

UPREGULATE TO DOWNREGULATE

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Parents mimic and influence their infant's autonomic state through dynamic affective state matching

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Summary

When we see someone experiencing an emotion, and when we experience it ourselves, common neurophysiological activity occurs [1, 2]. But although inter-dyadic synchrony, concurrent and sequential [3], has been identified, its functional significance remains inadequately understood. Specifically, how do influences of partner A on partner B reciprocally influence partner A? For example, if I am experiencing an affective state and someone matches their physiological state to mine, what influence does this have on me – the person experiencing the emotion? Here, we investigated this using infant-parent dyads. We developed miniaturised microphones to record spontaneous vocalisations and wireless autonomic monitors to record heart rate, heart rate variability and movement in infants and parents concurrently in naturalistic settings. Overall, we found that infant-parent autonomic activity did not covary across the day – but that ‘high points’ of infant arousal led to autonomic changes in the parent, and that instances where the adult showed greater autonomic responsivity were associated with faster infant quieting. Parental responsivity was higher following peaks in infant negative affect than in positive affect. Overall, parents responded to increases in their child’s arousal by increasing their own. However, when the overall arousal level of the dyad was high, parents responded to elevated child arousal by decreasing their own arousal. Our findings suggest that autonomic state matching has a direct effect on the person experiencing the affective state, and that parental co-regulation may involve both connecting, and disconnecting, their own arousal state from that of the child contingent on context.

Keywords: infant, parenting, emotion regulation, affect matching

Results

Since John Donne asserted that ‘No man [or woman] is an Iland, intire of itselfe’ [4], many researchers have followed him in operationalising affective states not as private mental concepts, but rather as properties that ‘resonate’ [5] in ‘interpersonal’ space [6-9]. Certainly, we know that common patterns of neurophysiological activity occur when we observe someone else experiencing emotional states such as disgust or pain, and when we experience them ourselves e.g. [1, 2]. But we understand little about how these time-lagged inter-personal influences, sometimes characterised formally as ‘sender-receiver’ relationships [10], influence functions such as emotion regulation, which are usually considered from an endogenous perspective [3, 5, 8, 11, 12].

To address this question, we developed miniaturised microphones, electrocardiograms, and actigraphs to record vocalisations and track both infants’ and parents’ autonomic changes across the day, in home settings (see Figure 1a-1b). We examined how adult and infant arousal levels co-fluctuate during the day (concurrent synchrony [3]), and whether changes in the infant’s arousal forward-predict changes in the parent’s, and *vice versa* (sequential synchrony [13]). We examined whether these bidirectional parent-child influences were present across all data analysed (analysis 2), or limited to moments of peak arousal in the infant (analysis 3); and whether they were stronger during negative, or positive, infant affect (analysis 3 and 4). We also examined whether parental responsivity to a ‘peak’ arousal event predicted infants’ subsequent recovery (analysis 5). Finally, we examined how parents’ responsiveness to arousal changes in their child varied contingent on the parent’s initial level of arousal (analysis 6).

INSERT FIGURE 1 HERE

Descriptive analyses – analysis 1. Figures 2a-2c show descriptive plots of our data.

INSERT FIGURE 2 HERE

Concurrent synchrony in parent-infant arousal – analysis 2. We conducted a cross-correlation analysis [13-15] to examine whether, across all samples, there is an association between the parent's arousal level and the infant's. This analysis (see Figure S2) identified only a weak, non-significant ($p=.15$) association between parents' arousal levels and their infant's. This suggests that autonomic activity between infants and parents does not covary across the day.

This finding leaves open the possibility that associations between a parent's and infant's arousal levels are present at certain times (e.g. when the infant's arousal levels are high), but not at others (e.g. when the infant's arousal is low). To examine this possibility, we examined parental reactivity to infant arousal 'peaks'.

Parental reactivity to infant arousal 'peaks' – analysis 3. Two criteria were used to identify moments of 'peak' infant arousal. The first (criterion 1) was to identify moments in which the infant's arousal exceeded a threshold, defined as the 95th centile for all samples recorded for that infant (Figure 3a); the second (criterion 2) was to identify moments of peak negative and positive affect in the infant's vocalisations (Figure 3b, 3c). The segments marked in red indicate the areas of significant ($p<.05$) event-related change. Overall, our results suggest that increases in adult arousal are observed relative to peak arousal moments in the infant, as well as relative to moments of peak negative and (to a lesser extent) peak positive affect in the infant.

INSERT FIGURE 3 HERE

Concurrent synchrony between parent and infant arousal – moving window – analysis 4.

Analysis 2 suggests that infant-parent autonomic activity does not co-fluctuate across the day. This leaves open the possibility, however, that there are certain times within the day when autonomic activity *does* co-fluctuate between infant and parent. To examine this, we repeated the analysis shown in analysis 2, but examining the co-fluctuation of infant-parent arousal across smaller segments of data, using a moving window analysis. A high cross-correlation value (Spearman's rho) indicates that, at times within that moving window when the adult's arousal is high, the infant's arousal is also high.

