



Foraging and inertia: Understanding the developmental dynamics of overt visual attention

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ABSTRACT

During early life, we develop the ability to choose what we focus on and what we ignore, allowing us to regulate perception and action in complex environments. But how does this change influence how we spontaneously allocate attention to real-world objects during free behaviour? Here, in this narrative review, we examine this question by considering the time dynamics of spontaneous overt visual attention, and how these develop through early life. Even in early childhood, visual attention shifts occur both periodically and aperiodically. These reorientations become more internally controlled as development progresses. Increasingly with age, attention states also develop self-sustaining attractor dynamics, known as attention inertia, in which the longer an attention episode lasts, the more the likelihood increases of its continuing. These self-sustaining dynamics are driven by amplificatory interactions between engagement, comprehension, and distractibility. We consider why experimental measures show decline in sustained attention over time, while real-world visual attention often demonstrates the opposite pattern. Finally, we discuss multi-stable attention states, where both hypo-arousal (mind-wandering) and hyper-arousal (fragmentary attention) may also show self-sustaining attractor dynamics driven by moment-by-moment amplificatory child-environment interactions; and we consider possible applications of this work, and future directions.

1. Introduction

‘mental work does not exhaust; it gives nourishment’

(Maria Montessori, quoted in di Stefano, 2022)

Attention control, defined as ‘our ability to choose what we pay attention to and what we ignore’, enables us to flexibly regulate perception and action to guide strategic behaviour in complex, dynamic environments (Doebel, 2020; Duncan, 2013; Hendry et al., 2019; Munakata and Michaelson, 2021; Posner and Rothbart, 2007; Richards, 2010; Rueda et al., 2021). At the moment, developmental scientists most often study attention control by designing experimental tasks. For example, in one popular paradigm, a target appears following a cue on one side of the screen for a number of discrete but contiguous trials, before switching to appear on the other side of the screen; the dependent variable is the number of trials on which the participant continues to perseverate in looking to the original side following the switch (Kovacs and Mehler, 2009; Wass et al., 2011). The aim of research such as this is to simulate real-world cognitive processes under controlled settings to

extract a domain-general attribute – of, for example, a participant’s ‘pure’ capacity for attention control, independent of context or setting (Wass and Goupil, 2022; Wass and Jones, 2023). Research using these types of paradigm generally finds that the capacity for attention control is weak but not non-existent (Gilmore and Johnson, 1995) during the first year of life, and begins to emerge more strongly from 12-months (Colombo and Cheatham, 2006).

Here we take a different approach. In this narrative review, we build on previous research in the adult (Flavell et al., 2022; Giesbrecht et al., 2024; Hayhoe and Lerch, 2022; Hayhoe and Matthis, 2018; Henderson, 2017; Land B., 2009; B. Tatler and Vincent, 2008) and developmental fields (Franchak and Yu, 2022; Richards, 2010) to examine how children spontaneously allocate visual attention when freely paying attention in complex, dynamic, real-world settings. We concentrate on analysing how real-world attention patterns change during the early years of life, during the period when experimental evidence (see above, and Section 2) suggests that the capacity for attention control is beginning to emerge.

In studying real-world attention patterns, we confine ourselves of

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necessity to measuring overt attention – i.e., measurable patterns of observable attention behaviours - rather than covert, internal attention shifts. This is even though the distinction between overt and covert attention is important and well-studied both in adults (Baird et al., 2014; M. R. Cohen and Maunsell, 2011; Smallwood et al., 2011; Stawarczyk et al., 2011a) and children (Aslin, 2007; Keulers and Jonkman, 2019; Richards and Gibson, 1997; Robertson et al., 2012; Ruff and Rothbart, 1996). We return to this point in Section 5.2.

We also confine ourselves to one of the two dimensions of overt attention. The first dimension is *where* within a complex 3-D array we orient our attention. The second is *when* we reorient attention – i.e., what determines the timing of when we maintain our attention where it is currently focused, and when we reorient it somewhere else. Here, we concentrate on the latter. Sometimes, attentional reorientations can be reactive: something changes in our visual field, and we shift attention in response (Land B., 2009). Often, though, they are not merely reactive: we shift attention even when no discernible change in our visual field has triggered that reorientation (Hayhoe and Lerch, 2022; Henderson, 2017; Nobre and van Ede, 2023). Our aim is to understand the factors that influence when these attention reorientations take place, and how they change over development.

