

Allostasis and metastasis: the yin and yang of childhood self-regulation

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Abstract

Most research has studied self-regulation by presenting experimenter-controlled test stimuli and measuring change between a baseline period and the stimulus. But in the real world we are not passive recipients of discrete chunks of external stimulation, to which we in turn respond; rather, the real world is continuous and we self-regulate by adaptively selecting which aspects of the social environment that we attend to from one moment to the next. Here, we contrast two dynamic processes that guide this process – the ‘yin’ and ‘yang’ of self-regulation. First, allostasis, through which we dynamically compensate for change to maintain homeostasis. This involves upregulating in some situations and downregulating in others. And second, metastasis, the dynamical principle underling dysregulation. Through metastasis, small initial fluctuations can become progressively amplified over time. We contrast these processes at the individual level (i.e. by examining moment-to-moment change in one child, considered independently) and also at the inter-personal level (i.e. by examining change across a dyad, such as a parent-child dyad). Finally, we discuss practical implications of this approach in improving the self-regulation of emotion and cognition, in typical development and psychopathology.

Keywords: self-regulation, attention control, self-control, emotion reactivity, emotion regulation, infancy, childhood

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1 Introduction

1.1 - Introduction

Hindu and other Eastern mythologies view the universe as a stable oscillator, in perpetual but stable motion (Capra, 2010). At a much smaller scale, and although the concept can be traced back to Hippocrates (Cofer & Appley, 1964), it was Claude Bernard who first proposed that maintaining the relative constancy of the internal environment might be one of the operational principles of life (Gross, 1998).

Our stress response (originally called General Adaptation Syndrome (Selye, 1951)), is the dynamical system through which we adaptively respond to external change in order to maintain internal constancy. Although our stress systems are multifarious (Gunnar & Quevedo, 2007; Sapolsky, 2015), here we concentrate on the Autonomic Nervous System (ANS) and the network of brain regions and neurotransmitters involved in controlling arousal and regulatory function (see Aston-Jones & Cohen, 2005; Cacioppo, Tassinary, & Berntson, 2000; Pfaff, 2018; S. V. Wass, 2018 S. Wass, 2020; Waterhouse & Navarra, 2019 Porges, 2007 for recent reviews). The ANS can be studied both as one reciprocally connected subsystem, and as multiple differentiable sub-systems (Pfaff, 2018; S. Wass, 2020 Calderon, Kilinc, Maritan, Banavar, & Pfaff, 2016). Both approaches are partially true (Calderon et al., 2016); here, we treat it mainly as the former. Optimal ANS arousal (henceforth ‘arousal’) lies at an intermediate point between over- and under-arousal (McCall et al., 2015; Samuels & Szabadi, 2008; Thayer, Hansen, Saus-Rose, & Johnsen, 2009; S. Wass, 2020).

Allostasis describes the active process through which internal equilibrium (homeostasis) is achieved and maintained (Cannon, 1929; McEwen & Wingfield, 2003; Ramsay & Woods, 2014; Sterling, 2012; Selye, 1951). When there is a discrepancy between the current level of activation and the optimal level or range for the given situation, the organism will typically engage in behaviour designed to shift activation to reduce the discrepancy (Fiske & Maddi, 1961). As an active process, allostasis can involve trade-offs between different systems in the body – the baroreflex, for example, involves changes in heart rate to compensate for variations in blood pressure (Berntson & Cacioppo, 2007). But it can also involve trade-offs over time: for example, the body cannot effectively mobilize fuel and oxygen to meet catabolic demands while simultaneously siphoning them off for growth and repair; allostasis involves managing trade-offs between the two (Sterling, 2012).

When used by psychologists and cognitive neuroscientists, allostasis typically refers to the behavioural processes through which an intermediate level of arousal is established, and maintained. In this article, we describe evidence for allostatic mechanisms during childhood. And we introduce a new distinction between allostasis, the dynamical principle underlying self-regulation, with its opposite process, which we characterise as metastasis - the dynamical principle underlying dysregulation. We present common-sense argumentation and empirical data that both point to the existence of metastatic processes during childhood, and we argue that these processes are relatively under-researched.

The remainder of the article is structured as follows. First, we contextualise our approach by laying out our motivation for studying self-regulation and dysregulation from a dynamic perspective (section 1.2). Next, we contrast the two processes of allostasis and metastasis (section 1.3), and offer common-sense arguments for the existence of the latter (section 1.4).

Then, in sections 2 and 3, we examine empirical data for the existence of these processes, considering separately actor-environment interactions (section 2) and actor-actor interactions (section 3). In section 4 we discuss outstanding questions, and in section 5 we describe quantitative approaches that might in future help to address these questions.

1.2 - 'Passive viewer' approaches to the regulation of emotion and cognition

“in real life, the environment generally does not deliver an isolated stimulus and then patiently wait for one to emit an isolated response.”

(Spivey & Dale, 2006)

Behavioural scientists commonly assess a child's capacity for self-regulation of emotion using experiments such as a toy removal task (Gagne, Van Hulle, Aksan, Essex, & Goldsmith, 2011). In this paradigm, a child is allowed play with a toy before an experimenter takes it and places it out of reach, before returning it after a time interval (Gagne et al., 2011). The same sequence is presented across a number of discrete but contiguous trials, and the child's behavioural and physiological responses are averaged.

Compare this with an ecologically valid equivalent – say, a child tantruming at not being allowed to buy a toy while out shopping. A child might pick up a toy, and announce that they want it; their parent, tired and in a hurry, might abruptly say 'no', and attempt to take the toy off them, perhaps leading to a physical tug of war. The child might lose this, sit down with a bump, and burst out crying. Or, they might start bashing the toy on the floor and break it; others in the shop might turn around to look at the noise. This series of events – being abruptly told

‘no’, a tug of war, sitting down with a bump, making a loud noise, being stared at by strangers – are all independent, exogenous causes of increased arousal. The toy removal is just a trigger for an ongoing cascade featuring multiple interconnected causative factors that interact nonlinearly.

It has been over a hundred years since Dewey first criticised our tendency to assume that stimulus-response sequences happen discretely, in serial, and without overlap: “What we have is a circuit, not an arc or broken segment of a circle. [. . .] The motor response determines the stimulus, just as truly as sensory stimulus determines movement. [. . .]” (Dewey, 1896, p. 365). Given this, the continued pervasiveness of the ‘stimulus-response doctrine’ is surprising (S. Edelman, 2016; Kingstone, Smilek, & Eastwood, 2008; Kolodny & Edelman, 2015; Osborne-Crowley, 2020; Risko, Richardson, & Kingstone, 2016; Spivey & Dale, 2006; but see Holleman, Hooge, Kemner, & Hessels, 2020). Even now, most experimental assessments of self-regulation rely on exposing the participant to experimenter-controlled events, and averaging participants’ responses.

Because of this, previous authors (Cole, Loughed, Chow, & Ram, 2020; Cole, Ram, & English, 2019; Cole, Ramsook, & Ram, 2019; Morales et al., 2018; Rabinovich, Muezzinoglu, Strigo, & Bystritsky, 2010; Thayer & Lane, 2000; Thelen, Schöner, Scheier, & Smith, 2001; Wichers, Wigman, & Myin-Germeys, 2015) have argued instead in favour of an approach that views self-regulation as the product of constant, dynamic interactions between factors endogenous to the child and factors exogenous to them. Dynamics is “the free interplay of forces and mutual influences among components tending toward equilibrium or steady states” (Kugler, Kelso, & Turvey, 1980, p.6). Reflecting this, we consider that self regulation is not an attribute *of* individuals. Rather, that self regulation takes place *through* interactions with the

environment (actor-environment interactions) and with other people (actor-actor interactions). If you take an individual away from their environment, and from other people, then you take away their capacity to self-regulate (G. M. Edelman, 1989; R. Feldman, 2009; Levenson, 1988; A. Sameroff, 2009).

1.3 Two dynamical principles

But what dynamical principles might underlie *how* we select our responses on a moment-by-moment basis? Here, we contrast two dynamical principles. The common property of these is that, in each case, a participant's response at time $t+1$ is systematically influenced by their state at time t . But the direction of the influence is opposite.

The first is allostasis – i.e., the process through which we dynamically compensate for change in order to maintain homeostasis (Atzil, Gao, Fradkin, & Barrett, 2018; McEwen & Wingfield, 2003). Allostasis is not a static mental resource – as is implicitly assumed by studies that measure an individual's the capacity for self-regulation in the same way that, for example, other researchers (Gathercole & Alloway, 2008) might attempt an individual's working memory capacity. Rather, allostasis is dynamical. For example, when something occurs that exogenously increases arousal, allostatic principles might drive us seek out a lower level of stimulation, thereby decreasing arousal. And when something that occurs to decrease arousal we might endogenously change our behaviour to increase arousal. In many ways, these processes are similar to negative feedback (see Figure 1) – but, as we describe in sections 2 and 3 below, they are not exactly the same. Allostasis is the dynamical principle underlying self-regulation.

