Annual Research Review. 'There, the dance is - at the still point of the turning world': dynamic systems perspectives on co-regulation and dysregulation during early development

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Abstract

During development we transition from co-regulation (where regulatory processes are shared between child and caregiver) to self-regulation. Most early co-regulatory interactions aim to manage fluctuations in the infant's arousal and alertness; but over time, co-regulatory processes become progressively elaborated to encompass other functions such as socio-communicative development, attention and executive control. The fundamental aim of co-regulation is to help maintain an optimal 'critical state' between hypo- and hyper-activity. Here, we present a dynamic framework for understanding child-caregiver co-regulatory interactions in the context of psychopathology. Early co-regulatory processes involve both passive entrainment, through which a child's state entrains to the caregiver's, and active contingent responsiveness, through which the caregiver changes their behaviour in response to behaviours from the child. Similar principles, of interactive but asymmetric contingency, drive joint attention and the maintenance of epistemic states as well as arousal/alertness, emotion regulation, and socio-communicative development. We describe three ways in which active child-caregiver regulation can develop atypically, in conditions such as Autism, ADHD, anxiety and depression. The most well-known of these is insufficient contingent responsiveness, leading to reduced synchrony, which has been shown across a range of modalities in different disorders, and which is the target of most current interventions. We also present evidence that excessive contingent responsiveness and excessive synchrony can develop in some circumstances. And we show that positive feedback interactions can develop, which are contingent but mutually amplificatory child-caregiver interactions that drive the child further *from their critical state. We discuss implications of these findings for future intervention research, and directions for future work.*

Keywords: co-regulation; self-regulation; emotion regulation; socio-communicative development; attention; ASD; ADHD; anxiety; depression

Why study interactions?

> "There is no such as thing as a baby [...] you are describing a baby and someone"
>
> (Winnicott, 1957), p.137)

> "At the still point of the turning world. Neither flesh nor fleshless;
> Neither from nor towards; at the still point, there the dance is,
> But neither arrest nor movement. And do not call it fixity,
> Where past and future are gathered. Neither movement from nor towards,
> Neither ascent nor decline. Except for the point, the still point,
> There would be no dance, and there is only the dance."
>
> (Eliot, 1922)

A new life emerges, literally, from the flesh of their parent. Winnicott's assertion that 'there is no such thing as a baby' considered on their own is, when we consider is the very early stages of life, self-evident. During prenatal development, the foetus is entirely dependent on their parent; throughout the first few months and years of postnatal development, we spend all of our waking hours in the company of an adult caregiver, and rely on them for everything. Over the first few years of life, we transition from inter-dependence to self-dependence; but the transition is a gradual one.

In most cases, young infants and their caregivers work jointly together to manage the basic regulatory functions that are essential for their survival. Like all regulatory functions, these are defined by temporal inter-dependencies: how the system changes between $time_x$ and $time_{x+t}$ is contingent on the state of the system at $time_x$ (Bergson, 2007; Cole et al., 2020; E. Lunkenheimer et al., 2020). But the crucial point of difference for coregulation is that it is also relational in essence: the change in partner 1 is contingent not just on the previous state of partner 1, but also on the state of partner 2 (Bales et al., 2023; Fogel, 1993; Schneirla, 1946). In this way, co-regulation is like a dance – or a series of intricate, interleaved dances across different levels and different systems, each essential for keeping us alive. (Feldman, 2007; Kopp, 1982; Munakata et al., 2012; Nigg, 2017; E. Tronick, 1982; X. Zhang et al., 2022). This dance for life is defined by movement "[n]either from not towards" that is "neither arrest nor movement". It is through both partners continually moving and responding to one another that we achieve stability – at "the still point of the turning world" (Eliot, 1922).

During early life, caregiver-infant co-regulation primarily exists to help manage fluctuations in infants' Central Nervous System (CNS) arousal across low-level functions such as sleep/wake cycles, feeding cycles, and so on. Over time, it progressively becomes elaborated through hierarchical, vertically integrative processes to include firstly emotional and socio-communicative functions, almost all of which develop through early child-caregiver interactions; and, later on, cognitive, epistemic and metacognitive states as well (Fogel, 1993; Geva & Feldman, 2008; Le et al., 2021; L. Smith & Gasser, 2005; X. Zhang et al., 2022).

Understanding these processes is practically important - for example, for understanding how to calm down a child when they are upset. When a child is upset, you take action to soothe them. Shouting at a crying child will generally make them cry for longer; but sitting completely still as you calm them is less effective than standing up yourself, picking up the child and walking around the room as you soothe them (Esposito et al., 2013; Ohmura et al., 2022). From this, we can tell that simply staying calm yourself is not the best way to help a child calm down.

Understanding how caregiver and child arousal states influence one another dynamically is practically crucial for soothing a distressed child.

Understanding the complexity of dyadic interactions is equally important when we consider the development of higher-order functions such as attention and learning. In contrast to traditional approaches which view learning as a process of static information transmission from an adult teacher to a child learner, more recent approaches suggest that social attention and learning also take place as a dance, with both partners continually and dynamically adapting and responding to one another (Begus & Southgate, 2018; Feldman, 2007; Masek et al., 2021; Yu & Smith, 2016). But how exactly do my behaviours affect my child? For example, if I am more or less energetic in the dance, then does this affect my child's ability to pay attention and control their behaviour when they are on their own during later development? And, if so, how?

In this paper we consider these questions, and we lay out a dynamic systems framework that aims to understand co-regulatory influences during development across multiple timescales and different levels of hierarchical integration.

First, we discuss the methods that have been used to study these processes. We describe how recent developments have allowed us to expand the time-scales over which we study development. This includes both fine-grained (e.g. dual EEG recordings at the millisecond level) and coarse-grained time-scales (e.g. recordings using home wearables over days, weeks and months). New methods drive new theories (Dale et al., 2023), and these new measurement techniques have opened important new perspectives on how co-regulatory influences develop over time.

Next, in part 2, we lay out our theoretical framework for how coregulatory dynamics influence early development, concentrating on the 0-4 years age range. First (part 2a) we describe how the end-point of regulation is to maintain an optimal 'critical' state between over-excitation and under-excitation. We describe how fine-grained analyses show that two interacting partners are constantly moving, and mutually adapting to one another, around this 'critical' state.

Then, we describe two different types of interpersonal influence that operate across child-caregiver dyads – regulatory processes (which move the dyad towards the critical state) (part 2b) and dysregulatory processes (which move them away from the critical state) (2c).

Both regulation and dysregulation take place through two types of mechanism. The first are passive or automatic processes, through which the simple presence of one partner in a particular state shifts the other partner into the same state. For example, a caregiver's stable arousal patterns might help a child to maintain stable arousal (a passive regulatory process); or their dysregulated daily rhythms might disrupt a developing child's sleep-wake cycles (a passive dysregulatory process).

The second type of mechanism is active or effortful processes, through which changes in one partner induce compensatory changes in the other partner. For example, a caregiver might pick up an upset child and soothe them (an active regulatory processes); or they might shout at their child to stop crying (an active dysregulatory process). Borrowing concepts from dynamic systems theory, we shall describe a multi-stable system, in which both regulatory and dysregulatory dynamics can become stable, persistent states over both short- and long- time-frames.

In part 3, we describe evidence that these two concepts, of regulation and dysregulation that can both operate through active/passive processes, can influence development across multiple hierarchical domains. First, we consider arousal within the central nervous system (part 3a). Second, we consider affective states and communicative signalling (part 3b). Third, we consider attention, executive control and metacognitive awareness (part 3c).

In part 4, we describe four ways in which co-regulatory processes can develop atypically. First, we consider passive processes (part 4a). Second, we examine two ways in which active negative feedback processes can be atypical – first, under-responsiveness (part 4b), then over-responsiveness (part 4c). Finally, we consider evidence for how positive feedback can give rise to dysregulatory processes during early caregiver child interactions (part 4d).

Finally, in part 5, we consider the implications of this framework for intervention research (part 5a), outline goals for future research (part 5b), and summarise (part 5c).

Part 1 - methods - how do we study child-caregiver interaction dynamics?

Using new methods to study development often opens up new thinking and theories for understanding development (Dale et al., 2023). Early research into child-caregiver interactions was mainly based on real-world observations of children and caregivers in different contexts (Bowlby, 2008). In more recent years, a common approach has been to video-tape short caregiver-child interactions, often in the lab, and codify them afterwards. Behavioural codings can be based either on global ratings, which measure for instance how sensitive or reciprocal a caregiver was (Feldman, 1998; Leclère et al., 2014). Or, they can be coded by dividing an interaction up into equally sized time windows, coding behaviours within those time windows, and using quantitative analyses to measure caregiver-child interaction dynamics (Cohn & Tronick, 1988). Analyses have examined behaviours across modalities, including eye gaze patterns, facial expressions, head movements, vocal behaviours, manual gestures, and noncommunicative postures (Beebe et al., 2016; Jaffe et al., 2001; Wass et al., 2021); as well as physiology (e.g. autonomic nervous system activity) (McFarland et al., 2020).

Important theoretical and practical insights into causal mechanisms can also come from intervention studies that target caregiver-child interaction - although clinical interventions tend to be relatively broad brush-stroke (for example, targeting aspects of the caregiver mental health symptoms on their own, as well as the caregiver-child interaction). This means that, when an intervention is effective, it can be hard to impute to underlying mechanisms.

In recent years, research has expanded how we study parent-child interaction at both ends of the time-scale. This is crucial for informing a dynamic systems view of coregulation in development. First, research is increasingly examining the temporally fine-grained organisation of child-caregiver interactions across a range of different modalities (Figure 1). This research, which has been inspired by fine-grained video-coding of visual attention and facial affect during face to face interactions (Ambady & Rosenthal, 1992; Cohn & Tronick, 1988), uses machine learning to code frame-by-frame changes in vocal behaviours and vocal affect, physical position and hand and head movements (see Figure 1). Researchers are also increasingly recording brain activity concurrently in interacting dyads, using fine-grained measures such as EEG. This high time-resolution approach is practically and theoretically important for reasons we describe below (see methodological challenge #3).

