations – where children vocalize while looking towards their caregivers, or alternate their gaze between their caregiver and a situation or object (Bates, 2014; Donnellan et al., 2020; Schieffelin, 2016).

Caregiver responsivity is thought to be crucial for this transition towards intentional communication (Albert et al., 2018; Locke, 2006; Matthews, 2020). Infants' dynamic behaviours, such as crying and smiling, influence their caregivers' behaviours (Feldman, 2007a), and negative vocalisations including cries elicit greater (Tronick, 2007; Wass et al., 2019, 2021) and faster (Yoo et al., 2018) responses from caregivers, while vocalisations that are more speech-like prompt more contingent responses (Albert et al., 2018). This signifies that caregivers are sensitive to variations in the acoustic and phonetic characteristics of their infants' vocalisations, and interpret them as serving various functions (e.g., cries are typically perceived as requiring a more urgent response). Yet it remains unclear whether, and if so how, infants' vocal and facial displays affect caregiver responsivity differently as a function of their arousal level, and how these relationships may vary as a function of environmental factor.

Few previous research studies have investigated simultaneously the relationship between infants' displays, their autonomic arousal, and caregiver responsivity. One recent study looked at vocalisation and arousal co-fluctuations across the day in naturalistic home environments; it found that negative affect vocalisations (including cries, which accounted

for 98% of negative vocalisations), occurred most frequently when the infant was highly aroused and with lower arousal stability (Wass et al., 2021) (see also (McFarland, 2001; McFarland et al., 2020; Wilder, 1974)). These types of vocalisations also elicited the highest frequency of caregiver contingent responses when compared to more positive vocalisations. High intensity infant vocalisations also coincided with bigger infant arousal changes, followed by a period of arousal stability across the dyad. This confirms that cries – as well as being particularly salient for caregivers – are an important tool for establishing co-regulation within the dyad (Wass et al., 2019, 2021). It thus seems important to understand what happens when a noisy, chaotic environment impacts how caregiver responsivity relates to infants' expressions of distress, potentially in turn affecting their self-regulatory skills.

To address this, in study 1 we used miniature wearable microphones and autonomic monitors to obtain day-long recordings in home settings from a cohort of N=74 12-month-old infants across the South-East of the UK. We examined how autonomic arousal, in infant and caregiver, changed relative to naturally occurring infant vocalisations during the day. Trained, blinded coders manually coded all infant vocalisations across two dimensions: first, vocal affect, ranging from negative (fussy and difficult) to positive (happy and engaged); and second, vocal intensity, reflecting the intensity with which the affect was expressed. For technical reasons our microphones recorded a 5-second sample every minute and therefore our analyses examined only large-scale arousal changes during the 10 minutes before and after each vocalisation. Importantly, although our recordings do not capture all vocalisations that occurred, the presence of undetected vocalisations can only have weakened any patterns of event-related change that we did observe. Participating caregivers also attended a lab visit, where the still face procedure (Ham & Tronick, 2009b), a widely used test of emotion regulation in infancy, was recorded (study 2).

We hypothesised that caregiver sensitivity to their infant's vocal (study 1) and facial (study 2) displays of distress would be lower in high chaos households, and that as a consequence there would be a more flexible association between arousal and displays in these infants. In study 1, we predicted that the level of caregiver responsivity would be related to infants' vocal displays; that lower levels of responsiveness would be related to less specific vocal displays; and that vocal displays would be related to the infant's autonomic arousal levels to varying degrees, dependent on the level of caregiver responsivity. In study 2, we hypothesized that there would be a similar disconnection between physiological arousal and facial displays in infants from chaotic households during the still face episode, and that this should be paralleled by reduced caregiver sensitivity.

Methods

Experimental participant details

The project was approved by the Research Ethics Committee at the University of East London. Participants were recruited from the London, Essex, Hertfordshire and Cambridge regions of the UK. In total, 91 infant-caregiver dyads were recruited to participate in the study, of whom usable autonomic data were recorded from 78. A further 4 participants failed to return the chaos questionnaire. Further details, including exclusion criteria, and detailed demographic details on the sample, are given in SM section 1.1 and Table S1. Of note, we excluded families in which the primary day-time care was performed by the male caregiver, because the numbers were insufficient to provide an adequately gender-matched sample. All participating caregivers were, therefore, female. Participants received £30 in Love2Shop gift vouchers as a token of gratitude for participation, split over two visits.

CHAOS scale

The *Confusion Hubbub And Order Scale* (henceforth ‘chaos’) questionnaire (Matheny Jr. et al., 1995) asks caregivers to self-rate on a series of statements such as “it’s a real zoo in our home” and “the atmosphere in our home is always calm”. Figure S1 (SM section 1.2) shows a histogram of the results obtained from the questionnaire. For the time series analyses reported in parts 2b, 2c, 3a-c and 4, where it is not possible to look at group differences based on a continuous group variable, data have been split using a median split, with quartile splits also reported in the Supplementary Materials. The median was 33; Table S1 provides a breakdown of the demographic data split by high/low chaos score, and associations between chaos score and other demographic variables are reported in the results.

Experimental method details – home data

Participating caregivers were invited to select a day during which they would be spending the entire day with their child but which was otherwise, as far as possible, typical for them and their child. The researcher visited the participants' homes in the morning (c. 7.30 - 10am) to fit the equipment, and returned later (c. 4 - 7pm) to pick it up. The mean (std) recording time per day was 7.3 (1.4) hours.

The equipment consisted of two wearable layers, for both infant and caregiver (see Figure 1). For the infant, a specially designed baby-grow was worn next to the skin, which contained a built-in Electrocardiogram (ECG) recording device (recording at 250Hz), accelerometer (30Hz), Global Positioning System (GPS) (1Hz), and microphone (11.6kHz). For technical reasons (limited storage capacity), the microphone recorded a 5-second snapshot of the auditory environment every 60 seconds.

A T-shirt, worn on top of the device, contained a pocket to hold the microphone and a miniature video camera (a commercially available Narrative Clip 2 camera). For the caregiver, a specially designed chest strap was also worn next to the skin, containing the same equipment. A cardigan, worn as a top layer, contained the microphone and video camera. The clothes were comfortable when worn and, other than a request to keep the equipment dry, participants were encouraged to behave exactly as they would do on a normal day.

Figure 1 – Equipment. a) picture showing the equipment used in the study. b) picture showing a caregiver and child wearing the equipment.

Figure 2 raw data sample showing, from top to bottom: infant arousal composite score (see SM sections 1.3-1.6); infant arousal after removal of the autocorrelation (AR (see SM section 1.7); infant vocal affect and infant vocal intensity (see Methods section); caregiver arousal; caregiver arousal after removal of the autocorrelation.

Quantification and statistical analysis – home data

Autonomic data parsing and calculation of the autonomic composite measure. Further details on the parsing of the heart rate (section 1.3; Figure S2, S3), heart rate variability (section 1.4), and actigraphy (section 1.5) are given in the SM. As shown in the SM (Figure S4) these three variables were highly interdependent, and so we collapsed them into a single composite measure of autonomic arousal (see SM section 1.6 for further details). In section 1.7 we present a description of how the autocorrelation was removed from the arousal data. Because we wished to examine large-scale arousal changes, all data were downsampled to one-minute epochs for all analyses.

Home/Awake coding. Our preliminary analyses suggested that infants tended to be strapped-in to either a buggy or car seat for much of the time that they were outdoors, which strongly influenced their autonomic data. For this reason, all the analyses presented in the paper only include data segments in which the dyad was at home and the infant was awake. A description of how these segments were identified are given in the SM (section 1.8). Following these exclusions, the mean (*std*) total amount of data available per dyad was 3.7 (1.7) hours, corresponding to 221.5 (102.4) 60-second epochs per dyad.

Vocal affect and intensity coding. *Post hoc*, trained, blinded coders identified samples in which the infant or caregiver was vocalising, and coded them on a five-point scale for vocal affect (negative: fussy and difficult, neutral or positive: happy and engaged), and on a five-point scale for vocal intensity of the affect expressed, from 1 (least intense) to 5 (most intense). Consistency of rating between coders was achieved through discussions and joint coding sessions based on an *ersatz* dataset, before the actual dataset were coded. In order to assess inter-rater reliability, 24% of the sample was double coded; Cohen's kappa was 0.60, which is considered acceptable (McHugh, 2012) . All coders were blind to study design,

participant details and hypothesised study outcome. In total, a mean (std) of 159 (36) vocalisations per infant was analysed.