INSERT FIGURE 1 HERE

Relatively less attention has been paid to the opposite processes (although see e.g. Cole, Bendezú, Ram, & Chow, 2017). In this article we coin the term ‘metastasis’ (derived from the Greek word ‘meta’ meaning ‘beyond’) to describe these. If allostasis is the dynamical principle underlying self-regulation, then metastasis is the dynamical principle underlying dysregulation. Models for similar processes abound in biology – such as metastatic tumours, for example. Where allostatic processes involve small initial increases and decreases in arousal becoming corrected for over time, metastatic processes are the opposite: they involve small initial increases and decreases in arousal becoming amplified over time. Again, this process is close but identical to ‘positive feedback’ (see Figure 1) – as we discuss further in section 3.

1.4 Real-world examples of metastasis

In section 1.2 we gave the example of a child tantruming in a shopping centre. We argued that, in the real world, emotion dysregulation takes place through multiple, reciprocally interconnected, self-sustaining and nonlinear interactions between the actor and the environment, and between the actor and other actors.

There are numerous other common-sense examples of similar self-sustaining, nonlinear emotion dysregulation dynamics. For example, most parents have observed a young, agitated child banging their spoon on the table at mealtimes, which seems to agitate them still further – or deliberately bashing the sides of their cot at night when they can’t sleep, which seems to keep them awake for longer. Similarly, many parents have observed an agitated child to move faster or less carefully, and to break something or hurt themselves, which seems to increase

agitation further, making them move still faster. But these types of self-sustaining cycles have received surprisingly little theoretical attention hitherto.

In adult psychology, similar processes are better understood. At the cognitive level, for example, clinical research has identified maintenance factors that actively maintain, and amplify, anxiety symptoms (Salkovskis, 1991). In panic disorder, for example, paying increased attention to physiological symptoms can cause their subsequent amplification (Clark, 1986). Similarly, rumination (Ehring, Frank, & Ehlers, 2008), attention biases to threat (Pine et al., 2005) and maladaptive compensatory strategies such as thought suppression (McMahon & Naragon-Gainey, 2018) are all thought to actively maintain, and amplify, initial symptoms (Salkovskis, 1997). Other research has, similarly, taken a systems-level perspective to investigate how attention regulation and affective processes interact during inhibition (such as disengaging from a distressing stimulus), and to contrast it with how these processes interact during *dysregulation* (such as paying increased attention to a distressing stimulus) (Friedman, 2007; Thayer & Lane, 2000; Pérez-Edgar, 2018).

In this article, we consider similar dynamical metastatic processes from the perspective of child development. And, in addition, we also consider the flip-side: as well as examining how *increases* in arousal can become amplified over time, we also consider whether similar processes might also explain how *decreases* in arousal can become amplified over time. Again, common-sense arguments appear to suggest that they do. Thus, for example, a child's arousal state can influence whether or not they engage with a complex new stimulus (Richards, 1987; Van der Meere & Sergeant, 1988; S. Wass, 2020); but engagement, and comprehension, is thought to *cause* changes in arousal (Pempek et al., 2010; Richards, 2010). Thus, decreased arousal might cause increased engagement, causing decreases in arousal (D. R. Anderson &

Lorch, 1983; Richards & Anderson, 2004), leading to a similar pattern of fluctuations in arousal becoming amplified over time.

Two recent papers have suggested that metastatic processes might influence naturalistic arousal during early childhood. For example, one study took day-long naturalistic recordings to examine fluctuations in autonomic arousal (derived from a mixture of heart rate, heart rate variability and movement) in 12-month-old infants (see Figure 2). Based on the above-discussed literature on allostatic regulation, they predicted that, if fluctuations above and below the mean are corrected for via self-regulation, then over longer time-scales intermediate arousal states should be more long-lasting than high or low arousal states (S. V. Wass, Clackson, & Leong, 2018; S. V. Wass, Smith, Clackson, & Mirza, 2020). In fact, they found the opposite: across multiple time-scales, high and low arousal states were more long-lasting than intermediate arousal states. One explanation for this finding is that different arousal states have different intrinsic levels of hysteresis. Another is that metastatic processes may operate during early childhood, similar to those identified in adult clinical psychology (see also Cole et al., 2020).

INSERT FIGURE 2 HERE

Both allostasis and metastasis can be instantiated through interactions between one actor and the environment (henceforth, actor-environment interactions). But they can also be instantiated through inter-personal relationships (henceforth, actor-actor interactions). We consider the former (actor-environment) interactions in section 2 and the latter (actor-actor) in section 3. In section 4 we discuss outstanding questions, and in section 5 we describe quantitative approaches that might help to address these questions.

2 – Actor-environment

2.1 Allostatic mechanisms

Even newborns have a tendency to close their eyes when overstimulated (Brazelton, 1983). Other early experiments examined video-coded behaviours such as gaze aversion, which down-regulates arousal (T. M. Field, 1981). Even at 5 months, infants were more likely to show gaze aversion following a experimenter-administered toy removal, which up-regulates arousal (Buss & Goldsmith, 1998; Stifter & Braungart, 1995 Kopp, 1982). Other research has examined other putative down-regulatory behaviours, such as distraction, self-soothing, calming self-talk and proximity seeking, across typical and atypical development (Ruth Feldman, Dollberg, & Nadam, 2011 Nigg, 2017 Doherty-Sneddon, Riby, & Whittle, 2012). Overall, these results are consistent with a framework in which even young infants are more likely to show down-regulatory behaviours following an external stressor. (Although of note, most studies have simply tested for the presence of behaviours that are assumed to be down—regulatory, without actually testing whether they are or not.)

In addition to studies which examine the likelihood of particular behaviours within particular time-windows, other studies have specifically examined how behaviours change over time. These studies are essential, for example, to differentiate children who show high reactivity but good regulation from those who show low reactivity (Kahle, Miller, Helm, & Hastings, 2018; Ursache, Blair, Stifter, & Voegtline, 2013); and also to study how the use of regulatory strategies affects emotional recovery (Cole et al., 2017; Cole et al., 2020; Cole, Ram, et al., 2019; Cole, Ramsook, et al., 2019). For example, one study continuously coded children's overt displays of emotions (facial and vocal affect) and their use of executive processes (e.g. thumb-sucking as self-soothing) during a frustration-eliciting task (Cole et al., 2020; see also

Morales et al., 2018). Dynamical modelling techniques (see section 5) were used to capture age-related changes in the bidirectional coupling between the two variables. Results showed coupling between the two variables, such that executive processes had a direct influence on changes in emotional displays at all ages. The strength of this coupling was stable between 24 months and 5 years. When examining coupling in the opposite direction – how emotional displays affect executive processes – they also found that emotions tended to inhibit the use of executive processes (Cole et al., 2020) (see also Cole et al., 2017 and section 4 for further discussion of this point).

The studies described thus far have examined how children down-regulate following increases in arousal. Only a smaller body of research has examined how children up-regulate following decreases in arousal, to maintain an optimal intermediate level. Gardner, Karmel and colleagues measured how young infants' preference for less arousing, low frequency visual stimuli vs more arousing, high frequency visual stimuli (see Figure 3) varied contingent on their own arousal (Gardner & Karmel, 1984, 1995; Gardner, Karmel, & Flory, 2003; Gardner, Karmel, & Magnano, 1992; Geva, Gardner, & Karmel, 1999). (The determination of whether low frequency visual stimuli were in fact more arousing was measured separately, by recording heart rate.) They found that highly aroused individuals preferred less arousing, low-frequency stimuli, whereas less aroused infants preferred more arousing, high-frequency stimuli (Gardner & Karmel, 1984, 1995). These results suggest that infants dynamically recalibrate their attentional behaviours to downregulate their own arousal when it is high, and to upregulate it when it is low. To our knowledge, these studies are the only ones to have shown this.

INSERT FIGURE 3 HERE

2.2 Metastatic mechanisms

In part 2.1 we considered allostatic actor-environment interactions, through which we compensate for increases (or decreases) in arousal by changing how we interact with the environment in such a way as to correct for the change in arousal. Here, in part 2.2, we consider the opposite processes: metastatic actor-environment interactions, through which we respond to increases (or decreases) in arousal by changing how we interact with the environment in such a way that the increases (or decreases) in arousal become amplified.

Researchers working in ADHD have examined how increases in arousal can become amplified over time. For example, a number of researchers have suggested that hyper-arousal may cause a preference for fast-paced visual stimuli (Beyens, Valkenburg, & Piotrowski, 2018), and for smaller but more immediate rewards (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Sonuga-Barke, Wiersema, van der Meere, & Roeyers, 2010); and that fast-paced visual stimuli and immediate rewards are, in turn, more likely to *cause* increases in arousal (Beyens et al., 2018; Van der Meere & Sergeant, 1988). However, this research has, to our knowledge, only been conducted at the trait-level (i.e., ‘do children with ADHD tend to be more aroused on average, and to prefer fast-paced stimuli’), and not at the state-level (i.e., ‘at times when a child is more aroused do they tend to prefer fast-paced stimuli’).