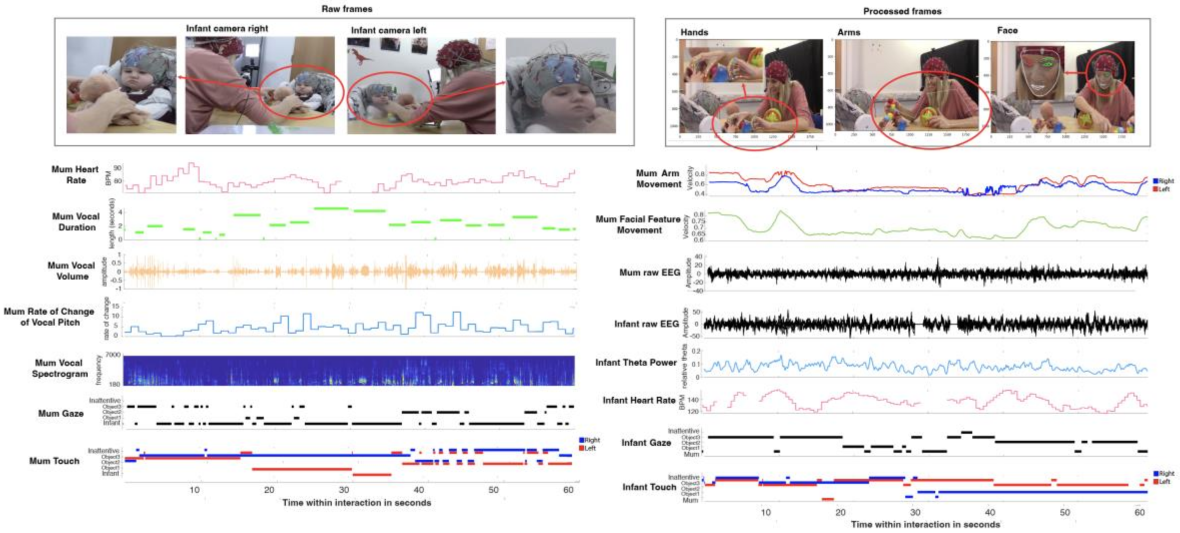

Figure 1: sample time-synchronised multi-modal raw data obtained from a single 60-second caregiver-child interaction

Second, some research is starting to examine the temporally coarse-grained nature of child-caregiver influences by using miniature home wearables to record much larger doses of caregiver-child interactions in home settings using microphones, video cameras, and physiological and neural wearable recording devices) (Hollenstein et al., 2017; Lahnakoski et al., 2020; Lazarus et al., 2023a; Stoop & Cole, 2022; Wass et al., 2019). Automatic analyses using machine learning classifiers can detect the presence of faces, facial affect, voices, vocal affect, caregiver child contingency and communicative behaviours automatically, opening up the possibility of analysing much larger datasets of parent-child interaction data than have previously been analysed. For example, these new methods allow us to study how interaction dynamics within a child-caregiver dyad can develop and change over days, weeks, months and years (Bornstein & Manian, 2013; Lavelli & Fogel, 2013).

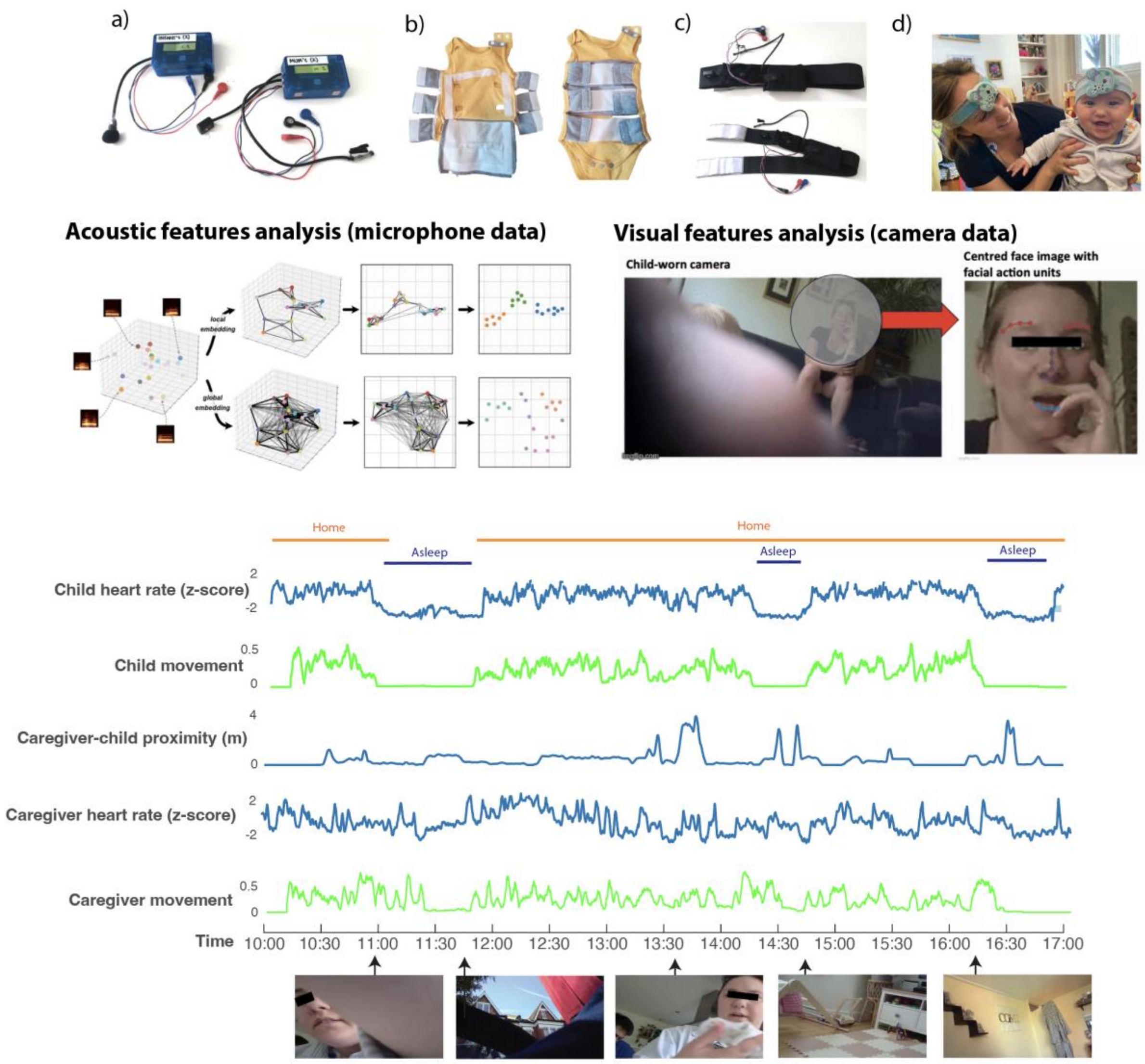

Figure 2: Sample time-synchronised wearable data obtained from a 7-hour long home recording.

Observing child-caregiver interactions over these diverse timescales is crucial for dynamic systems theory, which studies how micro-level dynamics interactively give rise to macro-level effects (Fogel & Thelen, 1987; Keating, 1990; Thelen & Smith, 1994). It is also important in other ways. For example, real-world child-caregiver interactions take place in ‘bursts and lulls’, and caregiver vocal responsiveness is much high in lab-based studies than in naturalistically recorded data (Abney et al., 2018; Warlaumont et al., 2022; Yoo et al., 2018a). And another well-recognised problem (Somers, Luecken, et al., 2021) is that it can be hard to elicit certain important aspects of real-world caregiver-child interactions, such as child-caregiver oppositionality, by recording short bursts of ‘best behaviour’ caregiver-child interaction collected when caregivers are acutely aware of being observed (although see (Granic & Patterson, 2006)).

Of course, even with these recent technological advances, several important methodological challenges remain. For example:

Methodological challenge #1: Most research has concentrated on measuring child-caregiver interaction by measuring modalities such as gaze and voice. But research has suggested that, whereas child-caregiver dyads in Western societies tend to primarily interact via gaze, vocalisations and object presentation, dyads in African, Middle-Eastern, or Far-Eastern cultures tend to interact more through bodily contact and physical touch (Feldman et al., 2006). Future data-driven approaches, such as machine learning and AI-based approaches applied to multi-modal interaction datasets (Gilkerson et al., 2017), will allow us to minimise the problem of cultural bias imposed by researchers pre-specifying which interaction modality they consider most developmentally relevant (Wang et al., 2023). Similarly, the majority of published papers examine mother-child interactions, and interactions with fathers and other caregivers are important but substantially under-researched (Feldman, 2007; Robinson et al., 2021).

Methodological challenge #2: The concept of synchrony has been extensively discussed within caregiver-child interaction (DePasquale, 2020a; Feldman, 2007; Thompson et al., 2020a). There are, certainly, mechanisms that might give rise to ‘true’ synchrony (i.e. genuinely co-occurring states) - such as actor-observer correspondences (Kingsbury et al., 2019) and common entrainment to environmental rhythms (Hoehl et al., 2020). However, we also know that there are fine-grained time-lagged relationships during interactions - for example, where one partner smiles and the other returns their smile shortly after (Cohn & Tronick, 1988). If we use an approach with too low a time-resolution (such as coding behaviour in 1- or 5-second epochs, or recording brain activity with fNIRS) it is possible for events to appear synchronous where one in fact occurred slightly after the other (Haresign et al., 2021). Mechanistically, it is important to differentiate leader-follower relationships (where the behaviour of partner A forwards-predicts partner B without it being true that B predicts A) from true synchrony (where the relationship of partner A to partner B is, by definition, symmetrical). This is important, for example, to distinguish active from passive forms of bidirectionality. To do this, it is often necessary to use multiple methods to study both micro- and macro-level behaviours.

Methodological challenge #3: One challenge familiar to readers of this journal is: how do we differentiate active environmental influences on developmental psychopathology (e.g. more anxious caregivers interacting differently with their children, and these interactional differences causing increased rates of psychopathology in the child) from passive genetic linkage (e.g. shared genetic influences might cause the co-occurrence of symptoms of psychopathology in families) (Ahmadzadeh et al., 2019; Aktar, Van Bockstaele, et al., 2019; Cheesman et al., 2020)? In the context of caregiver-child dynamics there also exist intermediate positions, such as the foetal programming hypothesis (Swanson & Wadhwa, 2008), which posits that postnatal behaviour can be influenced by the environment experienced in the womb.

Most of the studies that we have included have not addressed this directly. One approach to doing so would be using a twin study design (Gjerde et al., 2021). Another would be to measure caregiver-child interaction repeatedly across multiple time points and, using a technique such as dynamic structural equation modelling, include genetic risk as a covariate by examining specific alleles that contribute to polygenic risk scores for anxiety but which are not shared between children and caregivers (Birmaher et al., 2022). Other approaches are to study special populations, such as caregivers raising genetically unrelated children (Harold et al., 2013), and interventions that specifically target child-caregiver behaviours to examine the long-term development of symptoms in the child (C. G. Smith et al., 2022a).