Permutation-based temporal clustering analyses. To estimate the significance of time-series relationships, a permutation-based temporal clustering approach was used. This procedure, which is adapted from neuroimaging (Maris, 2012; Maris & Oostenveld, 2007), allows us to estimate the probability of temporally contiguous relationships being observed in our results, a fact that standard approaches to correcting for multiple comparisons fail to account for (Maris, 2012) (see also (Oakes et al., 2013)). See further details in SM section 1.10.

Control analysis. Participant by participant, for each vocalisation that was observed, a random ‘non-vocalisation’ moment was selected as a moment during the day when the dyad was at home and the infant was awake but no vocalisation occurred. The same moving window analysis described above was then repeated to examine change relative to this ‘non-vocalisation event’. The same procedure was repeated 1000 times and the results averaged. Real and observed data were compared using the permutation-based temporal clustering analyses described above.

Experimental method details – lab data

The task was a standard version of the still face protocol (Weinberg & Tronick, 1996). Caregiver and child were seated across a 80cm-wide table, and instructed to play naturally with four toys positioned on the table. After four minutes, on an instruction from the experimenter,

the caregiver was instructed not to respond to the infant and to hold a neutral face for two minutes. On a further instruction from the experimenter, the play resumed for a further two minutes. If the infant became distressed during the still face period, as judged using the standard guidelines (Weinberg & Tronick, 1996), the experiment was curtailed.

Quantification and statistical analysis – lab data

Facial and vocal affect coding. Facial and vocal affect was coded in 5-second bins using a 5-point scale, where -2 is extreme negative affect, 0 is neutral, and +2 is extreme positive affect. To ascertain inter-rater reliability, 20% of the sample was double coded, and Cohen's Kappa was calculated. Inter-rater reliability was found to be 0.66, which is considered acceptable.

Autonomic data parsing. The parsing of the ECG data was conducted using the same procedures as used for the home data. Because of technical problems with equipment during the recording of heart rate data from the still face protocol, data from this task are only available from a N=17 subset of the sample. Further details of the parsing of the ECG data are given in the SM (section 1.3; Figure S2, S3).

Results

The results section is structured as follows. First (part 1) we include descriptive statistics, showing how scores on the chaos scale correlated with household noise, demographics, caregiver mental health, tonic arousal, and average vocalisation rate affect and intensity.

Second (part 2) we examine infant arousal around vocalisations in home settings (study 1), subdivided by household chaos. In part 2a we examine the two-way split between arousal and vocalisation affect/intensity; in part 2b we examine infant arousal changes around vocalisations; in part 2c we examine the temporal clustering of infant vocalisations.

Third (part 3) we examine caregiver arousal around infant vocalisations in home settings (study 1). In part 3a we examine caregiver arousal changes around vocalisations, subdivided by household chaos; in part 3b we examine caregiver arousal changes around vocalisations, subdivided by infant arousal at the time of the vocalisation; in part 3c we examine the temporal clustering of adult vocalisations around infant vocalisations.

Fourth (part 4) we examine infant behaviour and physiological changes during the lab-based still face protocol (study 2).

Part 1 - Descriptives

See Table S1 for demographic split.

Before conducting our primary analyses (described from Part 2 onwards) we first calculated some descriptive statistics to report on: i) face validity of the chaos scale – association with microphone noise and people in the household; ii) association of chaos with demographics and caregiver mental health; iii) association of chaos with tonic arousal; iv) association of chaos with vocalisation rate, affect and intensity.

Face validity of chaos scale – association with microphone noise levels and people in the household. First, we examined the face validity of the scale by examining the relationship between household noise levels (taken from the average dB levels on the microphones worn by infants) and caregiver household chaos ratings. Because not all variables were normally distributed, more conservative non-parametric Spearman correlations are reported throughout. A significant association was identified between chaos and microphone noise levels while the infant was sleeping ($\rho=.28$, $p=.016$), and a marginally non-significant association was identified between chaos and ambient waking microphone noise levels ($\rho=.22$, $p=.069$). An association was also observed between chaos and the number of people living in the household ($\rho=.41$, $p<.001$).

Demographics and caregiver mental health. We examined the relationship of the chaos scale to the demographic variables recorded: maternal education and household income. In our sample, no significant relationships were identified (all $p>.55$). In addition, we examined the relationship of the chaos scale to caregiver mental health, as assessed using the Generalised Anxiety Disorder 7-item screen (GAD-7) (Spitzer et al., 2006) and the Patient Health Questionnaire 9-item (PHQ-9) screen for depression (Kroenke et al., 2001). An association was observed between chaos and caregiver depression $\rho=.23$, $p=.026$ but not anxiety ($p=.26$).

Association with tonic arousal. First we examined the association between tonic arousal, defined from average heart rate, heart rate variability and movement levels in infant and caregiver. Two categories were examined: segments while the dyad was at home and the infant was awake; and those where the infant was asleep. No significant associations were found between any of these variables and household chaos (all p s < .34).

Association with vocalisation rate, affect and intensity. No association was observed between chaos and average infant vocal intensity ($\rho = -.07$, $p = .60$); a marginally non-significant positive association was observed between chaos and infant vocal affect ($\rho = .24$, $p = .084$) (higher chaos associated with more positive affect). No association was observed between chaos and the vocalisation rate of infants or adults ($\rho = -.04/.12$, both p s > .3), but a marginally non-significant positive association was noted between chaos and the proportion of adult vocalisations that were infant-directed ($\rho = -.22$, $p = .098$) (higher chaos associated with a lower proportion of infant-directed vocalisations).

Part 2 – Infant arousal around vocalisations

a) Stacked bar charts

In order to examine how the relationship between vocalisation type and autonomic arousal differed contingent on household chaos we first subdivided our all vocalisations by vocal affect and physiological arousal, and plotted two separate stacked bar charts for the low and high chaos groups, determined by a median split (Figure 3a). In the SM section 2.1 (Figure S5) we also include the same plots subdivided using a quartile split.

Statistical analyses were conducted by calculating ANOVAs separately for each vocal affect bin and each group to examine whether, for that bin, there was a significant relationship with arousal. Multiple comparisons were corrected for using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995). Figure 3a shows the results of this analysis for the low (left) and high (right) chaos groups. In the low chaos group there is – as expected - a significant relationship between extreme negative affect vocalisations and arousal $F(4,134)=6.7$, FDR-corrected $p=.006$, such that extreme negative affect vocalisations are more likely at elevated arousal. This relationship is not present in the high chaos group ($p=.62$). For moderate negative affect vocalisations in the low chaos group the same relationship was present but did not survive correction for multiple comparisons ($p=.074$). Again, this relationship is absent in the high chaos group ($p=.62$). In the SM (Fig S5) we present the same analysis based on a quartile (rather than median) split by chaos, showing that this relationship is observed across all quartiles and is most marked in the bottom (lowest chaos) quartile group.

Figure 3b shows the same relationship, but examining the correspondence between vocal intensity and arousal. In the low chaos group there is a similar relationship for extreme intense vocalisations, which are more likely at elevated arousal, although this relationship did not survive correction for multiple comparisons (pre-correction $p=.046$; post-correction $p=.082$). This relationship is absent in the high chaos group ($p=.92$). Although differences also appeared evidence for low intensity vocalisations, these were non-significant due to the relatively lower frequency of this type of vocalisation in our data. Again, in the SM (Fig S5) we present the same analysis based on a quartile split by chaos, showing that the relationship is continuous across the sample.

Finally, in Figure 3c we examine the relationship between vocal affect and intensity. This shows that, for both groups, extreme negative and positive affect vocalisations are more common at high vocal intensity. ANOVAs showed highly significant associations between affect and intensity across all bins examined; no differences contingent on chaos were observed.