Within adult psychology, as discussed in section 1.3, research has also identified factors that can dynamically maintain, and amplify, anxiety symptoms (Salkovskis, 1991; Thayer & Lane, 2000). Similarly, research with infants and children has suggested that increased vigilance to novelty and threat may cause the emergence of anxiety symptoms during later development

(Pérez-Edgar et al., 2010; Dudeney, Sharpe, & Hunt, 2015; Pérez-Edgar, 2018; Roy, Dennis, & Warner, 2015). Attention mechanisms may lead behaviourally inhibited children to resort to habitual and inflexible repertoires in new environments (Pérez-Edgar, 2018), which amplifies behavioural inhibition. Certainly, trait-level anxiety can affect bottom-up capture and the processing of irrelevant stimuli (Rossi & Pourtois, 2017), which affects how children explore and exploit the environment (Reader, 2015). Importantly, however, and as with the research in ADHD described above, both of these ideas have thus far only been explored as trait- and not state-level features.

We can also consider the opposite type of amplificatory process: how *decreases* in arousal can become amplified over time. As we described in section 1.2, we know that a child's arousal state can influence how they react when a complex or slow-paced new stimulus is presented (Richards, 1987; Van der Meere & Sergeant, 1988) – either engaging with it, or not. At the same time, comprehensible stimuli (e.g. TV programs with the shots correctly ordered vs randomly re-shuffled) elicit greater changes in arousal (Pempek et al., 2010; Richards, 2010). Thus, a decrease in arousal might cause increased engagement with a complex or slow-paced stimulus, which causes further decreases in arousal. This might explain why attention patterns in naturalistic settings show a non-linear self-sustaining character – such that, the longer a look lasts, the more its likelihood of ending during the next successive time interval diminishes (Daniel R Anderson, Alwitt, Lorch, & Levin, 1979; D. R. Anderson & Lorch, 1983; Richards & Anderson, 2004).

In section 4 we discuss outstanding questions with regard to both allostasis and metastasis. First, though, in section 3, we consider allostasis and metastasis from the perspective of actor-actor interactions.

3 Actor-actor

3.1 Allostatic mechanisms

Co-regulation (within the dyad), as opposed to self-regulation (within the individual), is considered particularly important during early development (Kopp, 1982; Tronick, 1982; Bridgett, Burt, Edwards, & Deater-Deckard, 2015; Butler, 2011; Fogel, 1993; A. J. Sameroff, 1983). Research has shown that increases in child arousal are corrected faster in the presence of a caregiver than in their absence (Ham & Tronick, 2009; Shih, Quiñones-Camacho, Karan, & Davis, 2018), and that how a parent responds when their child is challenged predicts how quickly the child recovers (Bornstein & Suess, 2000; Leerkes, Su, Calkins, Supple, & O'Brien, 2016; Shih et al., 2018). This suggests that allostatic actor-actor mechanisms are important, at least during early development. Infants are sensitive to whether their partner is contingently responding to them (Murray, 1985; Rayson, Bonaiuto, Ferrari, Chakrabarti, & Murray, 2019), and dyads showing more contingent caregiver-child interactions also show superior affect regulation (Beebe et al., 2010; Murray, 1985), as well as superior infant attention and learning (Goldstein, Schwade, Briesch, & Syal, 2010; Jaffe et al., 2001; Mason, 2018; Mason, Kirkpatrick, Schwade, & Goldstein, 2019). Recent theories have also suggested that allostasis plays a role at other levels, such as in the development of Bayesian predictive coding mechanisms in the brain (Atzil et al., 2018).

However, although the concept of actor-actor allostasis is well advanced, there are inconsistencies in *how* adults are thought to modulate their own arousal state in response to an increase (or decrease) in child arousal. Affective states are contagious (Heyes, 2018; Waters, West, Karnilowicz, & Mendes, 2017; Waters, West, & Mendes, 2014). We could predict, then, based on the concept of negative feedback discussed in section 1.3, that adults would perform

the opposite changes to those shown by their child – e.g. reducing their arousal at times when their child’s arousal is high. Through this, they would *disconnect* their own state from that of the child in order to help their child’s arousal to regain equilibrium through affect contagion. In fact, though, the majority of the literature into how allostatic mechanisms operate across dyads has looked for the *opposite* relationship: that parents *match*, or *connect* their own state to that of the child (Dezecache, Jacob, & Grezes, 2015) in order to help the child regain equilibrium (R. Feldman, 2007). This is motivated by research findings showing that empathy involves matching one’s own physiological or neural state to the state of the person with whom one is empathising (Levenson & Ruef, 1992; Wicker et al., 2003).

Sometimes, both types of response can be observed within a single study. For example, a recent study found that parent’s starting arousal level determines whether they respond to an increase in their child’s arousal by increasing their own arousal (to connect) or by decreasing their own arousal (to disconnect) (Wass. et al., in press). One further distinction that may be important here is between emotional contagion, which is early-developing and involuntary, and more controlled processes of interpreting those feelings, which are later developing and effortful (Heyes, 2018 (see also Dezecache et al., 2015; Singer & Klimecki, 2014). Heyes calls the former Empathy1 and the latter Empathy2 (Heyes, 2018). Possibly, ‘connecting’ may involve Empathy1-type responses and ‘disconnecting’ may involve Empathy2-type responses.

Also of note, not all theorists consider that allostasis is the sole principle underlying co-regulation. For example, some research has suggested that the ideal interaction is not of absolute coordination, but rather is “messy”, involving the mismatch of responses and their subsequent repair (Ham & Tronick, 2009; Jaffe et al., 2001; Tronick, 2007). Tronick suggests

that these moments of disconnection do have a functional significance, but it not the systematic ‘negative feedback’ disconnection discussed here (Ham & Tronick, 2009).

3.2 Metastatic mechanisms

Research into metastatic processes within caregiver-child dyads is most well advanced for ADHD, where parental expressed emotions (i.e., hostility, criticism, low warmth) are thought to operate both as causes, and as consequences, of oppositional child behaviour (Harold et al., 2013; Taylor, 1999) (see also Baker, Fenning, Howland, & Huynh, 2019; Combs-Ronto, Olson, Lunkenheimer, & Sameroff, 2009; Overbeek, Creasey, Wesarg, Huijzer-Engbrenghof, & Spencer, 2020). For example, one study found that parents with higher expressed emotions had children with larger cortisol responses, and that child cortisol reactivity mediated the link between parental expressed emotions and child oppositional behaviours (Christiansen, Oades, Psychogiou, Hauffa, & Sonuga-Barke, 2010). Again, however, this research has been conducted at the trait-level (i.e., ‘do parents of children with ADHD tend to show more expressed emotions on average?’) rather than the state-level (i.e., ‘how do child/parenting arousal and parenting strategies tend to co-fluctuate during the day?’). Because of this, we understand little about what triggers, and what defuses, amplificatory parent-child interactions; whether parent-child oppositionality occurs in multiple brief bursts or fewer, more sustained episodes; and how, for example, parents may use different disciplining tactics contingent on their own fluctuating physiological stress.

Other research has examined similar processes in dyads where the parent has anxiety or depression (R. Feldman et al., 2009; T.M. Field, Healy, Goldstein, & Guthertz, 1990; Granat, Gadassi, Gilboa-Schechtman, & Feldman, 2017; Smith et al., in press). Parents with high

anxiety are thought to adopt an overloaded, high stimulating interactional style (R. Feldman et al., 2009), and to over-respond to small-scale physiological changes in their child (Smith et al., in press); whereas parents with depression are thought to be generally under-responsive (Amole, Cyranowski, Wright, & Swartz, 2017; T.M. Field et al., 1990). However, the metastatic underpinnings of these processes (i.e. how the child's behaviour affects the adults, which in turn affects the child, and *vice versa*) remain inadequately understood.

Similar ideas have also been discussed, but again remain relatively underexplored, in Autism Spectrum Disorders (ASD). For example, it is thought that, in at least some children with ASD, increases in arousal may associate with eye gaze avoidance (Kaartinen et al., 2012; although see Nuske, Vivanti, & Dissanayake, 2015); and a separate series of studies has shown that parents of children who show less parental engagement start, in turn, to make fewer efforts to engage with their children (Wan, Green, & Scott, 2019) – which, given the known role of parent-child engagement in co-regulation of arousal (Kopp, 1982), may contribute to a metastatic cycle. Again, however, these ideas have thus far been explored at the trait- and not the state-level.

In section 3.1, we discussed problems with considering allostasis purely as a 'negative feedback' process. This is because parental responding sometimes involves disconnecting their own arousal level from the child's (e.g. responding to an increase in child's arousal by decreasing their own arousal, in order to help the child's arousal decrease); whereas at other times it involves the opposite (responding to an increase in the child's arousal by increasing their own arousal in order to help the child's arousal decrease). Is metastasis always as a 'positive feedback' process (see Figure 1)? Certainly, the ADHD literature would suggest that increases in child arousal tend to be matched by increases in parental arousal (i.e., positive

feedback). In depression and anxiety, however, the picture is more mixed (R. Feldman et al., 2009; T. Field et al., 2003; Granat et al., 2017; Smith et al., in press). This is a question for future research.