Part 2 - theory - co-regulation and dysregulation

2a Stability, symmetry and asymmetry

In this section we lay out a theoretical framework for understanding both co-regulation and dysregulation within an interacting dyad. In later sections we go on to describe how this framework can influence development across multiple hierarchical domains (part 3) and describe four ways in which co-regulatory processes can develop atypically (part 4).

Our framework is couched within dynamic systems theory, which is a flexible mathematical framework for understanding how dynamical systems self-organise, and how stability can emerge from fluidity across multiple timescales (e.g., (Fogel & Thelen, 1987; Keating, 1990; Thelen et al., 1987; Thelen & Smith, 1994; Van Geert, 1991)). One key concept in dynamic systems theory is that of attractors: – i.e., absorbing states that “attract” the system from other potential states. A single dynamic system can develop multiple attractors, giving rise to a system which is ‘multistable’ (i.e., stable in a variety of different states). Changes between different attractors are referred to as phase transitions, and manifest as nonlinear changes in the organisational structure of the caregiver-child dyad (Granic & Patterson, 2006). Most dynamic models emphasise that total synchrony (e.g., within a child and caregiver dyad) is not desired;

rather, what is important is the flexible ability to synchronise (or enter an attuned state from one of misattunement) when necessary (Tognoli & Kelso, 2014) (see (Grumi et al., 2022)).

The aim of regulation is to maintain an optimal ‘critical state’ between over- and under-excitation (Shriki et al., 2013; Wass, 2021b). Most often we shall describe an optimal, critical state of arousal (i.e. activity within the Central Nervous System (CNS) (Pfaff, 2018; Pfaff & Banavar, 2007)); but similar ideas of an optimal intermediate level exist for behaviour and affect, too – although they remain substantially under-operationalised (Leyendecker et al., 1997).

Even from birth, infants show some capacity to act by themselves to maintain this optimal intermediate critical state. For example, even neonates are thought to have a tendency to close their eyes when overstimulated (Brazelton, 1983). Even at 5 months, infants were more likely to show gaze aversion, which downregulates arousal (T. M. Field, 1981), following a experimenter- administered toy removal, which upregulates arousal (Buss & Goldsmith, 1998; Kopp, 1982; Stifter & Braungart, 1995). Other research has examined other putative downregulatory behaviours, such as distraction, self-soothing, calming self-talk, and proximity seeking, across typical and atypical development (Doherty-Sneddon et al., 2012; Feldman et al., 2011; Nigg, 2017).

The term co-regulation describes regulatory processes that operate through the dynamic, bidirectional coordination between two interacting partners. This is not the sole aim of caregiver-child interactions: smiles and play, for example, appear not to have a regulatory function (Kidby et al., 2023; Murray et al., 2016). But it is central to early development (Feldman, 2006). Early in life, across most systems (such as CNS arousal) children are thought to show lower self-contingency – i.e., a lower probability that the prior state or behaviour predicts the current state behaviour (Wass, 2018). (In other words, an average child's mood states (for example) tend to be less stable over the course of the day than an average adult's). And a number of studies have shown that all child-caregiver interactions are bidirectional (i.e., caregiver influences child and child influences caregiver), but early interactions in particular are *relatively* more asymmetric (Beebe et al., 2016; E. A. M. Phillips et al., 2023; Sander, 1977; Somers, Luecken, et al., 2021). (In other words, the caregiver adapts to a young child relatively more than the child adapts to the caregiver.)

Bidirectional child-caregiver influences operate over a short-term, second-by-second scale; but we shall present evidence showing that they also operate over longer times too – across hours, days, weeks, months and years. These long-term relationships are also bidirectional: atypical child interactive behaviours influence how caregivers behave in response, which influences in turn how the child interacts with the caregiver, and *vice versa*.

2b Regulation

Passive regulatory processes

Arousal and affective states are contagious: the arousal state of one partner directly affects and influences that of their partner. In its simplest form, experimental evidence suggests that caregiver->child arousal state contagion can operate even in the absence of caregiver behaviours such as speech and eye contact (Waters et al., 2014), but is facilitated by touch (Waters et al., 2017).

The contagion of arousal and affective states can influence passive regulatory processes in two ways. First, as described above, caregiver arousal and affective states tend to be inherently more stable than those of a young child (eg (Beebe et al., 2016; Lavelli & Fogel, 2013)). Caregiver states can influence child states directly through a process described as 'buffering', whereby caregivers' more stable states create a downregulatory influence when the child's state is high and an upregulatory influence when the child's state is low; and, through that, create increased stability in the child (see Figure 3a).

The second way in which passive regulatory processes are thought to operate during early development is through the child 'piggybacking' on the caregivers' stable physiological rhythms until they show similar physiological rhythms themselves (Figure 3b) (Feldman, 2006; Stern, 2018; Wass et al., 2021). For example, caregivers follow daily sleep-wake cycles, and because of these they will tend to be more likely to be at home, to darken the house, and to be less interactive with their child at night. Even though these behaviours do not take place in response to the child, they nevertheless influence the child. Thus, caregivers' own, naturally occurring physiological rhythms will tend to create similar physiological rhythms in a child (K. F. Davis et al., 2004; Feldman, 2006; Spagnola & Fiese, 2007. Similar principles are also thought to contribute to the development of physiological rhythms on other timescales as well (Feldman et al., 2011; Hofer, 2013). And, as we shall describe in Part 3 below, passive regulatory processes also influence co-regulation and development in other domains, such as attention and executive control.

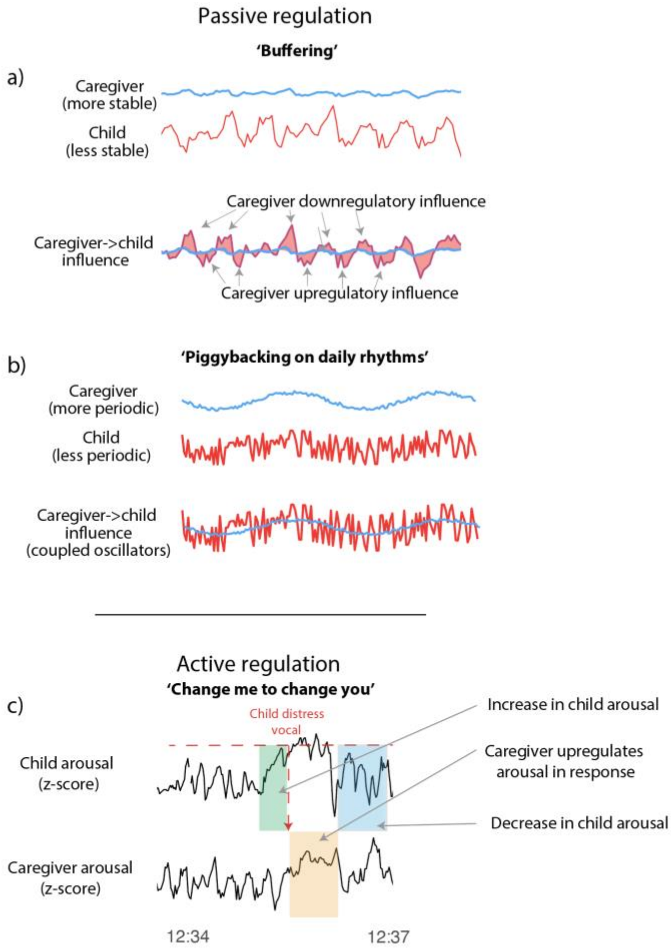

Figure 3 schematics illustrating a) passive regulation via 'buffering', through which more stable states in one partner (e.g. the caregiver) create a downregulatory influence when the child's state is high and an upregulatory influence when the child's state is low, b) passive regulation via 'piggybacking on daily rhythms', through which on partner (e.g. the caregiver's) naturally occurring rhythms will tend to create similar rhythms in a child c) active regulation, through which one partner (e.g. the caregiver) actively changes their behaviour in response to child distress.

Active regulatory processes

In addition to passive processes, there also exist active processes through which one partner (e.g. the caregiver) actively changes their behaviour in response to changes in the other partner (the child). In active co-regulation, changes in one partner away from the 'critical state' induce compensatory changes in the other partner whose effect is to move the first partner back closer towards the ‘critical state’ (Atzil et al., 2018; Hollenstein, 2015; X. Zhang et al., 2022). This processes is known as allostasis, which is the active process through which homeostasis is maintained (Cannon, 1929; McEwen & Wingfield, 2003; Ramsay & Woods, 2014; Sterling, 2012) (see Figure 4a). For example, an increase in child arousal might be followed by a child distress vocalisation, which might be followed by a change in caregiver behaviour (such as picking up the child and singing to them), which is followed by a reduction in child arousal (Ham & Tronick, 2009). As we describe below, micro-analytic behavioural methods have shown that, across different domains and modalities, the form of the response (i.e. the attunement of the response to the child’s current state) is most important for in-the-moment regulation and later developmental outcomes.

But how, though, should I change my own state in order to influence my partner? For example, how should I react if my child falls over, hurt themselves and then start to cry, causing an increase in their physiological arousal? Should I decrease my own arousal, to ‘set a good example’? Or should I increase my own arousal to match theirs, to empathise? The former process is known as negative feedback, through which changes in one partner induce compensatory changes of the opposite effect in the other partner, in order to counteract that effect (Beebe et al., 2016; Carver & Scheier, 2008). The latter process is known as positive feedback, through which changes in one partner induce changes in the same direction in the other partner.

We shall argue that, for both arousal and attention, optimal responses can include a mixture of positive and negative feedback. For example, caregivers in naturalistic settings show an increase in their own arousal time-locked to increases in child arousal, and to child distress vocalisations; the more caregivers upregulate arousal in response to child distress, the faster the child calms (Amado et al., pre-print; Wass et al., 2019, 2022). This is consistent with other research suggesting that caregivers calm infants more effectively if they first get up and walk while calming the child before sitting - compared to when they remain sitting throughout (Esposito et al., 2013; Ohmura et al., 2022). This is a mixture of first positive and then negative feedback. Similarly, when we discuss co-regulation and attention in section 3, we shall review evidence suggesting that, in response to child inattention, caregivers first upregulate their own salience (e.g. the pitch inflection patterns in their voice), and then downregulate them when the child becomes attentive (E. A. M. Phillips et al., 2023). Again, this is a mixture of first positive and then negative feedback.