Overall, these results show that, in the low chaos group, negative affect vocalisations such as cries are more likely to occur at elevated arousal. This relationship is absent in the high chaos group.

a) Vocal affect vs arousal

b) Vocal intensity vs arousal

c) Vocal intensity vs vocal affect

*Fig 3: Stacked bar charts showing: a) the relationship between vocal affect and arousal at the time of vocalisation, split between the low (left) and high (right) chaos groups. * shows the significance of the statistical analyses reported in the main text * - $p < .05$ after correction for multiple comparisons; (*) – $p < .05$ before but not after correction; b) the relationship between vocal intensity and arousal at the time of vocalisation, split between low (left) and high (right) chaos groups; c) the relationship between vocal intensity and vocal affect, split between low (left) and high (right) chaos households. For c), statistical analyses showed that all bins in both groups were significant.*

b) Arousal changes before and after vocalisations

Next, we examined arousal changes around vocalisations. First, we calculated the average change in infant arousal around all negative (Figure 4a) and positive affect infant vocalisations, subdivided using a median split into low/high chaos groups. In the SM we also include the same analysis based on a quartile split by household chaos, to examine how continuously these group differences were observed in our data (see SM Figure S6).

For each plot, the average change in arousal for the period from 10 minutes before to 10 minutes after each vocalisation is shown. In order to analyse the significance of group differences, a permutation-based clustering analysis was conducted to correct for multiple comparisons, as described in the Methods. For negative affect vocalisations, two significant ($p = .001$) clusters were found: one between -1 to +1 minutes, and one from +4 to +5 minutes following the vocalisation (Fig 4a), suggesting that the high chaos group showed smaller arousal changes around vocalisations. For positive affect vocalisations, a significant ($p = .025$) difference was observed from +1 to +2 minutes following the vocalisation (Fig 4b). For low

intensity vocalisations, a significant ($p=.018$) difference was observed from +2 to +3 minutes following the vocalisation (Fig 4c); for high intensity vocalisations a significant ($p=.025$) difference was observed from -3 to +3 minutes around vocalisations. In each case the direction of these effects was the same: the high chaos group showed smaller arousal changes around vocalisations. Results presented in the SM (Figure S6) show that, when the analysis is repeated using a quartile split by household chaos, the relationship is continuous across the sample.

Overall, these results show infants in the low chaos group show larger changes in autonomic arousal across all types of vocalisations; differences appear most marked for negative affect, and high intensity, vocalisations. This suggest that there is a disconnection between vocal displays and physiological arousal in the high chaos group.

Figure 4: Line graphs showing average infant arousal around different types of vocalisations, split by median split into children from low (blue) and high (red) chaos households. a) Negative affect vocalisations; b) positive affect vocalisations; c) low intensity

*vocalisations; d) high intensity vocalisations. Shaded areas show standard error. * - sections identified as showing significant group differences by the permutation-based cluster analysis $* < .05$.*

c) Temporal clustering of vocalisations

Finally, as an additional analysis, we examined how likely infant vocalisations are to occur in clusters, and how this differs contingent on household chaos, and between negative and positive affect vocalisations. To do this we used the following procedure: for each vocalisation, we calculated the average likelihood of another vocalisation during a given one-minute time window (e.g. 1-2 minutes following an initial infant vocalisation – see Figure 5a). To estimate whether the observed likelihood differed from chance we performed a control analysis in which we inserted random ‘non-vocalisation’ events into the data and repeated the analysis relative to these ‘non-vocalisations’, and compared the ‘real’ and ‘control’ datasets using a nonparametric Mann-Whitney U test (see Figure 5a). We then repeated this analysis across multiple time windows from 10 minutes before the vocalisation to 10 minutes after.

For each time window, the significance of each Mann-Whitney U test compared the observed vocalisation rate with change is shown in Figure 5b: a large dot indicates a significant difference between the observed and the control data (i.e. that a vocalisation was significantly more likely to occur during that time window compared with chance). Our results showed that, in the low chaos group, a significantly greater than chance vocalisation likelihood was observed from 9 minutes before each vocalisation to 7 minutes after (although not all intermediate bins were significant – see Fig 5b). In the high chaos group, greater than chance

vocalisation rates were observed from 8 mins before to 10 mins after (although again not all intermediate bins were significant).

In addition, we also directly compare the vocalisation rates between the high and low chaos groups, using a Mann-Whitney U test and a permutation-based clustering analysis to correct for multiple comparisons. This test identified a significantly higher vocalisation rate ($p < .001$) in the low chaos group from -1 to +1 mins following the vocalisation, suggesting higher caregiver responsivity for negative vocalisations in this group.

Figure 5c shows an identical plot of positive affect vocalisations. In the low chaos group, greater than chance vocalisation likelihoods were observed between 8 minutes before each vocalisation to 10 minutes after (although again not all intermediate time windows were significant). In the high chaos group, greater than chance vocalisation rates were observed between 9 mins before to 10 mins after. No direct group comparisons were significant, suggesting no differences in caregiver responsivity for positive vocalisations.

Overall this suggests that, in the low chaos group, negative affect vocalisations are more likely to be accompanied by other vocalisations during the period immediately around the event. No significant group differences were observed for positive affect vocalisations.

Fig 5: a) sample violin plot showing the analysis for one time interval that was then repeated iteratively across multiple time intervals in b. The plot shows the likelihood of a subsequent negative affect vocalisation in the time window 0-1 minutes following a negative affect vocalisation, comparing real with control data. b) same analysis repeated across multiple time windows, subdivided between low (red) and high (blue) chaos households. For each time window, the size of the dot indicates the significance of the Mann-Whitney U test comparing the observed and control data. Large dot – $p > .05$; small dot – $p < .05$. * - sections identified as showing a significant group differences by the permutation-based cluster analysis $p < .05$.

Part 3 – Caregiver arousal around vocalisations

a) Caregiver arousal changes before and after infant vocalisations

In order to better understand why caregivers were less responsive in the high-chaos group we also examined how caregiver arousal patterns change relative to infant vocalisations (Figure 6). These analyses were conducted identically to those described in Part 2 above (Figure 4), but examining caregiver arousal changes relative to infant vocalisations, rather than infant

arousal changes. Figure S7 shows the same analysis, but subdivided using a quartile split by household chaos.

For all infant vocalisations (Fig 6a), permutation-based clustering analyses revealed a significant ($p=.023$) group difference from 0 to +2 minutes and from +5 to +6 minutes following the vocalisation (Fig 6a), such that caregivers in the high chaos group showed smaller arousal changes around infant vocalisations. For negative affect vocalisations, a significant ($p=.045$) difference was observed from -1 to 0 and from +1 to +2 minutes relative to infant vocalisations (Fig 6b). For positive affect vocalisations (Fig 6c) no group differences were observed. Results presented in the SM (Figure S7) show the same analysis repeated using a quartile split by household chaos. These analyses show that the relationship is linear across the sample, and driven by greater caregiver arousal reactivity to infant vocalisations in the bottom quartile (lowest household chaos) subgroup.

No significant group differences were observed when we examined caregiver arousal changes to infant vocalisations subdivided by vocal intensity, subdivided by household chaos (Fig S8a and S8b). However, the same analysis broken down using a quartile split by household chaos (Fig S8c, S8c) show that, again, greater caregiver arousal reactivity to infant vocalisations is observed in the bottom quartile (lowest household chaos) subgroup.

Overall this suggests that caregivers in the low chaos group show larger changes in autonomic arousal around infant vocalisations, and that this is driven by greater responsivity to negative affect vocalisations.

*Fig 6: Line graphs showing average caregiver arousal around different types of infant vocalisations, split by median split into children from low and high chaos households. a) all vocalisations; b) negative affect vocalisations; c) positive affect vocalisations. Shaded areas show standard error. * - sections identified as showing significant group differences by the permutation-based cluster analysis $p < .05$.*

b) Caregiver arousal changes before and after infant vocalisations – subdivided by infant arousal

We also repeated the same analyses as shown in Figure 6, but instead of subdividing vocalisations by household chaos and manually coded vocal affect, we subdivided all vocalisations according to the infant's arousal at the time of the vocalisation. Separately for each infant we performed a median split to differentiate between high and low arousal vocalisations (relative to the average arousal level for that child). Results are shown in Figure 7a. The same permutation-based temporal clustering analysis was performed as described above. This suggested that high arousal vocalisations were accompanied by significantly ($p < .001$) greater changes in caregiver arousal during the time period from 0 to +3mins after the vocalisation. We then further subdivided these vocalisations by household chaos, to create four categories – high arousal vocalisations from the low chaos group, high arousal vocalisations from the high chaos group, low arousal vocalisations from the low chaos group,

and low arousal vocalisations from the high chaos group. We found that only the low chaos group appeared to respond differentially to high arousal vocalisations (Fig 7b).