It should also be noted that metastatic actor-actor processes are not the *only* dyadic mechanism thought to underlie the development of child self-regulatory deficits. For example, trait-level parental under-responsiveness is considered an independent route to later child self-regulatory problems (Bornstein & Manian, 2013; Slagt, Dubas, van Aken, Ellis, & Deković, 2017).

4 Outstanding questions

4.1 Allostasis

In this article, and in agreement with others (Cole, Ramsook, et al., 2019; Thayer & Lane, 2000; Thelen & Smith, 1994), we have argued that a continuing majority approach that views self-regulation primarily as a static mental resource has obscured a deeper understanding of how self-regulation emerges *through* dynamical interactions. For example, no research to our knowledge has examined whether different children have different levels of ‘optimal’ arousal (cf Zuckerman, 1979), such that a given arousal level might elicit down-regulation in one child (because that arousal level is above the ‘optimal’ arousal level for that child) – but up-regulation in another child. Similar principles might also underlie differences within parent-child dyads, as well as between individual children (S. V. Wass, Smith, Clackson, et al., 2019).

It is also worth noting that almost all previous research has merely examined for the presence or absence of behaviours which are assumed to up- or down-regulate arousal, without actually

testing whether they do or not. Because of this, no research has quantitatively contrasted which behaviours are effective down-regulatory behaviours, and which are not. Similarly, no research has examined whether allostatic mechanisms might work cross-modally – such that an increase in one subsystem (e.g. sensory) might be compensated for by a decrease in another system (e.g. motor) (Calderon et al., 2016; Nigg, 2017).

The final point is that, as we have noted, *intermediate* levels of ANS arousal are considered optimal for attention and learning (Aston-Jones & Cohen, 2005; S. Wass, 2020). But the vast majority of research has examined how children down-regulate following increases in arousal. Much less research has examined how children upregulate following decreases in arousal (although see Gardner et al., 2003; Zuckerman, 1979). This may be for a number of reasons. First, hypo-arousal can be detected using autonomic monitoring, but may not be detectable using purely behavioural observations of facial affect. Behavioural coding may be suitable for examining hyper- but not hypo-arousal, whereas autonomic recordings can capture both extremes. Second it may be merely because young children in particular tend towards hyper-arousal, in particular during psychopathology, and so hypo-arousal may simply be less common. From a theoretical perspective, though, it seems important to consider whether up- and down-regulatory processes operate in similar ways, using similar mechanisms.

4.2 Metastasis

We have also argued throughout that relatively little research has examined metastatic processes – from the perspective either of actor-environment, or actor-actor interactions. Furthermore, what research there is has examined it at the trait level (e.g., ‘are children with

anxiety more likely to be aroused, and to show attention biases?') rather than at the state level (e.g., 'are all children more likely to show attention biases when aroused?'). As we discuss further in section 5, below, one reason for this may be because metastatic processes are generally harder to elicit using experimenter-controlled paradigms and in the lab. Because of this we understand little about what might trigger, and defuse, metastatic actor-environment and actor-actor interactions. For example, are parenting styles influenced by child and parent arousal? And do parenting styles directly influence child and parent arousal? We also know little about the time-scale of processes: whether mutually amplificatory parent-child interactions are more likely to occur in multiple brief bursts or fewer, more sustained episodes. Answering both of these questions would be of immediate benefit within applied psychology.

From both a theoretical and an applied perspective, however, one question seems crucial: how, and why, do we transition between allostatic and metastatic processes? For example, Cole showed that increased emotionality precedes decreased use of executive processes (Cole et al., 2020 see section 2.1), a process which they characterised as regulatory interference (Cole et al., 2017). But is it, for example, that small increases (or decreases) in arousal trigger allostatic (corrective) mechanisms, whereas larger increases in arousal trigger metastatic processes? Or are differences best observed between individuals (and, if so, why) (Cole et al., 2017)?

A second aim is to discover why metastatic processes develop in the first place. Previous researchers have compared inhibitory processes – i.e. negative feedback circuits that interrupt ongoing behaviour (e.g., disengaging from a distressing stimulus) – with positive feedback loops (e.g., paying increased attention to a distressing stimulus) (Thayer & Lane, 2000). They suggested that positive feedback loops may promote perseveration and continued activation of systems, thereby limiting their availability for other processes (Thayer & Lane, 2000; see also

Pérez-Edgar, 2018). Understanding how, and why, positive feedback loops develop as attractors – i.e. what gives them their self-sustaining character - is central to our ability better to target these mechanisms in future.

5 Dynamical methods for quantifying attention-arousal-environmental interactions

One reason why so many of the real-world regulatory processes that we have been discussing remain unexplored is a methodological one. Many of the metastatic processes we have discussed are hard to trigger using experimenter-controlled procedures. And others – such as oppositional parent-child interactions – are naturally hard to observe *in vivo*.

Recently, several groups have developed time-series analyses to examine naturalistic fluctuations in arousal, based either on long segments of lab-collected data (Cole et al., 2020) or on home data collected using miniaturised wearable cameras, microphones, and autonomic recording devices (see Figure 4; Maitha et al., 2020; de Barbaro, 2019; Fausey, Jayaraman, & Smith, 2016; S. V. Wass et al., 2020; S. V. Wass, Smith, Clackson, et al., 2019). In this section, we briefly discuss how these types of large, uncontrolled, multi-dimensional datasets could be analysed in order to address some of the questions laid out in section 4.

INSERT FIGURE 4 HERE

A number of methods are available. For example, researchers may want to examine how one variable (e.g. child arousal) changes before and after particular events (e.g. parent vocalisations). The main aim, however, will be to analyse time-series relationships between

two (or more) continuous variables. These variables might be ambient sound and a child's autonomic arousal; or they might be arousal and self-generated movements; or they might be the child's arousal and the parents' arousal; or they might be the child's vocalisations and the parent's arousal; and so on.

More in-depth discussions of methods available for analysing multidimensional time-series data have been published elsewhere (Chatfield, 2004; Chow, 2019; Thorson, West, & Mendes, 2018; Xu, de Barbaro, Abney, & Cox, 2020). Here, we briefly characterise three types of analysis that can be applied to these data.

The first are analyses derived from cross-correlations and Granger prediction (Granger, 1969). These can identify two types of synchrony: concurrent ('when A is high, B is high') and sequential ('changes in A forward-predict changes in B') (see also Sugihara et al., 2012).

The second are dynamic systems models, such as the damped oscillator models used by Cole, Ram and colleagues (Cole et al., 2020; Morales et al., 2018). These can be used to examine how quickly a child's arousal levels return to baseline following a spontaneous increase (Morales et al., 2018) (see also Lewis, 2005), and how the dynamic coupling between two variables fluctuates over time.

One limitation of both of these approaches is their capacity to examine nonstationary and nonlinear processes (Grossberg, 1988) – such as 'attractor basins' – i.e. the states of a dynamic system that can show increased stability, relative to other states (Ham & Tronick, 2009). Cross-Recurrence Quantification Analysis allows us to track this, by identifying recurrent patterns of

matching and non-matching (Coco, Mønster, Leonardi, Dale, & Wallot, 2020; Shockley, Butwill, Zbilut, & Webber Jr, 2002).

6 Conclusions

We are used to thinking of emotions as properties that ‘resonate’ (Buchanan, Bagley, Stansfield, & Preston, 2012) in ‘interpersonal’ space (Butler, 2011; Ham & Tronick, 2009; Hatfield, Cacioppo, & Rapson, 1993; Waters et al., 2014). However, most researchers persist in conceptualising (and measuring) self-regulation as a static, time invariant, mental resource. We have argued that regulatory processes are similarly best understood as ‘resonant’ properties viewed the systemic level, as the product of dynamic and constantly fluctuating actor-environment and actor-actor interactions (R. Feldman, 2007; A. Sameroff, 2009).

We also discussed two principles that can guide these interactions. In both cases, behaviours at time $t+1$ are systematically influenced by behaviours at time t – but in different directions. The first is allostasis, through which we actively compensate in order to maintain equilibrium. The second are metastatic processes, through which small initial increases and decreases become progressively amplified over time.

We have also pointed to a number of areas where our current understanding is incomplete. Most particularly, we know little about the influence of the real-world environment, and how we as active agents dynamically modulate our internal state through actor-environment interactions.

We tend to pay theoretical attention only to phenomena that we can easily study in the lab.

Metastatic processes are hard to observe, and yet studying them may develop our understanding across a range of psychopathologies. Developing our research in this area may help understand: what triggers, and defuses, metastatic processes when they occur; how they change over time; and what intervention techniques are effective for preventing and defusing them.