Over time, these short-term interactive dynamics are thought to affect the long-term development of the caregiver-child relationship. Whereas early short-term influences are mainly (but not exclusively) unidirectional – the caregiver responds to the child more than *vice versa* – these long-term influences are bidirectional (Beebe et al., 2016; Fogel, 2017a; Hollenstein, 2015; E. Lunkenheimer et al., 2020; L. Smith & Gasser, 2005; Yu & Smith, 2017). We shall present evidence indicating how the caregiver's way of responding to the child determines how the child communicates with the caregiver; and how the child responds to the caregiver determines how the caregiver responds to the child. In this perspective, rather than conceptualising interactions as chains of signals and responses, inter-dyadic co-ordination is considered a complex, hierarchically nested system, characterised by a dynamic, inter-dyadic flow of information between levels and across systems (Cole et al., 2020; Fogel, 2017b; Knoblich & Sebanz, 2008; L. Smith & Gasser, 2005; Yu & Smith, 2012, 2017).

2c Dysregulation

Passive dysregulatory processes

The same two mechanisms that drive passive regulatory processes also drive passive dysregulatory processes (Fig 3a, 3b). First, because arousal and affective states are contagious, in conditions where a caregiver's arousal states are unstable, this will directly cause more unstable states in the child (the opposite of the buffering/inertia illustrated in 3a). Second, in settings where adult arousal changes are less periodic (e.g. where sleep-wake cycles in the caregiver are unstable (Boivin, 2000)), this may also affect the development of diurnal rhythms in the child (i.e., the opposite of the processes illustrated in 3b).

Active dysregulatory processes

Active dysregulatory processes are the opposite of the allostatic mechanisms described above. They are processes through which changes that move a child away from the optimal 'critical state' induce active changes in adult behaviour whose effect is to move the child still further from the 'critical state' (Granic & Patterson, 2006). We have coined the term 'metastatic' to describe these processes, as the opposite of 'allostatic' (Wass, 2021a).

There are many possible examples of this in developmental psychopathology. For example, an increase in child arousal might cause an increase in child oppositional behaviour, which causes an increase in caregiver arousal, which causes the caregiver to shout at the child, which causes a further increase in child arousal (see Figure 4c) (E. Lunkenheimer et al., 2017; Reid et al., 2002). Because this pattern is self-reinforcing, in the sense that an initial increase in child arousal triggers a series of events that each increase child arousal still further, it gives rise to an attractor – i.e. an absorbing state that "attracts" the system from other potential states (Granic

& Patterson, 2006). As we describe below, these types of active dysregulatory processes have been documented in the context of conditions such as maternal anxiety and child ADHD.

Just as we described above how active regulatory processes can involve a mixture of both positive feedback, and negative feedback, so active dysregulatory processes can also involve both positive and negative feedback. For example, a caregiver might respond to a child starting to shout either by shouting back at them, or by pointedly ignoring them. Both of these are active dysregulatory processes, insofar as they are changes in adult behaviour that occur in response to child behaviours, but which have the effect of moving the child further from their 'critical state'. But shouting at a child is positive feedback, insofar as it involves the caregiver matching their state with the child's; whereas ignoring a child is negative feedback, insofar as it involves the caregiver moving their own state further from the child's.

The attractors we have discussed thus far explain how self-sustaining dynamics can develop over a timeframe of seconds, minutes, or hours. But dynamic systems theory can also explain how the same mechanisms can also develop into recurrent patterns that become increasingly long-lasting and predictable over weeks, months and years. Below, we shall describe how active regulatory processes (e.g. the child cries, and the caregiver comforts them) may contribute to the development of attachment. Coercion theory focuses on active dysregulatory processes, and how they develop over time (Patterson, 2002; Reid et al., 2002). It focuses on how behavioural contingencies can explain how parents and children mutually "train" each other to behave in ways that increase the probability that children will develop aggressive behaviour problems and that parents' control over these aversive behaviours will decrease.

Although we have described active dysregulatory processes by focusing on arousal and affect, it is likely that similar patterns also explain coregulatory processes in other domains, such as attention. For example, children's behaviours are influenced by caregiver speech: when they are engaged with an object, then caregiver object-related speech increases, which further engages child attention (Anderson et al., 2022). (An active regulatory process.) But it is also possible that dysregulated behaviour may also develop attractor dynamics: an inattentive child may be more likely to elicit high levels of parental expressed emotion, which increases child stress, which causes further inattention. (An active dysregulatory process.)

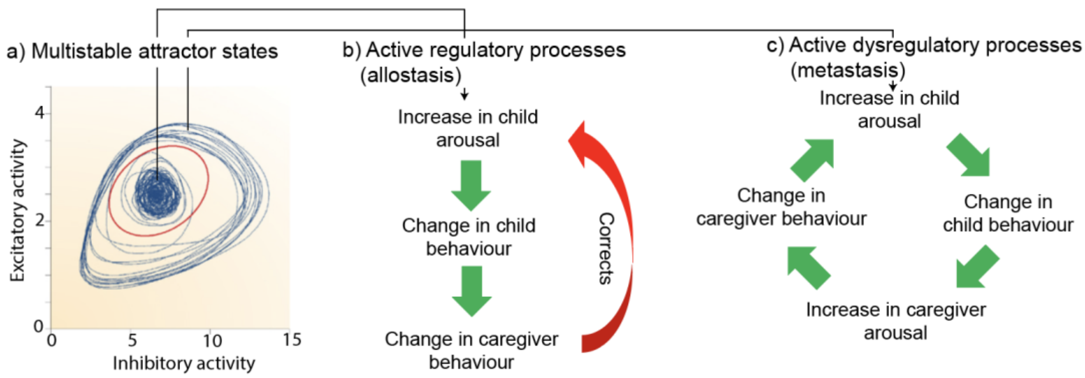

Figure 4 - schematic illustrating multi-stable interaction dynamics. a) a state-space plot, illustrating possible bi-stable attractor states; b) schematic illustrating the first possible stable attractor state - increases in child arousal induce compensatory changes in adult behaviour which correct for the changes in child arousal (allostasis/negative feedback); c) schematic illustrating the second possible attractor state - increases in child arousal induce changes in adult behaviour which amplify the changes in child behaviour (metastasis/positive feedback).

2d Interactions between active and passive processes

Thus far, we have talked about the distinction between active processes (where one partner actively changes their state in response to changes in their partner) and passive processes (in which the simple presence of one partner in one state influences their partner). It is also important to note, though, that these two processes are not entirely independent. For example, the pre-existing state of one partner (e.g. the state that a caregiver is in before an expression of child distress) systematically influences how they respond to child distress when it occurs. Although evidence in this area is lacking (see Part 5), we predict a U-shaped relationship between caregiver arousal and the likelihood of them producing an effective calming response will show (Figure 5c). This U-shaped relationship is created by a combination of two factors. The first is the likelihood of the caregiver producing any response at all – which increases with increasing caregiver arousal (Figure 5a). The second is the likelihood that the caregiver's response will be regulatory vs dysregulatory. At high arousal, it is more likely that the caregiver response will give rise to active dysregulation (Figure 5b).

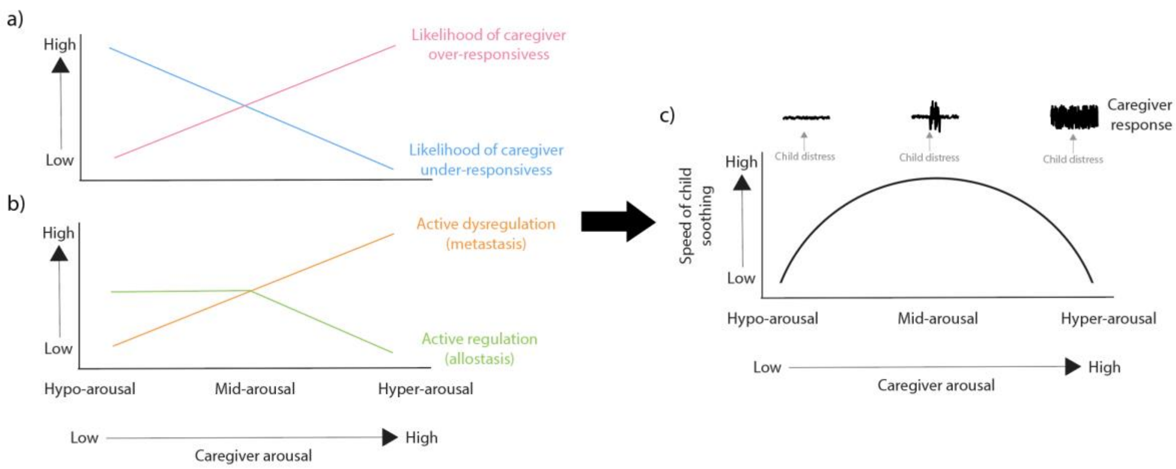

Figure 5: Schematic illustrating the relationship between: a) caregiver arousal and under-/over-responsiveness; b) caregiver arousal and responses that leave to active regulation/dysregulation; c) caregiver arousal and speed of child soothing.