Overall, this suggests that caregiver arousal changes are greater following high arousal infant vocalisations compared with low arousal vocalisations. However, this finding is limited to the low chaos group.

*Fig 7: a) Line graph showing average caregiver arousal around infant vocalisations, split by median split by the infant's arousal at the time of the vocalisation. b) Same figure as 7a, but further subdivided by household chaos, to create four categories. For a-b, shaded areas show standard error. * - sections identified as showing significant group differences by the permutation-based cluster analysis $* < .05$. c) sample violin plot showing the analysis for one time interval that was then repeated iteratively across multiple time intervals in c. The plot shows the likelihood of a subsequent caregiver vocalisation in the time window 0-1 minutes following an infant vocalisation, comparing real with control data. d) same analysis repeated*

*across multiple time windows, subdivided between high and low arousal vocalisations. e) same analysis repeated across multiple time windows, further subdivided by household chaos. For c-e, the size of the dot indicates the significance of the Mann-Whitney U test comparing the observed and control data. Large dot – $p > .05$; small dot – $p < .05$. * indicates sections identified as showing a significant group differences by the permutation-based cluster analysis, $p < .05$.*

c) Caregivers' vocal responsivity

We also repeated the same analyses as reported in Part 2c to examine the likelihood of caregivers vocalising during the time period before and after infant vocalisations. Figure 7d shows caregiver vocalisation likelihood subdivided between high and low arousal infant vocalisations. As with the plots in Figure 5, the size of the dots in Fig 7d indicates the significance of the statistical analyses comparing the observed vocalisation rate with chance; the results suggested that, in all bins examined (apart from -9 mins for low arousal vocals) the observed vocalisation rates were greater than chance. In addition, the observed vocalisation rates were directly compared between the two conditions. Permutation-based temporal clustering analyses suggested that caregivers are significantly more likely to vocalise during the time period 0 to +2 mins following high arousal vocalisations. Figure 7e shows the same plot, but further subdivided by household chaos. Overall, these results suggest that caregivers are more likely to vocalise in the time period following high arousal infant vocalisations, with the highest response rate observed from caregivers in the low chaos subgroup in response to high arousal vocalisations.

Part 4 – Child affect regulation – lab battery

Figure 8a shows the experimental set-up that we used for the still face procedure. First, we examined the change in infant facial affect during the still face procedure, subdivided into high and low chaos groups (Fig 8b). The same permutation-based temporal clustering analysis as described above was applied to test for group differences while correcting for multiple comparisons. This identified a significant ($p=.034$) difference in facial affect in the time period 1:20 to 1:40 during the still face procedure, such that the high chaos group showed less negative affect. By contrast, when we examined physiological changes, we found no significant difference between groups (although the N for this analysis is lower, as described in the Methods). However, we did identify a trend-level correlation between chaos and heart rate recovery following the still face ($\rho=.47$, $p=.056$), such that higher household chaos associated with slower recovery following the still face. Overall, these results suggest that infants from high chaos households display less negative facial affect during the still face, along with a trend towards slower physiological recovery afterwards.

*Fig 8: a) screen grabs illustrating the experimental set-up; b) line graph showing change in facial affect during the still face, subdivided by high and low household chaos; c) line graph showing change in heart rate during all three phases of the experiment, subdivided by high and low household chaos. Shaded areas show standard error. * - sections identified as showing significant group differences by the permutation-based cluster analysis $* < .05$.*

Discussion

Using day-long home recordings obtained using miniaturised wearable autonomic monitors and microphones, we examined caregiver-infant physiological arousal and vocal affective displays in high- and low-chaos households. We examined within-individual relationships (how infant autonomic arousal relates to infant vocal affects) and cross-dyad relationships (how caregiver arousal relates to infant vocalisations). We also examined differences in facial displays and autonomic arousal in infants from the different households during the still face paradigm. From our results the following conclusions can be drawn:

First, children in the low chaos group are more likely to produce negative affect vocalisations such as cries at elevated arousal; this relationship is absent in the high chaos group (Fig 3). Second, children from high chaos households showed smaller arousal changes around vocalisations, in particular around negative affect and high intensity vocalisations such as cries (Fig 4). The findings from the high-chaos group are in contrast with those from the low-chaos group, and from previous research in general populations (i.e. not subdivided by household chaos level) (Kreibig, 2010; Wass et al., 2021) which show that negative vocalisations occur most often at high arousal states. This is consistent with the idea that initially, infant vocalisation are not functionally flexible, but directly determined by levels of arousal (Ghazanfar & Zhang, 2016; Wass et al., 2021; Zeskind, 2013). This suggests that high chaos infants are not using high intensity vocalisations to communicate their high arousal states, revealing a disconnect between infants' levels of arousal – which is likely to reflect what they are experiencing - and what they are actually expressing.

Importantly, we observed no relationship between household chaos and infant vocalisation rates, and no relationship between household chaos and overall vocalisation intensity or vocal affect. Thus, it is not the case that infants in the high-chaos group are experiencing different autonomic arousal, or vocalizing differently overall. Instead, it is how their vocalizations relate to their arousal levels that is atypical, both as compared to the low-chaos group in the present study, and as compared to what we expected based on past research (Wass et al., 2021).

Our results also suggest that caregivers from high chaos households show smaller arousal changes around infant vocalisations (Fig 6a), in particular around negative affect vocalisations (Fig 6b). When we examined how caregiver responsivity varies as a function of infant arousal at the time of the vocalisation (Fig 7) we found that all caregivers are less responsive to low arousal vocalisations (Fig 7a, 7d). However, when we subdivided this by household chaos we found that, whereas low chaos caregivers did differentiate between high and low arousal vocalisations, high chaos caregivers did not (Fig 7b, 7e). In other words, infant arousal at the time of the vocalisation influenced the likelihood of a caregiver response in low chaos households, but the same relationship was not observed in high chaos households.

This is relevant to theories of selective reinforcement in communication (Albert et al., 2018; Goldstein & Schwade, 2008; Locke, 2006; Oller & Griebel, 2020; Zhang & Ghazanfar, 2016). Our findings suggest that specific signals perhaps lose the potential functional significance that we assume they had in earlier infancy for children in high chaos households, potentially resulting in negative affect vocalisations such as cries becoming less specific. Consistent with this is our finding that, in the low chaos group, negative affect vocalisations such as cries are more likely to occur at elevated arousal, but this relationship is absent in the

high chaos group (Fig 3a). Possibly this indicates that, in contrast with previous studies in general populations which found that negative affect vocalisations were more likely to occur at high arousal states (Tronick, 2007; Wass et al., 2019, 2021), these infants have learned that expressing distress when aroused does not have consequences, so they stop doing it. It doesn't matter *how* they communicate, the resulting feedback will be the same.

Interestingly, we found a similar disconnection between affective displays and physiological arousal in a lab-based still face protocol: children from high chaos households showed less negative facial affect (Fig 8b). This contrasts with previous selective reinforcement interpretations of the still face paradigm in general populations, in which infants are said to increase their vocal and facial displays in order to gain a previously conditioned response from their caregiver (Ham & Tronick, 2009b). For instance, Goldstein and colleagues found that 5-month-old infants responded to their caregiver's neutral face with increased behavioural signals (clusters of vocalisations) followed by quietness. The authors interpreted this as a classic extinction burst (Goldstein et al., 2009).

Here, our findings mirror those in the more naturalistic data: infants from high chaos household show similar levels of arousal during the still face; but, in contrast with children from low chaos households, they do not match this with their facial display. There is again a disconnection between their physiological response and their communicative behaviour. This could mean that there is no/under regulation by the caregiver of their child's distress during the post-still face; or, it could indicate that this behaviour had perhaps not been previously reinforced; and so facial affect too has possibly lost potential functionality (Conradt & Ablow, 2010; Enlow et al., 2014; Feldman, Singer, et al., 2010; Gunning et al., 2013; Haley & Stansbury, 2003; Ham & Tronick, 2009b; Provenzi et al., 2015b). Our autonomic data show the physiological correlates of this, indicating that infants from high chaos household

showed a trend towards slower recovery of their arousal level (return to baseline) during the post-still face period. Of note, though, the sample for this last analysis was lower than the other analyses in this paper.