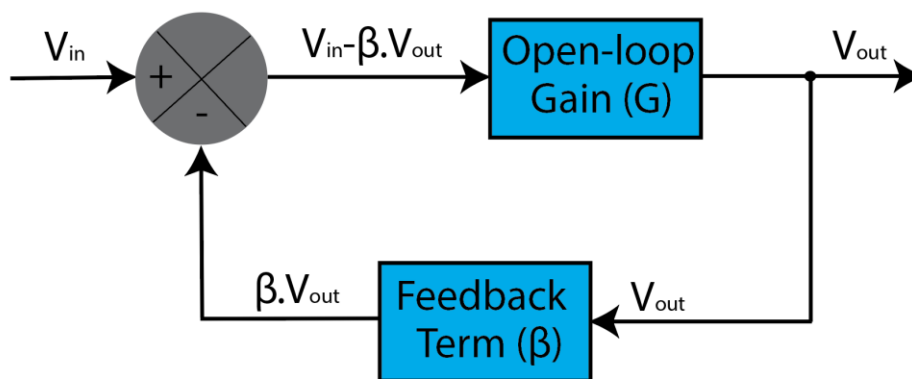
Figures

Figure 1: Schematic illustrating negative and positive feedback loops, as commonly used in electronics. The circuit represents a system with gain (G) and feedback (β). V_{in} and V_{out} show the input and output. The summing junction at its input subtracts the feedback signal from the input signal to form the error signal $V_{in} - \beta G$, which drives the system. In a negative feedback system, the feedback term β is negative. Feedback reduces the overall gain of a system with the degree of reduction being related to the system's open-loop gain. (Also known as degenerative feedback.) In a positive feedback system, the feedback term is positive and so feedback increases the overall gain of a system. (Also known as amplificatory feedback.)

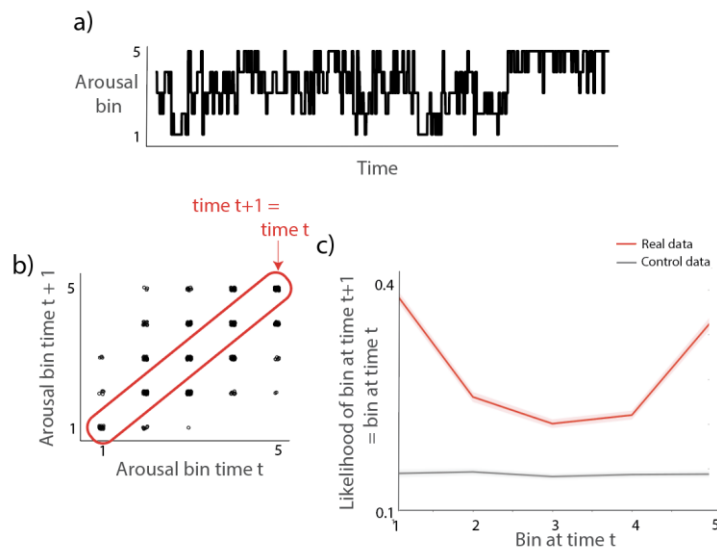


Figure 2: a) illustrative example day-long excerpt of autonomic arousal data (derived from a composite of heart rate, heart rate variability and movement) from a single participant after data were binned into 5 equally sized bins and downsampled to 60-second epochs (data from S. V. Wass et al., 2020). b) illustrative example of an adapted Poincaré plot in which arousal bin at time t is plotted against arousal bin at time $t+1$, showing that rapid transitions in arousal (e.g., from bin 1 at time t (x-axis) to bin 5 at time $t+1$ (y-axis)) are rare. c) plot based on arousal data downsampled to 60-second epochs which shows, separately for each arousal bin at time t , the likelihood of time $t+1$ being the same as time t . Red line shows the real data; grey the control data. Shaded areas show Standard Error of the Means. The U-shape indicates that extreme low and high arousal states are more long-lasting than intermediate states. The same phenomenon is observed across multiple time-scales (S. V. Wass et al., 2020).

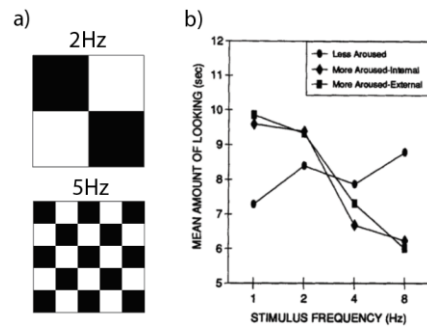


Figure 3: a) illustrations of the checkerboards of varying frequency used by Gardner et al., 1992). b) from Gardner et al., 1992 showing that highly aroused infants prefer to look at less arousing, low-frequency stimuli; whereas less aroused infants prefer more arousing, high-frequency stimuli.

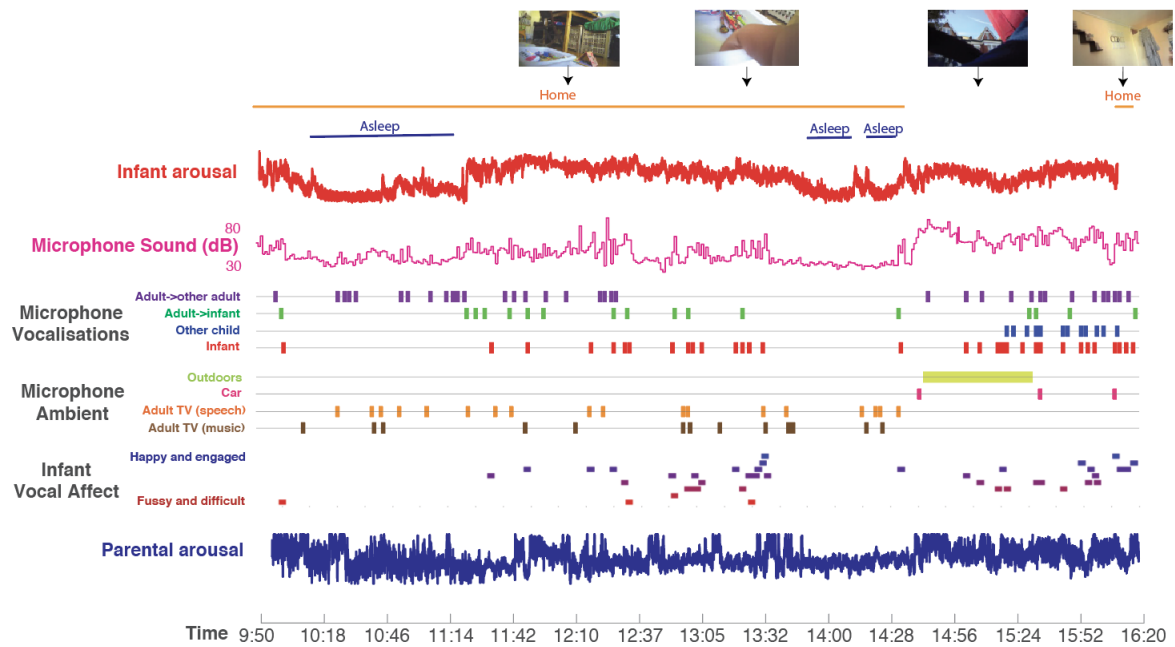


Figure 4: an example of real-world naturalistic data recorded from a 12-month-old infant and their parent. From top to bottom: photos from a wearable camera worn by the infant; coding of when participants were at home and asleep; infant autonomic arousal (measured via heart rate, heart rate variability and movement); sound levels from the microphone worn by the infant; vocalisations recorded on the microphone; ambient noise from the microphone; infant vocal affect; parent autonomic arousal. From (S. V. Wass, Smith, Clackson, et al., 2019; S. V. Wass, Smith, Daubney, et al., 2019).

References

- Amole, M. C., Cyranowski, J. M., Wright, A. G., & Swartz, H. A. (2017). Depression impacts the physiological responsiveness of mother–daughter dyads during social interaction. *Depression and Anxiety, 34*(2), 118-126.
- Anderson, D. R., Alwitt, L. F., Lorch, E. P., & Levin, S. R. (1979). Watching children watch television *Attention and cognitive development* (pp. 331-361): Springer.
- Anderson, D. R., & Lorch, E. P. (1983). Looking at television: Action or reaction? . In J. Bryant & D. R. Anderson (Eds.), *Children's understanding of television: Research on attention and comprehension*. New York: Academic Press.
- Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28*, 403-450. doi:10.1146/annurev.neuro.28.061604.135709
- Atzil, S., Gao, W., Fradkin, I., & Barrett, L. F. (2018). Growing a social brain. *Nature Human Behaviour, 1*.
- Baker, J. K., Fenning, R. M., Howland, M. A., & Huynh, D. (2019). Parental criticism and behavior problems in children with autism spectrum disorder. *Autism, 23*(5), 1249-1261.
- Beebe, B., Jaffe, J., Markese, S., Buck, K., Chen, H., Cohen, P., . . . Feldstein, S. (2010). The origins of 12-month attachment: A microanalysis of 4-month mother–infant interaction. *Attachment & human development, 12*(1-2), 3-141.
- Berntson, G. G., & Cacioppo, J. T. (2007). Integrative physiology: Homeostasis, allostasis, and the orchestration of systemic physiology.