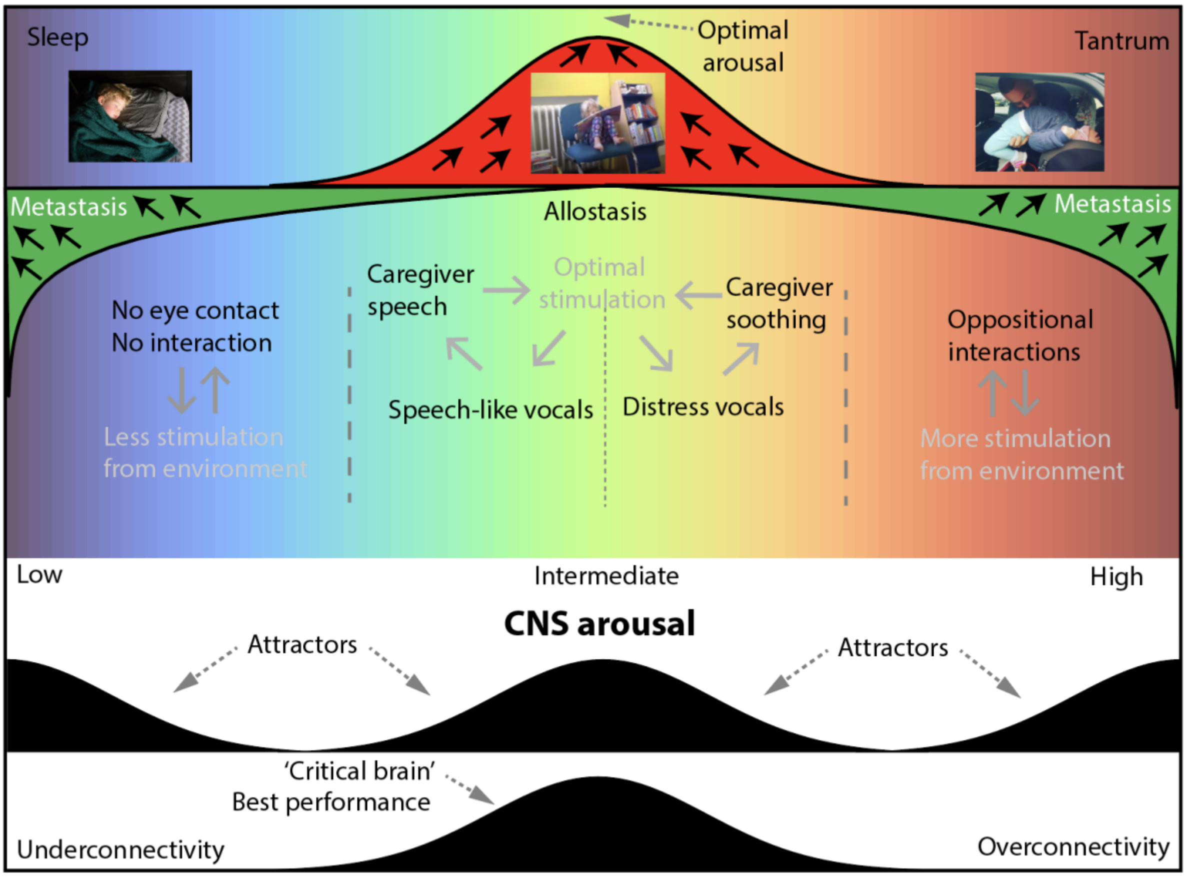

Figure 6 - Schematic illustrating key thematic themes developed in this article. When an individual is close to their intermediate 'critical state', they use allostatic interactive mechanisms to maintain a critical state - for example, by using techniques such as distress vocalisations to decrease CNS arousal following hyper-activity, or speech-like vocalisations to elicit caregiver speech interactions to avoid falling into hypo-arousal. Further from the 'critical state', however, allostastic mechanisms fail and 'metastatic', dysregulatory mechanisms develop which actively prolong increases and decreases in arousal - for example, by oppositional child-caregiver interactions which act both a consequence and a cause of

increased CNS arousal within a child-caregiver dyad (E. Lunkenheimer et al., 2017; Wass, 2021a).

Glossary [will be in a side box] [reviewers please note – these terms are all defined in ‘friendly’ terms through the text, and this glossary is only intended as a reminder, and for readers reading the text out of order]

Active influence - processes through which one partner 2 actively changes their state in response to changes in partner 1; and, through that, influences partner 1.

Allostasis - the active process by which homeostasis (i.e. internal, physiological equilibrium) is maintained by an organism. This is normally achieved through negative feedback.

Critical state - an optimal level of brain/behaviour activity, intermediate between under-activity and over-activity (Shriki et al., 2013).

Contagion - a mutually amplificatory, positive feedback interaction that moves the child away from the critical state.

Contingency - behaviours which occur conditional to the behaviours of the other party (Beebe et al., 2016).

Co-regulation - regulatory processes that operate through the dynamic, bidirectional coordination between two interacting partners.

Metastasis - the opposite of allostasis. Active processes through which increases and decreases are not corrected for but instead become progressively amplified over time, leading to disequilibrium (Wass, 2021a).

Negative feedback - the diminution or counteraction of an effect by its own influence on the process giving rise to it, e.g. when a high level of a particular hormone inhibits the further secretion of that hormone.

Ostensive cues - signals from a communicator to generate an interpretation of communicative intention in an addressee (Csibra & Gergely, 2009).

Passive influence - processes through which the presence of one partner in a particular state shifts the other partner into the same state.

Positive feedback - the opposite of negative feedback. A process that occurs when a shift away from the critical state triggers further reactive changes away from the critical state, e.g. when a high level of a particular hormone causes further secretion of that hormone.

Regulation - the ongoing, dynamic and adaptive modulation of internal state (emotion, cognition) or behaviour, mediated by central and peripheral physiology (Nigg, 2017).

Synchrony - a zero-lag, simultaneous relationship: e.g., 'at times when A is high, B is also high' or 'at times when A is high, B is low'. Unlike entrainment, synchrony is undirected: A->B is indistinguishable from B->A.

Part 3 – hierarchies across domains

In part 2 we explained how regulation and dysregulation can both operate through both active and passive processes. In this section, we describe how these principles can influence development across development at a range of different levels. To illustrate this, we look at development across a range of different levels – considering first the coregulation of CNS arousal; then affective states and socio-communicative development; then attention, executive control and megacognitive awareness. This process, through which similar principles influence development across a range of different levels, has been characterised as a hierarchically nested, vertically integrative elaborative process (Geva & Feldman, 2008) (Stern, 2018). These different domains are partly developmental, in the sense that early development in one domain influences subsequent development in later-developing, 'higher order' domains (Geva & Feldman, 2008). But is it not exclusively developmental: there also evidence that 'higher order' domains such as executive control are present in trace elements from birth (Hodel, 2018; Wass, 2021b), and 'lower order' domains such as CNS arousal regulation remain active even in adulthood. The list of domains that we consider is, of course, illustrative and non-exhaustive.

3a CNS arousal

Our arousal/regulatory systems involve a network of brain regions from the brainstem to the forebrain via the hypothalamus and the thalamus (Pfaff, 2018), as well as neurotransmitter systems including noradrenaline (norepinephrine) and acetycholine (Aston-Jones & Cohen, 2005). These brain regions are some of the earliest to become functionally mature (Wass, 2021b).

Many arousal/regulatory systems develop periodic, cyclic organisation through early life, across a range of time-scales - including feeding and digestion, sleep and vigilance transitions, respiration, vagally mediated heart rate variability, and so on (Feldman, 2006; Robertson, 1993; Wass et al., 2021). It is commonly thought that these influence the child via passive processes (Feldman, 2009; Geva & Feldman, 2008; Stern, 2018), which include both direct influences (a caregiver's arousal directly influencing a child's and *vice versa*), and indirect influences (caregivers directly structure a child's environment by providing daily routines - through feeding, turning off the lights at night-time, and so on (Spagnola & Fiese, 2007)). Importantly, though, although they are much discussed in the literature, the evidence base supporting the existence of these long-term passive influences is relatively sparse. This is mainly due to the practical difficulties in recording large-scale datasets from caregivers and children, and due to the impossibility of obtaining adequate controls (e.g. children growing up without caregivers).

In addition to passive regulatory processes, there is also evidence for active regulatory influences on CNS arousal. For example, long-term physiological recordings suggest that peak moments in naturally occurring child arousal during the day reliably elicit peaks in caregiver arousal in response (Wass et al., 2019). The opposite pattern is not observed, indicating an asymmetric relationship. The more caregivers upregulate their own arousal in response to child distress, the faster the child calms during the minutes afterwards (Amado et al., under review; Wass et al., 2019). As we described in section 2 above, this optimal response is a mixture of positive and negative feedback: the caregiver first increases their own arousal in response to increases in child arousal, before subsequently reducing it. Often these arousal peaks co-occur trigger proximity-seeking behaviours, such as vocalisations – as we describe in the next section.

In addition to these passive and active *regulatory* influences, there is also evidence for passive and active *dysregulatory* influences on CNS arousal with child-caregiver dyads - as we describe further in Part 4 below.

3b Affective states and socio-communicative development

Infants use socio-communicative signalling to communicate to a caregiver when they are upset and need support. Early in development, the link between arousal and communicative behaviours is strong. For example, micro-behavioural analyses of day-long home recordings show that 10-month-old infants are very likely to cry when they are aroused (Wass et al., 2019, 2022); and that these cries reliably elicit co-regulation, including reductions in caregiver-child proximity and increases in caregiver-child arousal synchrony, that are followed by subsequent decreases in child arousal (Amado et al., pre-print; Wass et al., 2019, 2022; Yoo et al., 2018b). Speech-like vocalisations also occur around elevated child arousal; but whereas cries lead to decreases in arousal, speech-like vocalisations lead to sustained increases in child arousal, and to an increased rate of speech-like vocalisations in response (Wass et al., 2022). When caregivers respond consistently and contingently to modulations in child behaviour, this increases the amount and complexity of their communicative cues over the duration of an interaction (Goldstein & Schwade, 2008; Miller & Gros-Louis, 2013).

By adulthood, however, there is no longer such a strong connection between arousal and socio-communicative behaviours. Caregiver speech appears not to be attuned to the caregiver's own arousal (in contrast to primate work, where it remains coupled even in adulthood (Y. S. Zhang & Ghazanfar, 2016)). When they are with their child, however, caregiver speech is attuned to the child's arousal (Wass et al., 2022), pointing to an asymmetric process through which children influence caregivers during early interactions more than *vice versa*.

These findings show how active co-regulatory processes – a child getting upset, signalling that to the caregiver, and the caregiver changing their behaviour in response – can drive a connection between CNS arousal and social communication. This link is not present within an individual; it is only seen when we consider an interacting child-caregiver dyad as a discrete system. The connection between arousal and social communication is strong during early development, when it is needed, but becomes progressively less strong over time.

As we discuss further in part 4, below, there is also evidence that this relationship between arousal and social communication can develop atypically in a number of different ways. Atypical behaviours from one member of the dyad lead gradually, over time, to compensatory changes in the other member of the dyad (Beebe et al., 2016; Lavelli & Fogel, 2013; Stern, 2018). For example, there is evidence that long-term conditions such as depression (which is often associated with hypo-tonicity) and anxiety (which is often associated with hyper-tonicity) affect child-caregiver interactions. As we describe in Part 4, hypo-tonicity is generally associated with under-responsiveness, and hyper-tonicity with over-responsiveness, along with an increased likelihood that the response will lead to dysregulatory (metastatic) processes Fig 5).

There is also evidence that, when caregivers are unresponsive, this can over time affect how a child communicates with their caregiver. For example, some evidence suggests that the children of unresponsive caregivers (operationalised by measuring how caregiver's arousal changes around negative child vocalisations) are more likely to 'overcommunicate' their arousal fluctuations - i.e., to produce intense negative vocalisations at times when their own arousal is lower (Wass et al, pre-print) – a phenomenon perhaps best described as 'shouting to be heard'. Over time, these atypical child behaviours in turn most likely affect the caregiver's responsiveness – for example by making them even less likely to respond to their child.