Attention reorientations can be studied at two spatio-temporal scales. The first is at the fine-grained spatio-temporal scale. Here, overt attention has two primary modes: fixations, where the eyeball is directed towards a static location in space and visual processing occurs (G. W. Bronson, 1990a; Henderson, 2006; B. W. Tatler et al., 2019; Yarbus, 1967); and eye movements, known as saccades, where the eye shifts rapidly from one location to another and visual processing temporarily shuts down (Hayhoe and Lerch, 2022). (There are also other modes, such as smooth pursuit (Richards and Holley, 1999), but we exclude these here.) These ‘micro-level’ attention behaviours are generally studied using fixation detection algorithms built into eyetrackers (Hessels et al., 2017, 2018; Wass et al., 2013, 2014).

The second is at a more coarse-grained spatio-temporal scale, such as when we shift from looking toward one object (e.g., a toy, or a TV screen) to looking at another (e.g. a different toy). These are normally defined either from video coding of participants’ gaze behaviour, or from experimenter-defined Areas of Interest (AOIs) in eyetracker footage. These more coarse-grained attention episodes may (or may not) include several fine-grained attention episodes (fixations); this is dependent on the size of the experimenter-defined objects or AOIs. Here, we call the time intervals between these coarse-grained attention shifts ‘look durations’ (consistent with e.g. Aslin, 2007; Reynolds and Richards, 2019). Similar principles underlie both fine- and coarse-grained attention shifting (‘fixations’ and ‘looks’): for example, gaze patterns at all ages show a fractal structure, such that the proportional relationship between the power (i.e., size of change) and the frequency (i.e., how frequently changes of that size occur) is consistent across multiple scales (Nakamura et al., 2007; Stallworthy et al., 2020).

We define ‘real-world’ attention as any study that measures children’s spontaneous attention patterns during free behaviour. We have included screen-based paradigms that measure children’s attention while they are viewing TV, and static 2D displays (Richards, 2010), as well as paradigms that record infants’ attention whilst they play or act freely in naturalistic settings - for example, while playing with toys at a tabletop or on a rug (Franchak and Yu, 2022). But we will always distinguish between screen-based and free-play paradigms, as the distinction is crucial. When I am playing with real-world objects, for example, I have a physical position relative to these objects, and I interact with them in a way which influences their salience (i.e., how automatically attention eliciting they are) (E. M. Anderson et al., 2022; Franchak and Yu, 2022). As motor development progresses, we become better able to control how we position ourselves relative to people and objects in the outside world; and, through that, to choose what we perceive (Candy et al., 2023; Mendez et al., 2023). In contrast, most static or dynamic 2D displays (such as TV) are non-interactive: my own

behaviours towards that stimulus do not influence how that stimulus appears to me. When considering screen-based studies we also distinguish between dynamic visual displays (such as TV) and static 2D displays, as this distinction is also important. Motion is thought to be one of the strongest drivers of exogenous (automatic) stimulus capture (known as salience (Itti and Baldi, 2009; Mital et al., 2010) (see Section 4 for further discussion)).

We only consider how children pay attention in a dyadic sense (i.e., considering the inter-relationship between a child and the object that they are paying attention to). Other research has considered attention in a triadic sense – i.e., how social factors (such as where social partners are paying attention, and how they are behaving) can influence how children allocate attention (Abney et al., 2020; Hessels, 2020; Phillips et al., 2023; Wass, Clackson, et al., 2018; Yu and Smith, 2016); but we do not include this research here.

In the sections that follow we first (Section 2) give an overview of how different attention mechanisms develop in the brain, that will underpin the discussion that follows. Then, in Section 3, we introduce the topic by discussing research that looks at how average attention durations change over time, and at correlations between average attention durations and experimental and questionnaire assessments of attention control.

Then, in the main body of the article, we describe some of the multiple factors that influence attention, and how optimal attention behaviours vary between settings. For reasons of emphasis, we follow others (L. B. Cohen, 1972; Richards, 2010) in dividing our discussion into two sections. In Section 4 we discuss attention shifting – i.e., the factors that might cause a new attention episode (either a micro-level fixation or a macro-level look) to be initiated. We discuss first periodic shifting (Section 4.1) and then aperiodic (Section 4.2) attention shifting. Then, in Section 5, we discuss attention holding – i.e., the factors that might cause an attention episode to be maintained. Of course, these two aspects of attention - attention shifting and attention holding - are inseparably inter-related; we follow this distinction purely for emphasis. Finally, in Section 6, we summarise and conclude.

2. The development of attention mechanisms in the brain

Our understanding of the neural mechanisms that subserve visual attention comes from a combination of animal studies and behavioural experimental research with humans (Atkinson, 2000; G. Bronson, 1974; L. B. Cohen, 1972; Colombo, 2001; Hunnius, 2007; Johnson, 1990; Oakes, 2023a; Posner et al., 2012; Richards, 2011). Three distinct attention systems are typically characterised. Here, we provide only a brief introduction to this literature, to guide the discussion that follows.