Results suggested that a short-term increase in infant-parent arousal correlation was observed relative to negative, but not positive, affect infant vocalisations (Figure 3d) (permutation $p < .001$). This is not an artefact of the increases in adult arousal documented previously (Figures 3a-3c) as a separate analysis (see Figure S5) indicated no relationship between adult arousal and parent-infant arousal cross-correlation ($\rho < .01$). This suggests that concurrent parent-infant arousal synchrony shows short-term increases relative to negative, but not positive, affect infant vocalisations.

Parent responsiveness predicting infant recovery – analysis 5.

We also examined whether instances in which the adult showed greater responsiveness were associated with faster infant recovery (see Figure 3e-g). To do this, we identified moments of peak ($>95^{\text{th}}$ centile) arousal from the infant, and recorded the change in adult's arousal response relative to that event (see Figure 3e). We then assessed whether a greater adult arousal response was associated with

lower subsequent infant arousal during the period after the event. Overall, results indicated that greater adult arousal responses relative to the event were associated with lower subsequent infant arousal (see Figure 3g).

Parental responsiveness – influence of parent’s initial level of arousal – analysis 6. Analyses 2-5 examined parents’ average responses to changes in their infant. These results suggested that, on average, parents respond to increases in their child’s arousal by increasing their own arousal. In addition, however, we also wished to examine how parents’ responsiveness to their child varied contingent on the parent’s initial level of arousal. To estimate this, we calculated a Vector plot (see Figure 4 and Methods).

INSERT FIGURE 4 HERE

Two patterns are evident. The first (which is seen by examining the vertical displacement of the vectors, comparing the bottom left and the bottom right of the vector plot) is that when the adult’s initial arousal level is low, their arousal *increases* more in instances where the infant’s arousal is high, than when it is low (Figures 4a, 4b). This suggests that, when their own arousal is low, parents up-regulate their arousal in response to elevated arousal in the infant. Figure 4c shows that no significant relationships were observed in the opposite direction, when we examined the systematic relationship between adult arousal and change in infant arousal across the entire dataset. The control analysis suggested that similar patterns were not observed in data that had been shuffled and re-paired across dyads (see Figure S3).

The second pattern (which is seen by comparing the top left and the top right of the vector plot) is that when the adult’s initial arousal level is high, their arousal *decreases* more in instances

where the infant's arousal is high, than when it is low (Figure 4a, 4b). In other words, when their own arousal is high, parents *down*-regulate their own arousal in response to increases in the infant. Again, Figure 4c shows that no significant relationships were observed in the opposite direction, considering how the adult's arousal influences the change in infant's arousal across the entire dataset, and the control analysis indicated that no relationships were present across shuffled and re-paired datasets (Figure S3).

Overall, these results suggest that how adults respond to increases in infant arousal varies contingent on their own starting level of arousal. When their arousal is initially low, they respond to increases in infant arousal by increasing their own arousal; however, when their arousal is initially high, they respond in the opposite way – by decreasing their own arousal in response to arousal increases in the infant.

Discussion

Infant-parent dyads operate as single, affective regulatory units [8]; with development comes a transition from co-regulation to self-regulation [3, 16, 17]. Within the dyad, allostatic mechanisms are bi-directional. Influences of the parent on the child have been demonstrated both directly, through mechanisms such as touch [18-20], and indirectly, through verbal mechanisms including parental teaching [21] and the parental modelling of positive affect [22]. Influences of the child on the parent have been demonstrated in Granger-causal analyses examining how children's and parents' facial affect and physiology change in response to stressors [8] and during tabletop play [23], as well as by measuring parents' autonomic and neural responses to recordings of infants' crying [24, 25].

Over the short term, child->parent influences are important insofar as they elicit responsive caregiving reactions from the parent [26]. But do they have a functional significance beyond that? To investigate this, we examined how infant-parent arousal co-fluctuates across all types of naturalistic settings, including neutral, positive and negative affect. We examined how spontaneous increases in infants' arousal relate to increases in parents' arousal, and assessed whether real-world instances in which the parent shows greater reactive changes in response to the infant associate with subsequently lower arousal in the infant.

Cross-correlation plots (see Figure S2) suggest that, across all data, no association was observed between parent and infant arousal (Analysis 2). Interpretation of this finding is limited by the fact that we have not differentiated degrees of proximity within our naturalistic sample – from holding the infant to being in separate rooms - although only samples recorded while the dyad was at home and the baby was awake were included. Consistent with this, the vector

plot (Analysis 5) indicates no relationship between infant arousal and change in adult arousal across intermediate levels of arousal. To our knowledge, previous research into arousal and affect contagion using lab-based experimental paradigms has not documented this point [27] [28].