- Beyens, I., Valkenburg, P. M., & Piotrowski, J. T. (2018). Screen media use and ADHD-related behaviors: Four decades of research. *Proceedings of the National Academy of Sciences, 115*(40), 9875-9881.
- Bornstein, M. H., & Manian, N. (2013). Maternal responsiveness and sensitivity reconsidered: Some is more. *Development and Psychopathology, 25*(4 0 1).
- Bornstein, M. H., & Suess, P. E. (2000). Child and mother cardiac vagal tone: Continuity, stability, and concordance across the first 5 years. *Developmental Psychology, 36*(1), 54.
- Brazelton, T. B. (1983). Precursors for the development of emotions in early infancy *Emotions in early development* (pp. 35-55): Elsevier.
- Bridgett, D. J., Burt, N. M., Edwards, E. S., & Deater-Deckard, K. (2015). Intergenerational transmission of self-regulation: A multidisciplinary review and integrative conceptual framework. *Psychological bulletin, 141*(3), 602.
- Buchanan, T. W., Bagley, S. L., Stansfield, R. B., & Preston, S. D. (2012). The empathic, physiological resonance of stress. *Social Neuroscience, 7*(2), 191-201.
- Buss, K. A., & Goldsmith, H. H. (1998). Fear and anger regulation in infancy: Effects on the temporal dynamics of affective expression. *Child Development, 69*(2), 359-374.
- Butler, E. A. (2011). Temporal interpersonal emotion systems: The “TIES” that form relationships. *Personality and Social Psychology Review, 15*(4), 367-393.
- Cacioppo, J. T., Tassinary, L. G., & Berntson, G. G. (2000). *Handbook of Psychophysiology* (2nd ed.): Cambridge University Press, Cambridge, UK.
- Calderon, D., Kilinc, M., Maritan, A., Banavar, J., & Pfaff, D. (2016). Generalized CNS arousal: an elementary force within the vertebrate nervous system. *Neuroscience & Biobehavioral Reviews, 68*, 167-176.

- Cannon, W. B. (1929). Organization for physiological homeostasis. *Physiological reviews*, 9(3), 399-431.
- Capra, F. (2010). *The Tao of physics: An exploration of the parallels between modern physics and eastern mysticism*: Shambhala publications.
- Castellanos, F. X., Sonuga-Barke, E. J., Milham, M. P., & Tannock, R. (2006). Characterizing cognition in ADHD: beyond executive dysfunction. *Trends in Cognitive Sciences*, 10(3), 117-123. doi:10.1016/j.tics.2006.01.011
- Chatfield, C. (2004). The analysis of time series: JSTOR.
- Chow, S.-M. (2019). Practical tools and guidelines for exploring and fitting linear and nonlinear dynamical systems models. *Multivariate Behavioral Research*, 54(5), 690-718.
- Christiansen, H., Oades, R. D., Psychogiou, L., Hauffa, B. P., & Sonuga-Barke, E. J. (2010). Does the cortisol response to stress mediate the link between expressed emotion and oppositional behavior in Attention-Deficit/Hyperactivity-Disorder (ADHD)? *Behavioral and Brain Functions*, 6(1), 45.
- Clark, D. M. (1986). A cognitive approach to panic. *Behaviour research and therapy*, 24(4), 461-470.
- Coco, M. I., Mønster, D., Leonardi, G., Dale, R., & Wallot, S. (2020). Unidimensional and Multidimensional Methods for Recurrence Quantification Analysis with crqa. *arXiv preprint arXiv:2006.01954*.
- Cofer, C. N., & Appley, M. H. (1964). Motivation: Theory and research.
- Cole, P. M., Bendezú, J. J., Ram, N., & Chow, S.-M. (2017). Dynamical systems modeling of early childhood self-regulation. *Emotion*, 17(4), 684.

- Cole, P. M., Lougheed, J. P., Chow, S.-M., & Ram, N. (2020). Development of Emotion Regulation Dynamics Across Early Childhood: a Multiple Time-Scale Approach. *Affective Science*, 1-14.
- Cole, P. M., Ram, N., & English, M. S. (2019). Toward a unifying model of self-regulation: A developmental approach. *Child Development Perspectives*, 13(2), 91-96.
- Cole, P. M., Ramsook, K. A., & Ram, N. (2019). Emotion dysregulation as a dynamic process. *Development and Psychopathology*, 31(3), 1191-1201.
- Combs-Ronto, L. A., Olson, S. L., Lunkenheimer, E. S., & Sameroff, A. J. (2009). Interactions between maternal parenting and children's early disruptive behavior: Bidirectional associations across the transition from preschool to school entry. *Journal of abnormal child psychology*, 37(8), 1151.
- de Barbaro, K. (2019). Automated sensing of daily activity: A new lens into development. *Developmental psychobiology*, 61(3), 444-464.
- Dewey, J. (1896). The reflex arc concept in psychology. *Psychological Review*, 3(4), 357.
- Dezecache, G., Jacob, P., & Grezes, J. (2015). Emotional contagion: its scope and limits. *Trends in Cognitive Sciences*, 19(6), 297-299.
- Doherty-Sneddon, G., Riby, D. M., & Whittle, L. (2012). Gaze aversion as a cognitive load management strategy in autism spectrum disorder and Williams syndrome. *Journal of Child Psychology and Psychiatry*, 53(4), 420-430.
- Dudeny, J., Sharpe, L., & Hunt, C. (2015). Attentional bias towards threatening stimuli in children with anxiety: A meta-analysis. *Clinical psychology review*, 40, 66-75.
- Edelman, G. M. (1989). *The remembered present: a biological theory of consciousness*: Basic Books.

- Edelman, S. (2016). The minority report: some common assumptions to reconsider in the modelling of the brain and behaviour. *Journal of Experimental & Theoretical Artificial Intelligence*, 28(4), 751-776.
- Ehring, T., Frank, S., & Ehlers, A. (2008). The role of rumination and reduced concreteness in the maintenance of posttraumatic stress disorder and depression following trauma. *Cognitive therapy and research*, 32(4), 488-506.
- Fausey, C. M., Jayaraman, S., & Smith, L. B. (2016). From faces to hands: Changing visual input in the first two years. *Cognition*, 152, 101-107.
- Feldman, R. (2007). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry*, 48(3-4), 329-354.
- Feldman, R. (2009). The Development of Regulatory Functions From Birth to 5 Years: Insights From Premature Infants. *Child Development*, 80(2), 544-561.
doi:10.1111/j.1467-8624.2009.01278.x
- Feldman, R., Dollberg, D., & Nadam, R. (2011). The expression and regulation of anger in toddlers: Relations to maternal behavior and mental representations. *Infant Behavior and Development*, 34(2), 310-320.
- Feldman, R., Granat, A., Pariente, C., Kanety, H., Kuint, J., & Gilboa-Schechtman, E. (2009). Maternal depression and anxiety across the postpartum year and infant social engagement, fear regulation, and stress reactivity. *Journal of the American Academy of Child & Adolescent Psychiatry*, 48(9), 919-927.
- Field, T., Diego, M., Hernandez-Reif, M., Schanberg, S., Kuhn, C., Yando, R., & Bendell, D. (2003). Pregnancy anxiety and comorbid depression and anger: effects on the fetus and neonate. *Depression and Anxiety*, 17(3), 140-151.

Field, T. M. (1981). Infant gaze aversion and heart rate during face-to-face interactions.

Infant Behavior and Development, 4, 307-315.

Field, T. M., Healy, B. T., Goldstein, S., & Guthertz, M. (1990). Behavior-state matching and synchrony in mother-infant interactions of nondepressed versus depressed dyads.

Developmental Psychology, 26(1), 7.

Fiske, D. W., & Maddi, S. R. (1961). Functions of varied experience.

Fogel, A. (1993). *Developing through relationships*: University of Chicago Press.

Friedman, B. H. (2007). An autonomic flexibility–neurovisceral integration model of anxiety and cardiac vagal tone. *Biological Psychology, 74*(2), 185-199.

Gagne, J. R., Van Hulle, C. A., Aksan, N., Essex, M. J., & Goldsmith, H. H. (2011). Deriving childhood temperament measures from emotion-eliciting behavioral episodes: Scale construction and initial validation. *Psychological assessment, 23*(2), 337.

Gardner, J. M., & Karmel, B. Z. (1984). Arousal effects on visual preferences in neonates.

Developmental Psychology, 20(3), 374.

Gardner, J. M., & Karmel, B. Z. (1995). Development of Arousal-Modulated Visual Preferences in Early Infancy. *Developmental Psychology, 31*(3), 473-482.

Gardner, J. M., Karmel, B. Z., & Flory, M. J. (2003). Arousal modulation of neonatal visual attention: Implications for development. *Perspectives on fundamental processes in intellectual functioning, 2*, 125-153.

Gardner, J. M., Karmel, B. Z., & Magnano, C. L. (1992). Arousal/visual preference interactions in high-risk neonates. *Developmental Psychology, 28*(5), 821.

Gathercole, S., & Alloway, T. P. (2008). *Working memory and learning: A practical guide for teachers*: Sage.