Taken overall, our findings thus reveal a disconnect between the arousal patterns in infants in high chaos households, and their vocalisation behaviours. This disconnect is not seen in infants from low chaos households. Previous research has highlighted the relationship between caregiver-child arousal levels (arousal coupling) as an important mechanism for co-regulation across the dyad (Feldman, 2007b; Smith et al., 2021; Wass et al., 2021). In part, infant arousal levels are communicated by vocalisations to elicit a caregiver response (Ghazanfar & Zhang, 2016; Oller & Griebel, 2020): infants are able to utilise their vocalisations to regulate their arousal levels (and overall arousal level across the child-caregiver dyad). If communication is in effect the sending and receiving of signals, the fundamental starting point must be that the overall outcome is beneficial to both partners (Oller et al., 2013). Our data indicate that in highly chaotic households, senders and receivers are not aligned anymore: infants are not expressing their levels of arousal, and caregiver arousal levels are under-responsive to their infants. Thus, communication is not happening within these dyads, and the interactions are not ‘beneficial’ in a co-regulation sense.

Although technical factors meant that we were confined to random sampling during the day rather than continuous recordings, our analyses examine event-related changes relative to vocalisations, and so the presence of undetected vocalisations can only have weakened the patterns of event-related change that we have observed. Another limitation (and strength) of our approach is that, although we only included data segments recorded while the dyad was at home and the infant was awake, our home-based recordings nevertheless contained all types of vocalisations across a variety of physical settings.

In future it would be interesting to explore the relationship between autonomic arousal, vocalisations, caregiver responsivity, and psychopathology. For example, one factor that may mediate our present findings is caregiver depression, which was positively associated with household chaos in our sample. Previous research has shown that more depressed mothers tend to be under-responsive to their infants' vocalisations and behaviours (Beebe et al., 2008; Field et al., 1990). Household chaos has previously been found to act as a mediator between caregiver depression and child outcomes (Hur et al., 2015). One further explanation for our findings could be the higher levels of stress experienced by adults in high chaos households (Bodrij et al., 2021), and associated lower levels of sensitivity (Andeweg et al., 2020). Yet, we note that there was no association with anxiety in our sample.

Overall, our present results suggested that, in infants from high chaos households, infant vocalisations tend to lose the functional significance that they originally held; and that this is in some way related to caregiver responsiveness; meaning that autonomic regulation following a stressor was slower. But other work from our group has shown that, in a general population, moments of high infant arousal were more likely to be accompanied by infant vocalisations, and by high intensity and negative affect vocalisations, including cries; and that this served as a mechanism for co-regulation across the dyad (Wass et al., 2021).

Understanding how arousal level and vocalisations likelihood relate to caregiver responsivity across typical and atypical development is an important goal for future research. Relatedly, longitudinal studies are needed to examine the association between infant arousal, vocalisations, and caregiver responsivity across development; how, for example, do vocalisations become functionally flexible over time, what is the relationship between functional flexibility and arousal, and how is this affected by caregiver responsiveness and psychopathological symptoms?

In summary, our data suggest that caregiver responsiveness largely shapes infant's communication of their distress, and that this influence may lead to adverse outcomes in high chaos households. In these households, infant vocalisations (in particular negative vocalisations and high intensity vocalisations) are not more likely to occur at times when infant arousal is elevated, and they do not elicit responsiveness in the caregiver. Our findings also suggest that vocalisations are an important driver of co-regulation: when sender-receiver communicative behaviours are finely attuned, which seems to be favoured by a less chaotic environment, vocalisations elicit caregiver responsiveness, aiding recovery in the infant.

References

- Albert, R. R., Schwade, J. A., & Goldstein, M. H. (2018). The social functions of babbling: acoustic and contextual characteristics that facilitate maternal responsiveness. *Developmental Science*, 21(5), e12641.
- Andeweg, S. M., Bodrij, F. F., Prevoo, M. J. L., Rippe, R. C. A., & Alink, L. R. A. (2020). Does sensory-processing sensitivity moderate the effect of household chaos on caregiver sensitivity? An experimental design. *Journal of Family Psychology*.
- Bates, E. (2014). *The emergence of symbols: Cognition and communication in infancy*. Academic Press.
- Beebe, B., Jaffe, J., Buck, K., Chen, H., Cohen, P., Feldstein, S., & Andrews, H. (2008). Six-week postpartum maternal depressive symptoms and 4-month mother–infant self-and interactive contingency. *Infant Mental Health Journal: Official Publication of The World Association for Infant Mental Health*, 29(5), 442–471.
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, 289–300.
- Bobbitt, K. C., & Gershoff, E. T. (2016). Chaotic experiences and low-income children's social-emotional development. *Children and Youth Services Review*, 70, 19–29.
- Bodrij, F. F., Andeweg, S. M., Prevoo, M. J. L., Rippe, R. C. A., & Alink, L. R. A. (2021). The causal effect of household chaos on stress and caregiving: An experimental study. *Comprehensive Psychoneuroendocrinology*, 100090.
- Bronfenbrenner, U. (1977). Toward an experimental ecology of human development. *American Psychologist*, 32(7), 513.
- Coldwell, J., Pike, A., & Dunn, J. (2006). Household chaos—links with parenting and child behaviour. *Journal of Child Psychology and Psychiatry*, 47(11), 1116–1122.

Conradt, E., & Ablow, J. (2010). Infant physiological response to the still-face paradigm:

Contributions of maternal sensitivity and infants' early regulatory behavior. *Infant Behavior and Development*, 33(3), 251–265.

Craig, K. D. (1992). The facial expression of pain Better than a thousand words? *APS*

Journal, 1(3), 153–162.

Deater-Deckard, K., Mullineaux, P. Y., Beekman, C., Petrill, S. A., Schatschneider, C., &

Thompson, L. A. (2009). Conduct problems, IQ, and household chaos: A longitudinal multi-informant study. *Journal of Child Psychology and Psychiatry*, 50(10), 1301–1308.

Deater-Deckard, K., Wang, Z., Chen, N., & Bell, M. A. (2012). Maternal executive function,

harsh parenting, and child conduct problems. *Journal of Child Psychology and Psychiatry*, 53(10), 1084–1091.

Donnellan, E., Bannard, C., McGillion, M. L., Slocombe, K. E., & Matthews, D. (2020).

Infants' intentionally communicative vocalizations elicit responses from caregivers and are the best predictors of the transition to language: A longitudinal investigation of infants' vocalizations, gestures and word production. *Developmental Science*, 23(1), e12843.

Dumas, J. E., Nissley, J., Nordstrom, A., Smith, E. P., Prinz, R. J., & Levine, D. W. (2005).

Home chaos: Sociodemographic, parenting, interactional, and child correlates. *Journal of Clinical Child and Adolescent Psychology*, 34(1), 93–104.

Enlow, M. B., King, L., Schreier, H. M. C., Howard, J. M., Rosenfield, D., Ritz, T., &

Wright, R. J. (2014). Maternal sensitivity and infant autonomic and endocrine stress responses. *Early Human Development*, 90(7), 377–385.

Evans, G. W., & Wachs, T. D. (2010). Chaos and its influence on children's development.

Washington, DC: American Psychological Association.

- Feldman, R. (2007a). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry*, 48(3-4), 329–354.
- Feldman, R. (2007b). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry*, 48(3-4), 329–354.
- Feldman, R., Gordon, I., Schneiderman, I., Weisman, O., & Zagoory-Sharon, O. (2010). Natural variations in maternal and paternal care are associated with systematic changes in oxytocin following parent–infant contact. *Psychoneuroendocrinology*, 35(8), 1133–1141.
- Feldman, R., Singer, M., & Zagoory, O. (2010). Touch attenuates infants’ physiological reactivity to stress. *Developmental Science*, 13(2), 271–278.
- Field, T. M., Healy, B. T., Goldstein, S., & Guthertz, M. (1990). Behavior-state matching and synchrony in mother-infant interactions of nondepressed versus depressed dyads. *Developmental Psychology*, 26(1), 7.
- Geeraerts, S. B., Backer, P. M., & Stifter, C. A. (2020). It takes two: Infants’ moderate negative reactivity and maternal sensitivity predict self-regulation in the preschool years. *Developmental Psychology*, 56(5), 869.
- Geeraerts, S. B., Endendijk, J., Deater-Deckard, K., Huijding, J., Deutz, M. H. F., van den Boomen, C., & Deković, M. (2021). The role of parental self-regulation and household chaos in parent-toddler interactions: A time-series study. *Journal of Family Psychology*, 35(2), 236.
- Ghazanfar, A. A., & Zhang, Y. S. (2016). The autonomic nervous system is the engine for vocal development through social feedback. *Current Opinion in Neurobiology*, 40, 155–160.