This relationship between arousal co-regulation and the long-term development of socio-communicative behaviours, is most well studied within the context of the development of child-caregiver attachment. Qualitative early observations suggested that social communicative behaviours (such as cries) tend first to be directed indiscriminately, before becoming increasingly directed towards a preferred figure over time (Ainsworth, 1979; Bowlby, 2008). These observations also suggested that it is active regulatory processes, as opposed to passive processes (such as the caregiver simply being present and providing routine 'caretaking' tasks such as feeding), that drive the development of child-caregiver attachment (Ainsworth, 1979; Bakermans-Kranenburg & van Ijzendoorn, 2011).

A number of studies have examined how fine-grained interactive behaviours during lab interactions associate with child-caregiver attachment. As expected, these have suggested that under-responsive caregiver-child dyads tend to develop insecure attachment. They have also suggested, though, that over-responsive caregiver-child dyads also develop atypical attachment, pointing to an optimal mid-range of interactivity during social communication (Beebe et al., 2011, 2023; Lavelli et al., 2022; Lemus et al., 2022a; McFarland et al., 2020; Mitsven et al., 2022). For example, Jaffe and colleagues examined micro-second vocalisation and pause rhythms in 88 mother-infant and stranger-infant pairs and found that mid-range interactional vocal contingency at four months predicted secure attachment at 12 months, while both high- and low- contingency predicted insecure attachment (Jaffe et al., 2001). Investigation of other multimodal behaviours shows a more complex picture, with differences in interactional contingency of facial affect, spatial approach/avoid patterns, spatial intrusion, mothers' affectionate touch, infant touch, and visual attention of both caregiver and infant associating with different attachment styles (Beebe et al., 2010; Khoury et al., 2022; Lyons-Ruth et al., 2003; Mitsven et al., 2022; Prince et al., 2021).

There remain, however, a number of important but unanswered questions about how arousal co-regulation affects the development child-caregiver social communication and attachment. For example, the available literature covers active regulatory processes (i.e. how one partner responds to another during a lab interaction); but we understand very little about long-term passive regulation. In Part 2 above we discussed, for example, how caregiver arousal stability can affect child arousal, both through the caregiver 'buffering' the child's arousal fluctuations and through the child 'piggybacking' on a caregiver's daily rhythms (see Figure 3). We understand very little about how these passive regulatory influences can affect the development of social communicative behaviours and attention. And little research has examined whether under-responsivity within a caregiver-child dyad specifically affects the long-term development of that child-caregiver relationship (as predicted based by Bowlby and Ainsworth), or whether it affects the child's relationships with all adults with whom they interact (Thompson et al., 2020b).

3c Attention, executive control and metacognitive awareness

When adults and children jointly attend towards the same object during shared play, children's attention durations are longer than towards objects that they attend to on their own (Yu & Smith, 2016). Child attention durations are also longer overall during joint, compared to solo play (McQuillan et al., 2020; Wass et al., 2018). In this section we describe how co-regulatory processes can give rise to higher order functions, such as attention, executive control and metacognitive awareness.

Evidence suggests that child-caregiver attention co-regulation operates through a combination of passive and active regulatory processes. Passive regulatory pathways exist because caregivers are naturally more goal-directed and attentive for longer periods, and children follow multimodal cues from the caregiver to 'piggyback' on the caregiver's shifting attention patterns (a process sometimes known as 'attentional scaffolding' (Bornstein & Sigman, 1986)). One study examined intra- and inter-dyadic associations between caregiver and infant touch and visual attention. It found that infants rarely used the focus of the adult's gaze to follow their attention (Yu & Smith, 2013). Instead, infant attention was strongly associated with the hand actions of both partners, and coupling between their attention, and the adult's hand actions markedly increased where infants followed their partner's attention towards an object (see also (Custode & Tamis-LeMonda, 2020; Franchak et al., 2018; Yu & Smith, 2017)).

In addition to these passive regulatory pathways, there is also evidence for active regulation. Just as with the social communicative behaviours discussed in the previous section, there is evidence that these active regulatory influences on attention are relatively more asymmetric (caregivers adapting to children, more than *vice versa*), but become less asymmetric over time. For example, recent research that recorded dual EEG and behavioural microdynamics has documented how caregivers dynamically modulate their gaze behaviour and vocal behaviour contingent on moment-by-moment variability in the child's behaviour, and how these relationships become less asymmetric over time (E. A. M. Phillips et al., 2023). Extensive evidence shows that children are behaviourally and neurally highly responsive to when a caregiver responds contingently to them (Murray & Trevarthen, 1986; E. Phillips et al., 2021; Tamis-LeMonda et al., 2014) showing the importance of active attention regulation.

The exact mechanisms that guide how caregivers actively respond to children during shared interaction appear similar to the 'capture, then hold' mechanisms described for arousal co-regulation. Caregivers respond to decreases in child attention by making themselves more salient (e.g. by increasing the rate of modulation of the voice); but then, when children's attention is re-engaged, they downregulate their salience (E. A. M. Phillips et al., 2023) and use other modalities such as task-related caregiver talk to actively prolong child attention durations (Slone et al., 2023; Suarez-Rivera et al., 2019). As with arousal regulation, this suggests that active attention regulation involves a mixture of first upregulating to match the child's state (positive feedback) and then downregulating (negative feedback).

Just as with arousal and social communicative development, research suggests that atypical attention behaviours in one member of the dyad lead over time to compensatory atypicalities in the other partner. For example, one study found that infants with shorter look durations during solo play paid attention to objects with their caregiver for longer where caregiver inputs were faster and more frequent (Parrinello & Ruff, 1988).

Just as in the last section we discussed how co-regulation of arousal contributes to social communicative development, so there is also evidence that social communicative development contributes to attention co-regulation. Caregiver speech and in particular, contingent caregiver vocalisations (i.e., those that occur specifically in reaction to an attention shift from the child) are especially predictive of child attention and learning (Goupil et al., pre-print; Mason et al., 2019; Suarez-Rivera et al., 2019)). This shows how socio-communicative development and attention development are inter-related.

Similarly, evidence also points to effects in the opposite direction: that atypical coordination of attention during social interaction can disrupt inter-dyadic processes important to the development of social communication. For example, one study examined children aged 2-3 years with an ASD diagnosis and found that contingent responsivity by the caregiver to the infant's attention associated with better language development, but only among children with lower language scores (Haebig et al., 2013). Another study found that toddlers at elevated likelihood of ASD who are hyporeactive to sensory stimuli have poorer communication skills, but that the relationship between hyporeactivity and later language development was significantly mediated by caregiver responsiveness, assessed on global rating scales (Grzadzinski et al., 2021).

Metacognitive awareness

In attention to research that examines how co-regulatory processes can influence the development of attention and executive control, a number of authors have discussed how active co-regulatory processes may also drive the development of emotional self-awareness and self-control. For example, Trevarthen discusses a shift from primary intersubjectivity – whereby the self is linked to the other by way of other-centric participation – to secondary intersubjectivity, characterised as self-in-the-presence of other, when the child is perceiving, thinking or acting alone but in the physical proximity of a caregiver (Stern, 2018; Trevarthen, 1979). Tronick refers to this as a “dyadic state of consciousness” (E. Z. Tronick et al., 1998). The caregiver, by contingently responding to the child, contributes to the child’s developing sense of agency and self-concept (“it was me that triggered that response”) (Feldman et al., 1999; Fotopoulou & Tsakiris, 2017).

Understanding these pathways may be crucial for understanding many of the long-term pathways we discuss in this article – such as understanding how increasing children’s awareness of their communicative behaviours affects the behaviours and intentions of an interacting partner (Feldman, 2007; Perlman et al., 2022; L. B. Smith & Breazeal, 2007; Thompson et al., 2020a). There is some indirect evidence in favour of this possibility. For example, caregivers’ contingent vocal responses to their infants’ communicative behaviours at 2 months associated with increased attempts by the child to re-engage their caregiver during the still-face paradigm where the caregiver ceases interacting with the child (Bigelow & Power, 2016, 2022). By 5 months, mirroring of infant facial affect during free-play is most predictive of directive bids by the infant to re-engage the adult (Bigelow & Power, 2016). However, direct empirical evidence in favour of these suggestions is currently lacking, because it is hard to measure metacognitive states accurately during early development (Goupil & Kouider, 2019).

Part 4 – atypical coregulatory dynamics

4a passive processes

As we described in Part 2, passive regulatory influences may operate through two pathways: first 'buffering', whereby (for example) caregivers' more stable states create a downregulatory influence when the child's state is high and an up-regulatory influence when the child's state is low; and, through that, create increased stability in the child (see Figure 3a). And second, through the child 'piggybacking' on the caregiver's stable physiological rhythms until they show similar physiological rhythms themselves (Figure 3b).

It is likely that both of these processes are atypical in dyads where the caregiver's behaviours are more unpredictable (Beebe et al., 2016; E. P. Davis et al., 2017, 2022; Glynn & Baram, 2019). There is evidence from short face-to-face interactions that caregivers and children whose facial expressions are more unpredictable are more likely to coordinate strongly with the partner's facial affect, suggesting that individuals who are more loosely self-organised are more open to the influence of that partner (Beebe et al., 2016). This suggests that, over short time-frames at least, active regulation may be stronger in dyads where the caregiver is more unpredictable. Over longer time-frames, however, it seems likely that unstable caregiver states would impede the processes of buffering and piggybacking that we have described, leading to passive influences on child dysregulation. However, this idea remains under-researched, due to the practical difficulties of making long-term large-scale recordings to test it.

A small number of studies have, though, examined how regular, fine-grained periodic changes in one partner influence the other partner during short face-to-face interactions in the lab. For example, preterm children show more irregular patterns of changes in facial expression during face-to-face play, which associated with weaker associations between changes in the child's facial expressions and changes in the mother's, which are thought to reflect disruptions in the biological underpinnings of social engagement (Lester et al., 1985). Less periodic child facial affect also associated with reduced caregiver-child synchrony during tabletop play in the lab (Feldman, 2006).

4b active processes - under-responsiveness

In addition to passive dysregulation, there are also a range of different ways in which one partner can respond atypically to the other during shared interaction, disrupting active regulatory mechanisms. For example, depressed caregivers are less responsive to child signals than caregivers without depression (Bernard et al., 2018), less likely to engage in mimicry (Salazar Kämpf & Kanske, 2023), and display more neutral and negative and less positive affect (Campbell et al., 1995). Seven-month-old infants in multi-problem families - including high levels of depression - had low interactive behavioural contingency (Ham & Tronick, 2009) and less affective synchrony with the child. Other studies have shown that depressed caregivers touch their children less frequently, and show less spontaneous positive affect (Beebe et al., 2008a; Brazelton et al., 1974; Feldman, 2007; T. Field et al., 1989; Jaffe et al., 2001; Quiñones-Camacho et al., 2023). Importantly, though, caregivers with depression do not show reduced responsiveness across all modalities; rather, they show under-responsiveness in some modalities and over-responsiveness in others (see section 4c below).