Broadly, although the accounts differ in several details, the traditional view holds that the earliest developing aspect of attention is arousal, mediated by brainstem reticular activating systems and instantiated primarily via norepinephrine neurotransmitter systems (Colombo, 2001; Wainstein et al., 2021). In young infants, arousal is more readily initiated by exogenous events (Wolff, 1965); over time, infants gain the ability to maintain an optimal state of arousal even in the absence of external stimulation (Colombo, 2001). This changing ability is thought to reflect developmental changes in the ascending influence of subcortical pathways on cortical targets (Colombo, 2001; Geva and Feldman, 2008; Pfaff, 2018). As we will describe further in subsequent sections, more recent research has delineated a range of ways in which arousal fluctuations co-occur with the widespread and dynamic reconfiguration of brain states (Shine et al., 2016). In animal studies, arousal tends to be measured by directly recording from the brainstem (most often the locus ceruleus); in human research, it is observed either by recording pupil size, which (under some circumstances) tracks brainstem activity, or by recording peripheral indicators such as heart rate.

The second widely recognised attention system is the orienting system or posterior attention network, which is thought to consist of spatial

orienting networks in the parietal cortex and object recognition pathways extending from the visual cortex to the temporal cortex (Posner and Petersen, 1990). During early infancy (<2 months) it is thought that failure to disengage visual attention can lead to a phenomenon traditionally described as 'sticky fixation' (Hood and Atkinson, 1993). Problems with disengaging attention from static stimuli gradually dissipate during infancy but persist longer for more salient stimuli (G. W. Bronson, 1994; Hood and Atkinson, 1993; Hunnius and Geuze, 2004). We discuss these findings further in Sections 4 and 5. Just as for the executive attention network (which is discussed in the paragraphs that follow), developmental increases in interregional connectivity are presumably important for the development of widely distributed systems such as the posterior attention network (Johnson, 2015).

Key elements of orienting are disengaging from an old visual target, and detecting a new one (Doherty et al., 2005). To do this, the brain must differentiate between the targets by showing selectivity to each. Animal studies show that one element of this is Hebbian-style plasticity (Hebb, 1949) of synapses and local circuits (Collingridge et al., 2010; Cooke and Bear, 2014; Espinosa and Stryker, 2012), such that targeted pharmacological disruption of plasticity prevents selectivity to visual input (e.g., Yoon et al., 2009). Another element is the plasticity of inhibitory neurons, which regulate the function of receptive fields (Hensch, 2005).

The third system is the executive attention system, which subserves attention control (as defined at the start of this article) (Colombo and Cheatham, 2006; Rueda et al., 2021). As we described in the first paragraph of this article, executive attention is typically studied using experimental paradigms which aim to simulate real-world cognitive processes such as cognitive conflict, violation of expectations and error detection (Hendry et al., 2019; Posner and Rothbart, 2007; Rueda et al., 2021). Neuroimaging studies show that performance on these experimental tasks associates with increased activity in areas such as the prefrontal cortex, ventroparietal network, and anterior cingulate (Colombo and Cheatham, 2006; Posner and Rothbart, 2007). Brain development in these regions is thought to show a relatively protracted developmental trajectory (Blumberg and Adolph, 2023; Deoni et al., 2011; Grayson and Fair, 2017; Johnson, 2015) (but see (Hodel, 2018)).

Consistent with this neuroimaging evidence, experimental studies suggest that the capacity for executive control over attention is the slowest to develop of these three attention mechanisms. Traditionally it is thought that the capacity first starts to emerge from around 12 months; but recent research has suggested that some trace elements are discernible before this age (Gilmore and Johnson, 1995; Hendry et al., 2019). In animal studies, it is shown that executive processes relate to plasticity involving a variety of receptors including the n-methyl-D-aspartate receptor (NMDAR) in the prefrontal cortex, which generates slow recurrent dynamics needed for working memory and goal maintenance (D. D. Wang and Kriegstein, 2008; H. Wang et al., 2008). The critical period of this plasticity is timed by a shift in the subunit composition of this receptor early in life (Erisir and Harris, 2003). A post-mortem study of human infants indicated that this shift largely occurs during the first year (Murphy et al., 2005); although correlative, this coincides with the age suggested by some developmental experimental studies as the time when the capacity for attention control begins to emerge (Colombo and Cheatham, 2006). Understanding the development of attention control and how it influences real-world attention behaviours is the primary aim of this article.

3. Developmental change in attention durations, and individual differences

In this section, we examine how the dynamics of real-world attention behaviours change across the first few years of life, during the period when experimental evidence suggests that the capacity for attention control emerges. Here, we concentrate on behavioural research that examined average attention durations, measured both at the micro-level

(fixations/saccades) and the macro-level (looks) (see Section 1). We examine how average attention durations change over time and describe research that examines correlations between average attention durations and experimental, and questionnaire measures of attention control. Our aim in this section is to report the main findings; in the two sections that follow (Sections 4 and 5) we interpret these findings in terms of differential contributions from different attention subsystems.