- Goldstein, M. H., & Schwade, J. A. (2008). Social feedback to infants' babbling facilitates rapid phonological learning. *Psychological Science, 19*(5), 515–523.
- Goldstein, M. H., Schwade, J. A., & Bornstein, M. H. (2009). The value of vocalizing: Five-month-old infants associate their own noncry vocalizations with responses from caregivers. *Child Development, 80*(3), 636–644.
- Gunning, M., Halligan, S. L., & Murray, L. (2013). Contributions of maternal and infant factors to infant responding to the Still Face paradigm: A longitudinal study. *Infant Behavior and Development, 36*(3), 319–328.
- Haley, D. W., & Stansbury, K. (2003). Infant stress and parent responsiveness: Regulation of physiology and behavior during still-face and reunion. *Child Development, 74*(5), 1534–1546.
- Ham, J., & Tronick, E. (2009a). Relational psychophysiology: Lessons from mother–infant physiology research on dyadically expanded states of consciousness. *Psychotherapy Research, 19*(6), 619–632.
- Ham, J., & Tronick, E. (2009b). Relational psychophysiology: Lessons from mother–infant physiology research on dyadically expanded states of consciousness. *Psychotherapy Research, 19*(6), 619–632.
- Hur, E., Buettner, C. K., & Jeon, L. (2015). Parental depressive symptoms and children's school-readiness: The indirect effect of household chaos. *Journal of Child and Family Studies, 24*(11), 3462–3473.
- Kopp, C. B. (1982). Antecedents of self-regulation: A developmental perspective. *Developmental Psychology, 18*(2), 199.
- Kreibig, S. D. (2010). Autonomic nervous system activity in emotion: A review. *Biological Psychology, 84*(3), 394–421.

- Kroenke, K., Spitzer, R. L., & Williams, J. B. W. (2001). The PHQ-9: validity of a brief depression severity measure. *Journal of General Internal Medicine*, 16(9), 606–613.
- Locke, J. L. (2006). Parental selection of vocal behavior. *Human Nature*, 17(2), 155–168.
- Maris, E. (2012). Statistical testing in electrophysiological studies. *Psychophysiology*, 49(4), 549–565.
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG-and MEG-data. *Journal of Neuroscience Methods*, 164(1), 177–190.
- Marsh, S., Dobson, R., & Maddison, R. (2020). The relationship between household chaos and child, parent, and family outcomes: a systematic scoping review. *BMC Public Health*, 20, 1–27.
- Martin, A., Razza, R. A., & Brooks-Gunn, J. (2011). Specifying the links between household chaos and preschool children's development. *Early Child Development and Care, iFirst Article*, 1–17.
- Matheny Jr., A., Wachs, T. D., Ludwig, J., & Phillips, K. (1995). Bringing order out of chaos: Psychometric characteristics of the Confusion, Hub- bub, and Order Scale. *Journal of Applied Developmental Psychology*, 16, 429–444.
- Matthews, D. (2020). Learning how to communicate in infancy. *Current Perspectives on Child Language Acquisition: How Children Use Their Environment to Learn. Amsterdam, The Netherlands: John Benjamins Publishing Company*, 11–38.
- McFarland, D. H. (2001). *Respiratory markers of conversational interaction*.
- McFarland, D. H., Fortin, A. J., & Polka, L. (2020). Physiological measures of mother–infant interactional synchrony. *Developmental Psychobiology*, 62(1), 50–61.
- McHugh, M. L. (2012). Interrater reliability: the kappa statistic. *Biochemia Medica: Biochemia Medica*, 22(3), 276–282.

- Miller, A. L., Song, J., Sturza, J., Lumeng, J. C., Rosenblum, K., Kaciroti, N., & Vazquez, D. M. (2017). Child cortisol moderates the association between family routines and emotion regulation in low-income children. *Developmental Psychobiology*, 59(1), 99–110.
- Mills-Koonce, W. R., Willoughby, M. T., Garrett-Peters, P., Wagner, N., Vernon-Feagans, L., & Investigators, F. L. P. K. (2016). The interplay among socioeconomic status, household chaos, and parenting in the prediction of child conduct problems and callous–unemotional behaviors. *Development and Psychopathology*, 28(3), 757–771.
- Oakes, L. M., Baumgartner, H. A., Barrett, F. S., Messenger, I. M., & Luck, S. J. (2013). Developmental changes in visual short-term memory in infancy: evidence from eye-tracking. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00697>
- Oller, D. K., Buder, E. H., Ramsdell, H. L., Warlaumont, A. S., Chorna, L., & Bakeman, R. (2013). Functional flexibility of infant vocalization and the emergence of language. *Proceedings of the National Academy of Sciences*, 110(16), 6318–6323.
- Oller, D. K., & Griebel, U. (2020). Functionally flexible signaling and the origin of language. *Frontiers in Psychology*, 11.
- Olson, S. L., & Lunkenheimer, E. S. (2009). *Expanding concepts of self-regulation to social relationships: Transactional processes in the development of early behavioral adjustment*.
- Provenzi, L., Borgatti, R., Menozzi, G., & Montiroso, R. (2015a). A dynamic system analysis of dyadic flexibility and stability across the Face-to-Face Still-Face procedure: application of the State Space Grid. *Infant Behavior and Development*, 38, 1–10.
- Provenzi, L., Borgatti, R., Menozzi, G., & Montiroso, R. (2015b). A dynamic system analysis of dyadic flexibility and stability across the Face-to-Face Still-Face procedure: application of the State Space Grid. *Infant Behavior and Development*, 38, 1–10.

- Schieffelin, B. B. (2016). Looking and talking: the functions of gaze direction in the conversations of a young child and her mother. In *Acquiring conversational competence* (pp. 50–65). Taylor and Francis.
- Shamama-tus-Sabah, S., Gilani, N., & Wachs, T. D. (2011). Relation of home chaos to cognitive performance and behavioral adjustment of Pakistani primary school children. *International Journal of Behavioral Development, 35*(6), 507–516.
- Smith, C. G., Jones, E. J. H., Charman, T., K., Clackson., Mirza, F. U., & Wass., S. v. (2021). Anxious parents show higher physiological synchrony with their infants. *Psychological Medicine*.
- Song, J.-H., Miller, A. L., Leung, C. Y. Y., Lumeng, J. C., & Rosenblum, K. L. (2018). Positive parenting moderates the association between temperament and self-regulation in low-income toddlers. *Journal of Child and Family Studies, 27*(7), 2354–2364.
- Spitzer, R. L., Kroenke, K., Williams, J. B. W., & Löwe, B. (2006). A brief measure for assessing generalized anxiety disorder: the GAD-7. *Archives of Internal Medicine, 166*(10), 1092–1097.
- Tronick, E. (2007). *The neurobehavioral and social-emotional development of infants and children*. WW Norton & Company.
- Vernon-Feagans, L., Willoughby, M., & Garrett-Peters, P. (2016). Predictors of behavioral regulation in kindergarten: Household chaos, parenting, and early executive functions. *Developmental Psychology, 52*(3), 430.
- Wass, S. v, Phillips, E., Smith, C., & Goupil, L. (2021). Vocalisations and the Dynamics of Interpersonal Arousal Coupling in Caregiver-Infant dyads. <https://Psyarxiv.Com/Gmfk7/>.

Wass, S. v, Smith, C. G., Clackson, K., Gibb, C., Eitzenberger, J., & Mirza, F. U. (2019).

Parents mimic and influence their infant's autonomic state through dynamic affective state matching. *Current Biology*, 29(14), 2415-2422. e4.