As we discussed in Part 3, atypical caregiver behaviour can contribute to the development of atypical child behaviour over time. For example, children raised in chaotic households, where caregivers are less responsive (Geeraerts et al., 2020; Song et al., 2018; Vernon-Feagans et al., 2016), are more likely to over-communicate arousal fluctuations (which can be described as 'shouting to be heard') (Wass et al., pre-print).

Child under-responsiveness can, over time, also affect caregivers' active regulatory behaviours (Geva & Feldman, 2008). For example, caregivers of pre-term children may compensate for under-responsive child behaviour by increasing co-regulatory support, a style that has been characterised as intrusive (Forcada-Guex et al., 2006) and yet may be appropriately adaptive to children's needs. For example, examining the attentional, affective, and emotional responsiveness of mothers and 4-month-old children during a home interaction, mothers of pre-term children were more likely than mothers of full-term controls to vocalise, to smile, and look at their infant following a vocalisation and to respond to infant fusses (Barratt et al., 1992; Reissland & Stephenson, 1999).

Similarly in ASD, infants developing ASD aged 12 months respond less often to their name being called, and look less frequently towards their caregiver during social interactions (Wan et al., 2019a). Concomitant difficulties in initiating episodes of joint attention also develop over the first two years (Jones et al., 2014): in naturalistic, free-flowing interactions, 12-month-olds at elevated likelihood of developing ASD use fewer vocalisations and gestures to direct their adult partner's attention (Yoshida et al., 2020), combine gestures with vocalisations less often (Leezenbaum et al., 2014), and produce fewer speech-like vocalisations (Warlaumont et al., 2014). Early atypical social orienting and joint attention has been shown to disrupt caregiver-child interactions (Wan et al., 2019a). For example, during triadic interactions, caregivers of children at elevated likelihood of ASD produce utterances with more directive content (Woolard et al., 2021), show fewer contingent responses to their children's vocalisations (Edmunds et al., 2019), and receive lower overall ratings of responsivity on global rating scales assessing interaction dynamics (Wan et al., 2019a). Some studies have also demonstrated the opposite effect, with caregivers of children at elevated likelihood of developing ASD showing more contingent responding to their infant's gestures, possibly indicative of compensatory behavioural strategies by the caregiver (Leezenbaum et al., 2014). Supporting the causative role of child atypicality in driving impaired inter-dyadic process, child behaviours, rather than caregiver interaction styles at 12 months, predict later ASD diagnosis (Wan et al., 2019b), and reduced production of speech-like vocalisations among children with autism associates with fewer contingent responses to these vocalisations by the caregiver (Warlaumont et al., 2014).

4c active processes - over-responsiveness

fMRI evidence indicates that anxious caregivers show hyperreactivity to negative cues in regulatory neural circuits (e.g., prefrontal cortex), while the ERP literature points towards hyperreactivity to, and sustained processing of, neutral infant cues (Yatziv et al., 2021). Home studies have suggested that anxious caregivers tend to over-respond to small-scale physiological changes in their child (C. Smith et al., 2021), relative to depressed and control caregivers (Beebe et al., 2008b; Granat et al., 2017a), and to show higher behavioural synchrony with their children during lab-based interaction (Granat et al., 2017b; Lemus et al., 2022b)(Doba et al., 2022). This is consistent with findings that higher levels of caregiver-child synchrony are observed in 'high-risk' samples (e.g., high socio-economic risk; Suveg et al., 2016). Higher synchrony levels in these contexts have been associated with poorer child self-regulation outcomes (DePasquale, 2020a).

During early childhood, caregivers with anxiety are thought to adopt an overloaded, highly stimulating interactional style, consisting of more frequent caregiver expressions (e.g., infant-directed speech and positive facial expressions; Feldman, 2007; Granat et al., 2017a; Murray et al., 2008) when compared with non-anxious, 'healthy' caregivers. As previously noted, this is not observed consistently across all behavioural modalities: over-responsiveness in some modalities associates with under-responsiveness in others (Beebe et al., 2008a). There is also evidence of increased intrusive behaviour, i.e., overcontrolling behaviour that restricts child autonomy (Feldman et al., 1997; Hakanen et al., 2019; Ierardi et al., 2019; Kaitz & Maytal, 2005; Wijnroks, 1999), which has been related to decreased emotion regulation in early childhood (Diemer et al., 2021). These atypical active co-regulatory dynamics impact on the long-term development of socio-communicative behaviours (Perlman et al., 2022).

4d active dysregulatory processes

Active dysregulation, of the sort shown in Figure 4c, is most widely discussed in the context of conditions such as ADHD (Christiansen et al., 2010; E. S. Lunkenheimer et al., 2011; Nigg et al., 2020). Global ratings of hostile, critical, intrusive/reactive and less sensitive caregiver behavioural styles associate with child ADHD symptoms, including hyperactivity, impulsivity and externalising behavioural symptoms, in both clinical and community-based samples (Claussen et al., 2022). It is difficult, however, to disentangle causation. For example, structural modelling approaches have demonstrated predictive associations between caregiver expressed emotions and oppositional behaviours in their children that are mediated by child cortisol levels (Christiansen et al., 2010), as well as longitudinal associations between more intrusive caregiving in the pre-school years and oppositional behaviours age 7 (Keown, 2012). By contrast, behavioural-genetic work suggests a causative role of child ADHD symptoms measured in middle childhood in evoking hostile and critical caregiver behaviours in their adoptive caregivers (Harold et al., 2013).

This work has so far, however, examined caregiver and child behaviour using static, time-invariant methods that assess trait-level characteristics. This makes it hard to distinguish passive dysregulation (as described in 4a) from active dysregulation (see Figure 4c). To better describe the role of inter-dyadic process in the development of ADHD symptomatology, we need to examine transient bi-directional, metastatic, amplificatory influences (i.e. positive feedback from the caregiver that amplifies episodes of negative emotionality in the child; see part 2, Fig.3 (Granic & Patterson, 2006; E. Lunkenheimer et al., 2017; Wass, 2021a)).

In typically developing populations, for example, naturalistic, day-long home recordings of caregivers and children have shown that negative emotional displays by children elicit dynamic and reactive change in caregiver behaviours and physiology. For example, compared to speech-like vocalisations, infant cries elicit faster and overlapping vocal responses from caregivers (Yoo et al., 2018a), and, measuring co-fluctuations in arousal, another study showed that the association between caregiver and infant arousal is stronger in the time following negative, compared to positive affect vocalisations (Wass et al., 2019). One important but untested hypothesis is that transient increases in the association between caregiver and child arousal may be observed in child-caregiver interactions in the ADHD, during active dysregulatory processes characterised (for example) by oppositional behaviour (Granic & Patterson, 2006).

Other research has examined how elevated caregiver anxiety can also give rise to mutually reinforcing active dysregulatory (metastatic) cycles, through which caregiver arousal and child arousal mutually reinforce one another over time (see Fig 4c). For example, one study looked at caregiver vocal behaviour in caregivers with elevated anxiety. In the high anxiety group, caregivers' high arousal levels were more likely to associate with high intensity vocalisations, and caregivers were more likely to vocalise in high intensity, long-lasting clusters (or 'bursts') compared to the low anxiety group (C. Smith et al., 2021). High intensity caregiver vocalisations led, in turn, to sustained increases in arousal among both in children and caregivers in the high, but not the low, anxiety groups (C. Smith et al., 2021).

Part 5 – conclusion

5a Implications for intervention research

It is not within the scope of this review to cover all the intervention work that has targeted child-caregiver interactions in developmental psychopathology (see e.g. (Aktar, Qu, et al., 2019; Rayce et al., 2020; C. G. Smith et al., 2022b) for recent reviews). Here, we confine ourselves to pointing out a few areas arising from our theoretical framework that may currently be under-explored.

Currently, almost all interventions that target child-caregiver interactions have focused on increasing caregivers' contingent responsiveness to their child's cues (Evans et al., 2014) – i.e., targeting the active regulatory influences that we described in Part 2. Other studies have suggested that interventions that target one member of the dyad individually can affect child-caregiver co-regulatory dynamics (Kaaresen et al., 2006); and that interventions targeting child-caregiver co-regulation can affect symptoms in each member of the dyad alone (C. G.

Smith et al., 2022b), with some exceptions (e.g. (Spittle et al., 2015; van der Pal et al., 2008)). Both findings are expected based on the framework we laid out in Part 2.

Our framework has also pointed to several avenues for intervention that, to our knowledge, have not currently been investigated, namely:

i) targeting an optimal mid-range of contingency. We have described extensive evidence from studies examining face-to-face interactions in lab-based studies that a mid-range of contingency is considered optimal; however, almost all interventions currently target under-attunement or low levels of synchrony. Future research should consider over-contingency, as described above in the context of ADHD and anxiety.

ii) identifying triggers for active dysregulatory cascades. Some previous intervention work has targeted active, mutually amplificatory dysregulatory cascades (Granic & Patterson, 2006). But future work with non-invasive home wearables will increase our understanding of how we transition between active regulation and active dysregulation. This includes the possibility of using personalised wearables to help identify specific triggers of child-caregiver dysregulation in individual families.

iii) capture, then hold. We described how, in the context both of arousal co-regulation and attention co-regulation, active regulatory influences do not simply take place through negative feedback (in which increases in one partner's arousal (for example) are met by compensatory decreases in the other partner's arousal). Rather, the process is one in which caregivers first upregulate their arousal (for example) in order to match the child's state, before subsequently down-regulating in order to help the chid calm down. This idea could be incorporated more widely into intervention research (see eg (Welch, 2016)).

iv) targeting compensatory mechanisms. In section 4 we discussed how atypical behaviours in one member of the dyad can, over time, lead to compensatory atypical behaviours in the other partner. It remains relatively under-explored, however, how these compensatory behaviours affect long-term psychopathology. Explicitly targeting compensatory caregiver behaviours (for example by raising caregiver awareness about how their child's interactional behaviours may be atypical, and what they can do to compensate for it) should be a target for future research (Green et al., 2020).

v) identifying individual differences in attractor states. In part 2 we described how the fundamental aim of co-regulatory processes is to maintain stability about an optimal 'critical state', intermediate between hypo- and hyper-activity. It is likely, although underexplored, that the location of this critical state (the state that elicits neither up- nor down-regulation) differs between dyads (Somers, Curci, et al., 2021). Understanding these differences may have important therapeutic potential. For example, a dyad accustomed to interactions with high levels of mutual arousal might find it easier to transition to a high arousal positive interaction than to an interaction focused on down-regulating arousal. However, our understanding in this area is currently limited.

vi) relationship between tonic state and phasic (contingent) responsiveness. In part 2d we described how the relative paucity of long-term home observation studies means that we understand little about how fluctuations with a caregiver's state systematically affect how a caregiver responds, for example, to child distress. Nevertheless, it is likely that there are systematic patterns of association (Fig 5). Biofeedback and metacognitive awareness training can specifically improve the caregiver’s responsiveness around these moments where their atypical state is likely to influence atypical phasic responsiveness to their child.