Geva, R., Gardner, J. M., & Karmel, B. Z. (1999). Feeding-based arousal effects on visual recognition memory in early infancy. *Developmental Psychology, 35*(3), 640.

- Goldstein, M. H., Schwade, J., Briesch, J., & Syal, S. (2010). Learning while babbling: Prelinguistic object-directed vocalizations indicate a readiness to learn. *Infancy, 15*(4), 362-391.
- Granat, A., Gadassi, R., Gilboa-Schechtman, E., & Feldman, R. (2017). Maternal depression and anxiety, social synchrony, and infant regulation of negative and positive emotions. *Emotion, 17*(1), 11.
- Granger, C. W. (1969). Investigating causal relations by econometric models and cross-spectral methods. *Econometrica: Journal of the Econometric Society, 424-438*.
- Gross, C. G. (1998). Claude Bernard and the constancy of the internal environment. *The Neuroscientist, 4*(5), 380-385.
- Grossberg, S. (1988). Nonlinear neural networks: Principles, mechanisms, and architectures. *Neural Networks, 1*(1), 17-61.
- Gunnar, M., & Quevedo, K. (2007). The neurobiology of stress and development. *Annu. Rev. Psychol., 58*, 145-173.
- Ham, J., & Tronick, E. (2009). Relational psychophysiology: Lessons from mother–infant physiology research on dyadically expanded states of consciousness. *Psychotherapy Research, 19*(6), 619-632.
- Harold, G. T., Leve, L. D., Barrett, D., Elam, K., Neiderhiser, J. M., Natsuaki, M. N., . . . Thapar, A. (2013). Biological and rearing mother influences on child ADHD symptoms: revisiting the developmental interface between nature and nurture. *Journal of Child Psychology and Psychiatry, 54*(10), 1038-1046.
- Hatfield, E., Cacioppo, J. T., & Rapson, R. L. (1993). Emotional contagion. *Current Directions in Psychological Science, 2*(3), 96-100.
- Heyes, C. (2018). Empathy is not in our genes. *Neuroscience & Biobehavioral Reviews, 95*, 499-507.

- Holleman, G. A., Hooge, I. T., Kemner, C., & Hessels, R. S. (2020). The 'Real-World Approach' and Its Problems: A Critique of the Term Ecological Validity. *Frontiers in Psychology, 11*, 721.
- Jaffe, J., Beebe, B., Feldstein, S., Crown, C. L., Jasnow, M. D., Rochat, P., & Stern, D. N. (2001). Rhythms of dialogue in infancy: Coordinated timing in development. *Monographs of the Society for Research in Child Development, 1*-149.
- Kaartinen, M., Puura, K., Mäkelä, T., Rannisto, M., Lemponen, R., Helminen, M., . . . Hietanen, J. K. (2012). Autonomic arousal to direct gaze correlates with social impairments among children with ASD. *Journal of Autism and Developmental Disorders, 42*(9), 1917-1927.
- Kahle, S., Miller, J. G., Helm, J. L., & Hastings, P. D. (2018). Linking autonomic physiology and emotion regulation in preschoolers: The role of reactivity and recovery. *Developmental psychobiology*.
- Kingstone, A., Smilek, D., & Eastwood, J. D. (2008). Cognitive ethology: A new approach for studying human cognition. *British journal of psychology, 99*(3), 317-340.
- Kolodny, O., & Edelman, S. (2015). The problem of multimodal concurrent serial order in behavior. *Neuroscience & Biobehavioral Reviews, 56*, 252-265.
- Kopp, C. B. (1982). Antecedents of self-regulation: A developmental perspective. *Developmental Psychology, 18*(2), 199.
- Kugler, P. N., Kelso, J. S., & Turvey, M. T. (1980). 1 on the concept of coordinative structures as dissipative structures: I. theoretical lines of convergence *Advances in psychology* (Vol. 1, pp. 3-47): Elsevier.
- Leerkes, E. M., Su, J., Calkins, S. D., Supple, A. J., & O'Brien, M. (2016). Pathways by which mothers' physiological arousal and regulation while caregiving predict sensitivity to infant distress. *Journal of Family Psychology, 30*(7), 769.

- Levenson, R. W. (1988). Emotion and the autonomic nervous system: A prospectus for research on autonomic specificity. *Social psychophysiology: Theory and clinical applications*.
- Levenson, R. W., & Ruef, A. M. (1992). Empathy: A physiological substrate. *Journal of personality and social psychology*, 63(2), 234.
- Lewis, M. D. (2005). Bridging emotion theory and neurobiology through dynamic systems modeling. *Behavioral and Brain Sciences*, 28(2), 169-194.
- Maitha, C., Goode, J. C., Maulucci, D. P., Lasassmeh, S., Yu, C., Smith, L. B., & Borjon, J. I. (2020). An open-source, wireless vest for measuring autonomic function in infants. *Behavior research methods*.
- Mason, G. M. (2018). Investigating Dyadic Social Coordination and Infant Attention in Typical and Atypical Development.
- Mason, G. M., Kirkpatrick, F., Schwade, J. A., & Goldstein, M. H. (2019). The Role of Dyadic Coordination in Organizing Visual Attention in 5-Month-Old Infants. *Infancy*, 24(2), 162-186.
- McCall, J. G., Al-Hasani, R., Siuda, E. R., Hong, D. Y., Norris, A. J., Ford, C. P., & Bruchas, M. R. (2015). CRH engagement of the locus coeruleus noradrenergic system mediates stress-induced anxiety. *Neuron*, 87(3), 605-620.
- McEwen, B. S., & Wingfield, J. C. (2003). The concept of allostasis in biology and biomedicine. *Horm Behav*, 43(1), 2-15.
- McMahon, T. P., & Naragon-Gainey, K. (2018). The moderating effect of maladaptive emotion regulation strategies on reappraisal: a daily diary study. *Cognitive therapy and research*, 42(5), 552-564.

- Morales, S., Ram, N., Buss, K. A., Cole, P. M., Helm, J. L., & Chow, S. M. (2018). Age-related changes in the dynamics of fear-related regulation in early childhood. *Developmental Science, 21*(5), e12633.
- Murray, L. (1985). Emotional regulations of interactions between two-month-olds and their mothers. *Social perception in infants, 177-197*.
- Nigg, J. T. (2017). Annual Research Review: On the relations among self-regulation, self-control, executive functioning, effortful control, cognitive control, impulsivity, risk-taking, and inhibition for developmental psychopathology. *Journal of Child Psychology and Psychiatry, 58*(4), 361-383.
- Nuske, H. J., Vivanti, G., & Dissanayake, C. (2015). No evidence of emotional dysregulation or aversion to mutual gaze in preschoolers with autism spectrum disorder: an eye-tracking pupillometry study. *Journal of Autism and Developmental Disorders, 45*(11), 3433-3445.
- Osborne-Crowley, K. (2020). Social cognition in the real world: reconnecting the study of social cognition with social reality. *Review of general psychology, 24*(2), 144-158.
- Overbeek, G., Creasey, N., Wesarg, C., Huijzer-Engbreng Hof, M., & Spencer, H. (2020). When mummy and daddy get under your skin: A new look at how parenting affects children's DNA methylation, stress reactivity, and disruptive behavior. *New directions for child and adolescent development, 2020*(172), 25-38.
- Pempek, T. A., Kirkorian, H. L., Richards, J. E., Anderson, D. R., Lund, A. F., & Stevens, M. (2010). Video Comprehensibility and Attention in Very Young Children. *Developmental Psychology, 46*(5), 1283-1293. doi:10.1037/a0020614
- Pérez-Edgar, K. (2018). Attention mechanisms in behavioral inhibition: Exploring and exploiting the environment *Behavioral inhibition* (pp. 237-261): Springer.

Pérez-Edgar, K., Bar-Haim, Y., McDermott, J. M., Chronis-Tuscano, A., Pine, D. S., & Fox,

N. A. (2010). Attention biases to threat and behavioral inhibition in early childhood shape adolescent social withdrawal. *Emotion, 10*(3), 349.

Pfaff, D. (2018). *How Brain Arousal Mechanisms Work: Paths Toward Consciousness* (Vol. 1): Cambridge University Press.

Pine, D. S., Mogg, K., Bradley, B. P., Montgomery, L., Monk, C. S., McClure, E., . . .

Kaufman, J. (2005). Attention bias to threat in maltreated children: Implications for vulnerability to stress-related psychopathology. *American Journal of Psychiatry, 162*(2), 291-296.

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74*(2), 116-143.

doi:10.1016/j.biopsycho.2006.06.009

Rabinovich, M. I., Muezzinoglu, M. K., Strigo, I., & Bystritsky, A. (2010). Dynamical principles of emotion-cognition interaction: mathematical images of mental disorders. *PLoS ONE, 5*(9), e12547.

Ramsay, D. S., & Woods, S. C. (2014). Clarifying the roles of homeostasis and allostasis in physiological regulation. *Psychological Review, 121*(2), 225.