Weinberg, M. K., & Tronick, E. Z. (1996). Infant affective reactions to the resumption of maternal interaction after the still-face. *Child Development*, 67(3), 905–914.

Wilder, C. N. (1974). Respiratory patterns in infant cry. *Developmental Psychology*, 6, 293–301.

Yoo, H., Bowman, D. A., & Oller, D. K. (2018). The origin of protoconversation: An examination of caregiver responses to cry and speech-like vocalizations. *Frontiers in Psychology*, 9, 1510.

Zeskind, P. S. (2013). Infant crying and the synchrony of arousal. *Evolution of Emotional Communication: From Sounds in Nonhuman Mammals to Speech and Music in Man*, 155–172.

Zhang, Y. S., & Ghazanfar, A. A. (2016). Perinatally influenced autonomic system fluctuations drive infant vocal sequences. *Current Biology*, 26(10), 1249–1260.

Supplementary Materials for:

Needing to shout to be heard? Affective dysregulation, parental under-responsivity, and a disconnection between vocal signalling and autonomic arousal in infants from chaotic households

Table of Contents

1	<i>Supplementary Methods</i>	45
1.1	Experimental participant details	45
1.3	Heart rate data	46
1.4	Heart-Rate Variability (HRV)	49
1.5	Actigraphy	49
1.6	Arousal composite	50
1.7	Removal of autocorrelation from arousal data	51
1.8	Home/Awake coding	52
1.8.1	Home/not home	52
1.8.2	Sleeping/waking	52
1.9	Vocal intensity coding	52
1.10	Permutation-based clustering analyses	52
2	<i>Supplementary Results</i>	54
2.1	Part 2a – repeated with quartile split by household chaos	54
2.2	Part 2b – repeated with quartile split by household chaos	54
2.3	Part 3 – repeated with quartile split by household chaos	55
2.4	Part 3 - Caregiver arousal changes around low- and high-intensity infant vocalisations	55

1 Supplementary Methods

2 Experimental participant details

This sample size was selected prior to the commencement of the study based on power calculations presented, and approved by peer review, in the funding application that supported this work (ESRC ES/N017560/1). Exclusion criteria included: complex medical conditions, skin allergies, heart conditions, parents below 18 years of age, and parents receiving care from a mental health organisation or professional. Full demographic details of the participants are given below.

		Whole sample	Low CHAOS	High CHAOS
Infant age (days) – mean		354.5	353.7	355.3
	- <i>SE</i>	4.6	6.8	7.8
Gender (% male)		39.3	37.8	43.2
Infant Ethnicity (%)	White British	50.0	48.6	51.4
	Other white	10.5	8.1	13.5
	Afro-Caribbean	9.2	13.5	5.4
	Asian, Indian & Pakistani	10.5	13.5	8.1
	Mixed - White/Afro-Carib	2.6	2.7	2.7
	Mixed - White/Asian	7.9	8.1	8.1
	Other mixed	9.2	5.4	10.8
Household Income (%)	Under £16k	30.3	37.8	24.3
	£16-£25k	27.6	27.0	27.0
	£26-£35k	11.8	10.8	13.5
	£36-£50k	11.8	13.5	10.8
	£51-£80k	10.5	2.7	16.2
	>£80k	7.9	8.1	8.1
Maternal education (%)	Postgraduate	32.9	43.2	21.6
	Undergraduate	50.0	40.5	59.5
	FE qualification	2.6	5.4	0
	A-level	3.9	2.7	5.4
	GCSE	5.3	8.1	2.7
	No formal qualifications	2.6	0	5.4

	Other	1.3	0	2.7
--	-------	-----	---	-----

Table S1: Demographic details for: a) the whole sample; b) and c) – data subdivided into low/high CHAOS groups using a median split, as described in the main text.

1.2 CHAOS questionnaire results

Figure S1: Histogram of CHAOS questionnaire results

2.3 Heart rate data

ECG was recorded at 250Hz. To ensure good quality recordings, the ECG device was attached using standard Ag-Cl electrodes, placed in a modified lead II position. Due to technical problems with the ECG recording leads (N=9) and to problems with attaching the ECG recording electrodes securely (N=2), the ECG data were unavailable for 11 of the 93 participants originally tested.

To ensure the accuracy of these recording devices, they were cross-validated by recording heart rate and heart rate variability using both the new devices at home and established recording devices (a Biopac MP150 amp recording at 2000Hz) in lab settings. High reliability was observed both for heart rate ($\rho=.57$, $p<.001$) and heart rate variability ($\rho=.70$, $p=.01$).

Analysis of the Inter-Beat Intervals (IBIs) was performed using custom-built Matlab scripts. These scripts were designed through an extensive piloting process to be optimal for the ECG device used for this study. First, data were parsed using a simple amplitude threshold (see e.g. (Aurobinda, Mohanty, & Mohanty, 2016) for a similar approach), with R peaks identified as moments where the raw ECG signal exceeded the threshold value. Initially, the threshold value was set high; the same process was then repeated at incrementally decreasing thresholds.

At each threshold value, the R peaks identified were automatically subjected to the following checks. These threshold values were set following extensive piloting and visual inspection of our infant ECG data using the visualisation shown in Figure S2. i) minimum temporal threshold: does the R peak occur at a time interval of greater than 300 msecs since the previous R peak (corresponding to a heart rate of 200 BPM); ii) maximum temporal threshold: does the

R peak occur at a time interval of less than 850 msec since the previous R peak (corresponding to a heart rate of 70 BPM); iii) maximum rate of change: when we calculate the R to R interval between this peak and the subsequent peak, and compare it with the R to R interval between this peak and the previous peak, is this difference less than 300msec? In setting these threshold values, careful attention was paid to visual inspection to determine the maximum and minimum 'genuine' heart rates observed in our infant data; in setting the maximum rate of change criterion, careful attention was paid to identify the maximum rate of vagally mediated heart rate changes in infants.

Figure S2 shows a sample screenshot from the Matlab processing algorithm that was used. Two separate types of artefact are shown. The first, highlighted by the call-out figures at a and d, are instances where the ECG signal for a particular beat was lower than the threshold, and a genuine beat was missed. It can be seen that in both instances, the R peaks either side of this missing beat have been automatically identified, and excluded. These artifacts were identified based on the maximum temporal threshold criterion in example a and d, and additionally based on the maximum rate of change criterion in example d. The second, highlighted by the call-out figures at b and c, are instances where the ECG signal exceeded the amplitude threshold, and an incorrect R peak was identified. In both instances, the incorrect beat has been identified based on the minimum temporal threshold criterion, and the R peaks either side of this incorrect beat have been identified and excluded. Please note also that the sample below has been selected in order to demonstrate how the program identified the most common artefacts in the data. Overall, the occurrence of both types of artefact in our data is relatively rare, as is shown in Figure S3, below.

These three criteria were applied separately to data after it had been parsed at each threshold value. Following this, at each threshold value, the proportion of candidate R peaks that were rejected was compared with the proportion of candidate R peaks that passed all three criteria. The threshold value with the lowest proportion of rejected candidate R peaks was chosen as the threshold used for that participant.

In addition, and as a further check, a trained coder who was naïve to study hypotheses double coded a randomly selected subsample of 1000 beats for 20% of the participants, coding them as genuine or artefactual. Cohen's kappa was calculated to measure inter-rater reliability between the manual coding and the automatic coding, based on the best-fitting threshold level. This was found to be 0.97, which is high (McHugh, 2012).

Figure S2: Sample screenshot from ECG parsing algorithm. 60 seconds' data is shown. From top to bottom: i) raw ECG signal. Coloured dots show the results of the three checks described in the main text, below (see legend); ii) smoothed second derivative of ECG signal. This measure was not used as our pilot analyses found it to be less effective than applying the

processing to the raw signal; iii) raw (unprocessed) actigraph data. This information was only used for visual inspection, and was not used in parsing; iv) RR intervals (in BPM), with rejected data segments excluded.

Figure S2 below shows a histogram of the proportion of candidate R peaks rejected for each participant, based on the best-fitting threshold value. The median (st. err.) is 1.07 (0.36) % data rejected. This relatively low figure was achieved through very close attention during the piloting phase to the selection and placement of the ECG electrodes, to the design of the device, and the gain settings on the recording device.