Our results do, however, suggest that adults show autonomic responsivity to moments of peak arousal in the infant (Analysis 3, 4). Peak negative and, to a lesser extent, positive affect vocalisations were also both associated with increases in adult arousal (Figure 3b, 3c). Our analyses also suggest that infant vocalisations lead to immediate increases in concurrent parent-infant arousal synchrony – although this only occurred following negative, and not positive, affect vocalisations (Figure 3d) (compare [8]). Finally, when we examined these naturally occurring ‘peak’ arousal instances (Analysis 5), we found that greater reactive changes in adult arousal were associated with lower subsequent infant arousal (Figure 3e-g).

When all data were averaged together, we found that parents responded to increases in their child’s arousal by increasing their own. However, when we subdivided our results according to the adult’s starting level of arousal (Analysis 6), we also found that parents’ responses to elevated arousal in the infant vary depending on their own arousal level. Where adult’s arousal is initially low, they respond to increases in infant arousal with increases in their own arousal - consistent with the pattern noted overall (Figure 3). However, where the adult’s arousal is initially high, the opposite pattern is noted: parents *downregulate* their own arousal in response to increases in infant arousal (Figure 3a, 3b). The same pattern was not noted in a control analysis in which adults’ and infants’ arousal datasets were randomly shuffled and re-paired (Figure S3), suggesting that this is not a statistical artefact of the data. This suggests that, in

response to increases in infant arousal, parents adaptively increase *or* decrease their own arousal, contingent on context [29].

Our findings build on the literature into how infants influence their parents during early social interactions [30]. Our finding that increases in parental arousal were observed following both negative and positive arousal peaks in the child is important (Fig 3c) insofar as it suggests that these mechanisms are not just specific responses to distress [24-26], but rather contingent parental responses to ‘peak’ arousal moments in the child. One effect of this may be to match the arousal state of the parent more closely to that of the child. Thus our findings may be consistent with previous research suggesting that, when we see someone else experiencing an emotion and when we experience it ourselves, common patterns of neurophysiological activity occur [1, 2].

Our findings here may parallel other recent findings into the importance of child->parent influences in other domains, such as attention and learning. For example, recent research examining the co-fluctuation of neural activity during shared parent-infant play has suggested, similar to the present findings, that adults show fine-grained changes in neural activity time-locked to their infants’ attention [31]. Similarly, behavioural micro-analyses have shown that specific forms of contingent behaviours in infant-parent social interactions – such as mirroring, and marking with a smile – predict the increase of these behaviours over time [32-34].

However, our findings also suggest that parental responsivity does not *always* involve matching the parent’s arousal state to the infant. Analysis 6 suggests that, when adults’ arousal is high, the opposite pattern occurs: parents respond to elevated child arousal by *decreasing* their own arousal (Figure 3a, 3b). The finding echoes the concept of ‘stress buffering’ – where

one individual moderates the stress level of another, while partners are experiencing different physiology [29]. It points, potentially, to the idea that adults may employ diverse tactics in order to maintain allostasis within the dyad [35] – dynamically increasing, or decreasing, their own level of arousal contingent on the total arousal levels of the dyad [36].

Thus, while building on our understanding of the importance of parents' contingent responsiveness to their child, our results also indicate a move beyond a simple model that 'more synchrony is better' (see also [37]). Our findings suggest that infant-parent arousal does not routinely co-fluctuate during the day, and that parental responsivity is limited to instances of 'peak' arousal in the child, encompassing both positive and negative affect. They also suggest that, contingent on context, and in order to maintain allostasis, parental responses can include both connecting, and disconnecting, their own arousal state from their infant's.

Future research can build on these findings in a number of ways. First, by exploring psychopathology. For example, recent research examining the naturalistic co-fluctuation of arousal in dyads where the parent has lower, or higher anxiety suggest that more anxious parent-child dyads show *greater* co-fluctuation in arousal across the day [38]. Parental responsivity to 'peak' infant arousal events was equivalent between dyads with high and low parental anxiety; but more anxious parents showed greater responsivity to small-scale arousal fluctuations in the child. Other research has suggested that abusive parents and adults at risk for physical abuse can respond with excessive physiological arousal to recordings of infants crying [39] - suggesting that some parents show *excessive* reactivity (see [40]). In future, it may be useful to examine whether the linear relationships documented in Figure 3g in fact show quadratic tendencies, such that both parental over- and under-reactivity is associated with slower infant recovery.

Second, our approach is also limited by the one-dimensional approach we have taken to studying arousal (see SM section 1.1). Future work may show discrete patterns of interpersonal influence between parasympathetic and sympathetic subsystems [41, 42].

Third, longitudinal studies would allow us to examine how the short-term influences that we have documented here relate to the infant's emotion regulation over longer time-frames [3, 11, 43, 44] - building on previous research that early infant-parent interactional styles can significantly predict longer-term attachment [37] and self-control [43] outcomes.

Fourth, future research could examine how interventions such as clinician-mediated parental sensitivity training (e.g. [45]) lead to changes in intra-dyadic autonomic influences. This would allow us to test causal mechanisms in more depth than the time-series correlations we tested here.

Figures

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