Rayson, H., Bonaiuto, J. J., Ferrari, P. F., Chakrabarti, B., & Murray, L. (2019). Building blocks of joint attention: Early sensitivity to having one's own gaze followed. *Developmental Cognitive Neuroscience, 100631*.

Reader, S. M. (2015). Causes of individual differences in animal exploration and search. *Topics in cognitive science, 7*(3), 451-468.

Richards, J. E. (1987). Infant visual sustained attention and respiratory sinus arrhythmia. *Child Development, 488-496*.

- Richards, J. E. (2010). The development of attention to simple and complex visual stimuli in infants: Behavioral and psychophysiological measures. *Developmental Review, 30*(2), 203-219. doi:10.1016/j.dr.2010.03.005
- Richards, J. E., & Anderson, D. R. (2004). Attentional inertia in children's extended looking at television *Advances in Child Development and Behavior, Vol 32* (Vol. 32, pp. 163-212).
- Risko, E. F., Richardson, D. C., & Kingstone, A. (2016). Breaking the fourth wall of cognitive science: Real-world social attention and the dual function of gaze. *Current Directions in Psychological Science, 25*(1), 70-74.
- Rossi, V., & Pourtois, G. (2017). Someone's lurking in the dark: The role of state anxiety on attention deployment to threat-related stimuli. *Biological Psychology, 122*, 21-32.
- Roy, A. K., Dennis, T. A., & Warner, C. M. (2015). A critical review of attentional threat bias and its role in the treatment of pediatric anxiety disorders. *Journal of Cognitive Psychotherapy, 29*(3), 171-184.
- Salkovskis, P. M. (1991). The Importance of Behaviour in the Maintenance of Anxiety and Panic: A Cognitive Account. *Behavioural Psychotherapy, 19*(1), 6-19.
- Salkovskis, P. M. (1997). *Frontiers of cognitive therapy*: Guilford Press.
- Sameroff, A. (2009). *The transactional model*: American Psychological Association.
- Sameroff, A. J. (1983). Development systems: Contexts and evolution. *Handbook of child psychology: formerly Carmichael's Manual of child psychology/Paul H. Mussen, editor*.
- Samuels, E. R., & Szabadi, E. (2008). Functional neuroanatomy of the noradrenergic locus coeruleus: its roles in the regulation of arousal and autonomic function part I: principles of functional organisation. *Current neuropharmacology, 6*(3), 235-253.

Sapolsky, R. M. (2015). Stress and the brain: individual variability and the inverted-U.

Nature Neuroscience, 18(10), 1344-1346.

Selye, H. (1951). The Physiology and Pathology of Exposure to Stress. *The Journal of Bone and Joint Surgery*, 33-A, 818-819.

Shih, E. W., Quiñones-Camacho, L. E., Karan, A., & Davis, E. L. (2018). Physiological

Contagion in Parent-Child Dyads During an Emotional Challenge. *Social*

Development.

Shockley, K., Butwill, M., Zbilut, J. P., & Webber Jr, C. L. (2002). Cross recurrence

quantification of coupled oscillators. *Physics Letters A*, 305(1-2), 59-69.

Singer, T., & Klimecki, O. M. (2014). Empathy and compassion. *Current biology*, 24(18),

R875-R878.

Slagt, M., Dubas, J. S., van Aken, M. A., Ellis, B. J., & Deković, M. (2017). Children's

differential susceptibility to parenting: An experimental test of "for better and for worse". *Journal of Experimental Child Psychology*, 154, 78-97.

Smith, C. G., Jones, E. J. H., Charman, T., K., C., Mirza, F. U., & Wass., S. V. (in press).

Anxious parents show higher physiological synchrony with their infants.

Psychological medicine.

Sonuga-Barke, E. J. S., Wiersema, J. R., van der Meere, J. J., & Roeyers, H. (2010). Context-

dependent dynamic processes in attention deficit/hyperactivity disorder:

differentiating common and unique effects of state regulation deficits and delay

aversion. *Neuropsychol Rev*, 20(1), 86-102. doi:10.1007/s11065-009-9115-0

Spivey, M. J., & Dale, R. (2006). Continuous dynamics in real-time cognition. *Current*

Directions in Psychological Science, 15(5), 207-211.

Sterling, P. (2012). Allostasis: a model of predictive regulation. *Physiology & behavior*,

106(1), 5-15.

- Stifter, C. A., & Braungart, J. M. (1995). The regulation of negative reactivity in infancy: function and development. *Developmental Psychology, 31*(3), 448.
- Sugihara, G., May, R., Ye, H., Hsieh, C.-h., Deyle, E., Fogarty, M., & Munch, S. (2012). Detecting causality in complex ecosystems. *Science, 338*(6106), 496-500.
- Taylor, E. (1999). Developmental neuropsychopathology of attention deficit and impulsiveness. *Development and Psychopathology, 11*(3), 607-628.
- Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine, 37*(2), 141-153.
- Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of affective disorders, 61*(3), 201-216.
- Thelen, E., Schönner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences, 24*(01), 1-34.
- Thelen, E., & Smith, L. B. (1994). *A Dynamic Systems Approach to the Development of Cognition and Action*. MA, US: MIT Press.
- Thorson, K. R., West, T. V., & Mendes, W. B. (2018). Measuring physiological influence in dyads: A guide to designing, implementing, and analyzing dyadic physiological studies. *Psychological methods, 23*(4), 595.
- Tronick, E. (1982). *Social interchange in infancy: Affect, cognition, and communication*: Univ Park Press.
- Tronick, E. (2007). *The neurobehavioral and social-emotional development of infants and children*: WW Norton & Company.

- Ursache, A., Blair, C., Stifter, C., & Voegtline, K. (2013). Emotional reactivity and regulation in infancy interact to predict executive functioning in early childhood. *Developmental Psychology, 49*(1), 127.
- Van der Meere, J., & Sergeant, J. (1988). Controlled processing and vigilance in hyperactivity: Time will tell. *Journal of abnormal child psychology, 16*(6), 641-655.
- Wan, M. W., Green, J., & Scott, J. (2019). A systematic review of parent–infant interaction in infants at risk of autism. *Autism, 23*(4), 811-820.
- Wass, S. (2020). The origins of effortful control: how early development within arousal/regulatory systems influences cognitive and affective control.
- Wass, S. V. (2018). How orchids concentrate? The relationship between physiological stress reactivity and cognitive performance during infancy and early childhood. *Neuroscience & Biobehavioral Reviews*.
- Wass, S. V., Clackson, K., & Leong, V. (2018). Increases in Arousal are More Long-Lasting than Decreases in Arousal: On Homeostatic Failures During Emotion Regulation in Infancy. *Infancy*.
- Wass, S. V., Smith, C., Clackson, K., & Mirza, F. U. (2020). In infancy, it's the extremes of arousal that are 'sticky': naturalistic data challenge purely homeostatic approaches to studying self-regulation. . *in press, Developmental Science*.
doi:<https://psyarxiv.com/vc98f/>
- Wass, S. V., Smith, C. G., Clackson, K., Gibb, C., Eitzenberger, J., & Mirza, F. U. (2019). Parents mimic and influence their infant's autonomic state through dynamic affective state matching. *Current biology, 29*(14), 2415-2422. e2414.
- Wass, S. V., Smith, C. G., Daubney, K. R., Suata, Z. M., Clackson, K., Begum, A., & Mirza, F. U. (2019). Influences of environmental stressors on autonomic function in 12-month-old infants: understanding early common pathways to atypical emotion

- regulation and cognitive performance. *Journal of Child Psychology & Psychiatry & Allied Disciplines*.
- Wass., S. V., Smith, C. G., Clackson, K., Gibb, C., Eitzenberger, J., & Mirza, F. U. (in press). Parents mimic and influence their infant's autonomic state through dynamic affective state matching. *Current biology*.
- Waterhouse, B. D., & Navarra, R. L. (2019). The locus coeruleus-norepinephrine system and sensory signal processing: A historical review and current perspectives. *Brain Research, 1709*, 1-15.
- Waters, S. F., West, T. V., Karnilowicz, H. R., & Mendes, W. B. (2017). Affect contagion between mothers and infants: Examining valence and touch. *Journal of Experimental Psychology: General, 146*(7), 1043.
- Waters, S. F., West, T. V., & Mendes, W. B. (2014). Stress contagion: Physiological covariation between mothers and infants. *Psychological science, 25*(4), 934-942.
- Wichers, M., Wigman, J., & Myin-Germeys, I. (2015). Micro-level affect dynamics in psychopathology viewed from complex dynamical system theory. *Emotion review, 7*(4), 362-367.
- Wicker, B., Keysers, C., Plailly, J., Royet, J.-P., Gallese, V., & Rizzolatti, G. (2003). Both of us disgusted in My insula: the common neural basis of seeing and feeling disgust. *Neuron, 40*(3), 655-664.
- Xu, T. L., de Barbaro, K., Abney, D. H., & Cox, R. F. (2020). Finding structure in time: visualizing and analyzing behavioral time series. *Frontiers in Psychology, 11*.
- Zuckerman, M. (1979). *Sensation seeking*: Wiley Online Library.