Figure S3: Histogram showing the proportion of rejected R peaks (as identified using the three criteria described above).

1.4 Heart-Rate Variability (HRV)

HRV was calculated using the PhysioNet Cardiovascular Signal Toolbox (Vest et al., 2018). In these scripts, which performed a completely separate analysis of the ECG data, a 60-second window with an increment of 60 seconds was implemented, and the default settings were used with the exception that the min/max inter-beat interval was set at 300/750 ms for the infant data and 300/1300 ms for the adult data. The Root Mean Square of Successive Differences (RMSSD) measure was taken to index Heart Rate Variability, but other frequency domain measures were additionally inspected and showed highly similar results, as expected (Vest et al., 2018).

1.5 Actigraphy

Actigraphy was recorded at 30Hz. To parse the actigraphy data we first manually inspected the data, then corrected artifacts specific to the recording device used, then applied a Butterworth

low-pass filter with a cut-off of 0.1 Hz to remove high-frequency noise, and then averaged from three dimensions into one. Actigraphy data were available for all participants tested.

2.6 Arousal composite

Previous research has shown significant patterns of tonic and phasic covariation between different autonomic measures collected from infants (Wass, Clackson, & de Barbaro, 2016; Wass, de Barbaro, & Clackson, 2015). Here, we include plots showing that the present dataset replicated and extended these results. The plots only show the sections of the data when participants were at home, comparing sections in which the infants were awake and asleep. Figure S2a shows cross-correlation plots examining the relationship between heart rate and movement. In both waking and sleeping sections the zero-lag correlation is 0.5. Figure S2c shows how these zero-lagged correlations vary on a per-participant basis. S2b shows an illustrative sample from a single participant. Sleeping sections show very low movement levels and lower heart rate. Of note, heart rate and movement do still inter-relate during the sleeping sections of the data (Figure S2c), albeit that the variability in heart rate and movement is lower. Figure S2 d)-f) show similar relationships between heart rate and heart rate variability, illustrating the strong and consistent negative relationships that were observed between these variables, as predicted.

Figure S4: Illustrating the relationship between the individual physiological measures included in the composite measure. a) Cross-correlation of the relationship between HR and Movement. b) Scatterplot from a sample participant. Each datapoint represents an individual 60-second epoch of data. c) Histograms showing the average zero-lagged correlation between 60-second epochs, calculated on a per-participant basis and then averaged. d)-f) Equivalent plots for Heart rate and Heart rate variability.

Extensive previous research has identified fractionation, and differentiation, within our autonomic response systems (Janig & Habler, 2000; Kreibig, 2010; Lacey, 1967; Levenson, 2014; Quas et al., 2014) – suggesting, for example that the sympathetic and parasympathetic subdivisions operate, to an extent, in a non-additive manner (Samuels & Szabadi, 2008). Although indubitable, these findings should be seen as rendering incorrect our treatment here of autonomic arousal as a one-dimensional construct. Like many other arguments concerned with general versus specific factors, the question is rather one of the relative proportions of variance that can be accounted for by a single common factor in comparison with the variance accounted for by the sum of specific factors (Graham & Jackson, 1970) (see also (Calderon, Kilinc, Maritan, Banavar, & Pfaff, 2016)).

As a result of these considerations, the three autonomic measures were collapsed into a single composite measure for Analysis 1. To do this, the actigraphy data was first subjected to a log transform (Thomas & Burr, 2008), to correct the raw results, which showed a strong positive skew (Wass et al., 2016; Wass et al., 2015) (see also SM section 1.6, below). Second, all three variables were converted to z-scores. Third, the HRV data were inverted because of the overall negative relationships noted between HRV and the other two measures (see Figure S4). Fourth, the three z-scores were averaged.

On the occasions where heart rate data were excluded due to artifact, data from actigraphy alone was used for the composite variable. Note that these occasions were relatively rare (accounting for a median $\sim 1\%$ of all data - see Figure S3), and that the zero-lag cross-correlation between movement and heart rate across all available data was high ($\sim .5$ – see Figure S4).

1.7 Removal of autocorrelation from arousal data

Autonomic arousal data are known to show autocorrelation (Wass et al., 2016). In order to preclude the possibility that differences in the autocorrelation may have influenced results, the autocorrelation was removed from the data prior to performing all calculations, using the following procedure. First, best-fit bivariate polynomials were calculated for the two time series independently, in order to remove linear and quadratic trends, and the residuals obtained were subjected to the Dickey-Fuller test to check that they showed stationarity, which they did. The residuals were used in subsequent analyses. Next, in order to remove the autocorrelation component from each time series independently, univariate autoregressive models were fitted to each time series, and the residuals were calculated (see e.g. Feldman, Greenbaum, & Yirmiya, 1999; Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011; Jaffe et al., 2001; Suveg et al., 2016 for similar approaches). The residual values (shown in Figure 1) were converted into z-scored values. These z-scored values were then used for all analyses. The only exception to this is the analyses specifically examining changes in autocorrelation relative to vocalisations, for which the raw uncorrected data were used.

2.8 Home/Awake coding

1.8.1 Home/not home

Coding of when participants were at home was performed using the GPS monitors built into the recording devices. The position of the participant's home was calculated based on the postcode data that they supplied, and any GPS samples within a 50m area of that location were treated as Home (corresponding to the accuracy of the GPS devices that we were using).

1.8.2 Sleeping/waking

To identify samples in which infants were sleeping, parents were asked to fill in a logbook identifying the times of infants' naps during the day. This information was manually verified by visually examining the actigraphy and ECG data collected, on a participant by participant basis. Actigraphy, in particular, shows marked differences between sleeping and waking samples (see Figure 1 in main text), which allowed us to verify the parental reports with a high degree of accuracy. N=4 of the participants recorded did not sleep during the day that we were recording.

2.9 Vocal intensity coding

The same analysis as described for the vocal affect coding in the manuscript was conducted to code intensity on a scale from 1 (least intense) to 9 (most intense), and the same criteria were used to collapse these into low intensity/neutral/high intensity. In order to assess inter-rater reliability, 24% of the sample was double coded; Cohen's kappa was 0.60, which is considered acceptable (McHugh, 2012). All coders were blind to intended analyses.

3 Permutation-based clustering analyses

To estimate the significance of the time-series relationships in the results, a permutation-based temporal clustering approach was used. This method examines temporally contiguous patterns of change in instances where the centre-point of the expected response window is unknown, or unimportant (Maris & Oostenveld, 2007). In each case, the test statistic (always specified in the text) was calculated independently for each time window. Series of significant effects across contiguous time windows were identified using an alpha level of .05. 1000 random datasets were then generated with the same dimensions as the original input data. To ensure that the same level of autocorrelation was present in the simulated data as in the original datasets, multivariate autoregressive models were fitted to each sample included in the original dataset using the Matlab function `ARfit.m` (Neumaier & Schneider, 2001), and the matching AR parameters were used to generate each of the random datasets using the Matlab function `ARsim.m` (Neumaier & Schneider, 2001). Then, the same sequence of analyses was repeated, and the longest series of significant effects across contiguous time windows was identified. The results obtained from the random datasets were used to generate a histogram, and the likelihood of observed results have been obtained by chance was calculated by comparing the observed values with the randomly generated values using a standard bootstrapping procedure.

Thus, a p value of $<.01$ indicates that an equivalent pattern of temporally contiguous group differences was observed in 10 or fewer of the 1000 simulated datasets created.

4 Supplementary Results

2.1 Part 2a – repeated with quartile split by household chaos

Figure S5: Identical to Figure 3, but based on a quartile split by household chaos.

2.2 Part 2b – repeated with quartile split by household chaos

Figure S6: Identical to Figure 4, but based on a quartile split by household chaos.

2.3 Part 3 – repeated with quartile split by household chaos

Figure S7: Identical to Figure 6, but based on a quartile split by household chaos.

2.4 Part 3 - Caregiver arousal changes around low- and high-intensity infant vocalisations

Figure S8: Identical to Figure 6 but examining caregiver arousal changes to infant vocalisations subdivided by vocal intensity. a) and b) show results broken down using a median split by household chaos. c) and d) show the same analysis, but subdivided using a quartile split by household chaos.