5b Goals for future research

Understanding co-regulatory dynamics across multiple time-scales. Almost all of the research we have reviewed has studied relatively short bursts of caregiver-child interaction, often recorded in the lab, across the time-scale of seconds and minutes. Studying both more fine-grained and more coarse-grained dynamics will help address a range of theoretical questions that currently are unanswered (Cole et al., 2020; Hollenstein, 2015). First, using techniques such as dual EEG to study interaction dynamics at the millisecond-level scale will help differentiate contingent interactions (in which one partner leads and other follows, or one partner predicts or anticipates the other) from truly synchronous interactions (in which concurrent processes take place). At the moment, the concept of synchrony is much discussed (DePasquale, 2020b; Feldman, 2007; Thompson et al., 2020b); but to achieve a full mechanistic understanding of whether synchrony emerges from contingency, or whether it emerges independent of it, a fine-grained temporal resolution is needed.

Second, larger-scale recordings over days, weeks, months and years, collected using home wearable devices, will allow us to address a range of unanswered questions. For example, we currently only have rudimentary understanding of passive dysregulatory influences, through which the simple state of one partner in one state induces the other partner to enter into the same state. Long-term recordings would help us to understand, and track, these potentially important long-term influences. We also currently only have limited understanding of how the tonic state of a caregiver (e.g. the state that they are in at the time when the child initially makes a communicative signal) influences how they respond to that communicative signal (part 2d, Figure 5). Long-term recordings would help us to improve our understanding here.

Larger-scale recordings would also help to identify some critical questions concerning co-regulation that currently are inadequately understood. For example, if the goal of co-regulation is to help the child to maintain an optimal ‘critical’ state intermediate between hypo- and hyper-arousal, then where exactly does this critical state lie (Somers, Luecken, et al., 2021)? Does it differ from child to child, and between settings? And does it change over time? One way to answer these questions is to collect large volumes of data and apply phase space analyses to identify attractor dynamics (Dezhina et al., 2023; Lazarus et al., 2023b) - i.e., intermediate states that attract neither up- nor down-regulation of arousal. This approach will also allow us to identify multistable dynamics (i.e. different states that are stable in different ways) - such as periods where metastatic, dysregulatory caregiver-child interaction dynamics dominate.

Do interaction dynamics become more, or less, important over development? We also understand remarkably little about how co-regulation dynamics change and evolve over time (Amado et al., under review; Gonçalves et al., 2020). It is likely that, for example, mutually dysregulatory caregiver-child cascades become more common as child oppositionality develops between infancy and toddlerhood (Fields-Olivieri & Cole, 2022; E. Lunkenheimer et al., 2017). But individual differences in the trajectory of child-caregiver co-regulation remain inadequately understood.

Understanding co-regulation of positive valence systems. In part 3 we discussed how children express negative affect to elicit co-regulation, to help manage hyper-arousal. The sharing of positive affect within child-caregiver interactions is also known to be atypical (in caregivers with depression, for example), but it remains poorly understood how positive valence systems - such as reward responsiveness, anticipation and valuation - are affected by, and develop through, caregiver-child co-regulation (Kidby et al., 2023; E. Lunkenheimer et al., 2020).

5c Summary

Co-regulation of arousal, affect and attention is multimodal, asymmetric, and child-led.

Co-regulatory influences on CNS arousal and emotional control operate in two pathways. First, via passive processes: adults' arousal patterns are generally stabler than those of children, and adult states directly influence child states because arousal states are contagious. Similar processes of passive co-regulation affect also affect attention development: adult attention patterns are longer, and drive sustained child attention, for example through object-related talk.

The second type of pathway through which co-regulatory pathways operate are active, interactive contingencies: the child initiates and the caregiver responds contingently. These processes are interactive, but (during early development) primarily asymmetric: caregivers adapt to the child more than *vice versa*.

Most current theories emphasise that social influences operate via a one-way flow of information from the adult 'teacher' to the child 'learner' (Csibra & Gergely, 2009), which emphasise how the child responds contingently to the adult (e.g. through imitation (Brooks & Meltzoff, 2014). But in fact, the picture emerging from the micro-dynamic analyses and dual-brain studies suggests that attention co-regulation is in fact quite similar to arousal co-regulation. Children rarely use ostensive signalling during early interactions (Beebe et al., 2016; E. Phillips et al., 2021; Yu & Smith, 2013) and can be remarkably insensitive to caregivers' ostensive signalling (Marriott Haresign et al., 2023). But during face-to-face, tabletop interactions, both shared entrainment and interactive contingencies develop (Moreno-Núñez et al., 2017; Wass et al., 2021). Just as for arousal co-regulation, interactive contingencies in attention tend to be asymmetric, with the child initiating, and the adult responding contingently. Children are highly sensitive to when their behavioural initiations elicit a caregiver response (E. Phillips et al., 2021).

We have also discussed convergent evidence suggesting that active regulatory influences do not simply take place through negative feedback (in which increases in one partner's arousal (for example) are met by compensatory decreases in the other partner's arousal). Rather, the process is one in which caregivers first upregulate their arousal in order to match the child's state, before subsequently down-regulating in order to soothe the child – a process of positive feedback followed by negative feedback. Similar principles apply for attention co-regulation as for arousal co-regulation, which may be adaptive in some circumstances but less adaptive in others.

We also discussed extensive evidence which suggests that atypical short-term interactive behaviours in one member of the dyad can, over time, contribute to the development of compensatory atypicalities in the other member of the dyad. These long-term influences are not asymmetric: we discussed evidence that atypical caregiver behaviours can lead to compensatory changes in the child, and that atypical child behaviours can lead to compensatory changes in the caregiver.

Atypical co-regulation.

We also outlined a range of ways in which these co-regulatory processes can become atypical. We found little research that directly examined atypical passive entrainment - for example, by examining how atypical long-term arousal patterns in the adult directly influence the child. This requires the collection of large corpora of home interaction data, which are still rare. There is, though, a large body of research that has examined atypical interactive contingencies, normally during short bursts of lab-based interaction.

Active under-responsivity. Some caregiver-child dyads can show under-responsivity - i.e. insufficient contingency. These atypicalities are limited to particular modalities of caregiver-child interaction: typical caregiver-child interactions show in fact only selective contingent responsiveness to certain modes of interaction (Murray et al., 2016), and these modalities likely differ between cultures, in a way that remains inadequately understood (Feldman, 2006). Nevertheless, we reviewed several studies which suggested, for example, that depressed caregivers respond less contingently to their children during both arousal co-regulation, and attention co-regulation; and that children with ASD are less responsive to their parents. We discussed how these atypical short-term dynamics affect long-term development across the dyad.

Although theoretical models predict that under-responsivity within a caregiver-child dyad ought to affect the long-term development of child-caregiver attachment (Ainsworth, 1979), and although we have reviewed considerable evidence that examines how short-term interactive dynamics differ across different attachment styles, there is currently little to no empirical evidence that specifically examines how early passive and active arousal coregulation gives rise to atypical communicative behaviours observed in attachment studies (Stern et al., 1975). And, while several authors have speculated that contingent caregiver responding may play a long-term role in facilitating the development of self-awareness and self-agency (L. B. Smith & Breazeal, 2007), and may contribute to the development of predictive neural coding mechanisms in the brain ((Köster et al., 2019), Hunnius, 2022) there is also little to no current evidence that tests these long-term effects.

Active over-responsiveness. We also presented evidence that insufficient contingency/synchrony is, on its own, insufficient to explain atypical coregulation. The literature review has pointed to an optimal mid-range of inter-personal entrainment (i.e. neither over- nor under-responsive) that is transient i.e. comes and goes when needed; (Granat et al., 2017a; Ham & Tronick, 2009; Jaffe et al., 2001). In conditions such as anxiety, research has pointed to *increases* in inter-personal entrainment. This suggests that the conventional model, that we should maximise child-caregiver contingency and, through that, child-caregiver synchrony, may be overly simplistic.

Another under-explored potential avenue for intervention research is in supporting anxious caregivers to develop skills akin to stress buffering (Palumbo et al., 2017). This might consist, for example, of assisting caregivers with downregulating mutually high levels of anxious arousal in the caregiver-child dyad, through a process of first understanding and recognising bodily signs of rising stress (in both adult and infant), and subsequently practising stress reduction techniques. To our knowledge, there is currently little to no intervention research looking at this from a dyadic perspective.

Active dysregulation. In part 2 we discussed how the goal of co-regulation is to help the child to maintain a 'critical state', intermediate between under-activity and over-activity (see Glossary for definition) (Atzil et al., 2018). But we have also discussed evidence that, in some situations, the opposite pattern can develop, giving rise to active dysregulation (metastatic processes) (Wass, 2021a). As we describe in the context of ADHD, for example, increases in child arousal might be followed by an increase in child oppositional behaviour, followed by an increase in caregiver CNS arousal, followed by an increase in caregiver expressed emotions, followed by a further increase in child arousal, and so on (Granic & Patterson, 2006; Hollenstein et al., 2017; E. Lunkenheimer et al., 2017; C. Smith et al., 2021; Wass, 2021a) (see Figure 3c). Because they are hard to elicit and study in the lab, these types of child-caregiver interactions are under-researched, both in the context of observational and intervention studies.

Future theoretical work is needed to help differentiate between active, or voluntary, contingent responding and passive, or involuntary responding, in order to help differentiate the causes of allostasis and metastasis. And future practical work will help to explore possible therapeutic implications of this research. For example, home wearables might in future be used in interventions to help individual dyads to identify their individual triggers for dysregulatory cascades, to help prevent them when they occur.

Conclusion

'Do not call it fixity,/Where past and future are gathered' (Eliot, 1922). Dyadic interactions are fluid and constantly changing; movement creates stability. Fine-grained analyses based on short lab-based interactions have uncovered much that is important about how child-caregiver interactions develop atypically, with important consequences for intervention research. In future, more long-term observational studies will teach us more about the long-term dynamics of this crucial early dance that we dance with our caregivers, which teaches us how to live.

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