3.1. Micro-level attention (fixations/saccades)

Several studies have examined fine-grained attention patterns in early development by recording fixation durations (see Section 1 for definition). In screen-viewing contexts, fixation durations are highly stable as a measure of individual differences, showing high test-retest reliability and consistency across different types of viewing material (e.g. 2D static vs 2D dynamic in 12-month-old infants) (Wass et al., 2011; Wass and Smith, 2014). Studies that recorded infants viewing 2D static images report that fixation durations decrease with increasing age. For example, when 1–2-month-olds view static visual stimuli, they show long fixations (modal fixation duration ~400–500 msecs), but by 3–4-months they show a greater proportion of shorter fixations (modal fixation duration 300–400 msecs) (G. W. Bronson, 1990b, 1994). This pattern continues throughout infancy and early childhood (see also (Helo et al., 2016; Hunnius, 2007; van Renswoude et al., 2020)). Fixation durations to dynamic stimuli last longer than fixation durations to static stimuli, even when smooth pursuit fixations are excluded, and this difference persists across development (G. W. Bronson, 1994; Wass and Smith, 2014).

A small number of studies have also looked at how questionnaire-based measures of attention control correlate with fixation durations in real-world settings. Three studies have reported that children who score better on questionnaire-assessed attention control show longer fixation durations during static 2D scene viewing. One study applied questionnaire assessments and fixation duration measurements at the same age (3–15-month-olds (van Renswoude et al., 2020)); two other studies measured fixation durations during infancy (8–11 months) and later questionnaire assessments during toddlerhood (Geeraerts et al., 2019; Papageorgiou et al., 2014).

Another group of studies has looked at correlations between fixation durations and performance on experimental measures of attention, as described here (Hendry et al., 2019). Wass and Smith found, for example, negative associations between average fixation duration during static 2D scene viewing and the Kovacs and Mehler measure of attention control described in the first paragraph of this article (Wass and Smith, 2014). No equivalent associations with fixation durations to dynamic 2D scenes were observed (Wass and Smith, 2014). These findings point to potential disparities between the construct of 'top down' attention control as measured by experimental tasks and the development of real-world attentional behaviours, which parental questionnaire measures may more accurately capture (Eisenberg et al., 2019).

To our knowledge, no research has measured correlations between performance on questionnaires and experimental tasks and fixation durations in real-world 3D settings.

3.2. Macro-level attention (looks)

In this section we review studies that examined more macro-level attention, defined as 'look durations' (see Section 1 for definition). Here, just as with the findings reviewed in Section 3.1, findings diverge markedly between static, and dynamic viewing stimuli.

Early in the first year (0–8 months), look durations towards static 2D scenes decrease with age (Colombo, 2001). Traditional interpretations suggest that this is due to developmental changes in the time needed to form an internal representation of the object being viewed (Colombo and Mitchell, 2009; Sokolov, 1963). Several studies have also reported

negative associations between look durations to static 2D scenes early in the first year of life and long-term outcomes (including experimental assessments of attention control) (Colombo and Mitchell, 2009; Rose et al., 2002). However, when measuring attention to dynamic 2D scenes, the opposite pattern generally emerges: look durations increase with age from 6 to 12 months (Courage et al., 2006), and look durations at 7 and 12 months positively predict performance on experimental assessments of attention control (Brandes-Aitken et al., 2019; Johansson et al., 2015). Similarly, questionnaire studies have suggested that children who look for longer at pictures in books at home show lower rates of conditions such as ADHD, which associate with poorer performance on experimental measures of attention control (Kostyrka-Allchorne et al., 2020; Shephard et al., 2022); although the same relationship has not yet developed by 10 months (Goodwin et al., 2021).

Importantly, however, recent work examining attention durations during early infancy in 2D and 3D settings has shown that individual differences in attention durations when viewing 2D scenes do not associate with variability in look durations in 3D table-top play contexts. Wass and colleagues found that, whilst 12-month-olds who showed longer average look durations towards 2D static arrays also show longer looks towards 2D dynamic arrays, no associations were observed between looks towards either type of 2D array and look durations towards toys in a tabletop play (Wass, 2014). Whilst no other work has so far examined associations between 2D and 3D macro-level attention durations, nor how attention in 3D settings associates with experimentally assessed attention control (Johansson et al., 2015), these findings highlight the need to consider the differential processes that drive infant attention in different settings - and how different looking patterns across varying contexts might inform our understanding of the development of real-world attention control. This is a theme to which we return in Section 5.

In summary, look durations towards static 2D stimuli shorten with age during the first year of life and are negatively associated with experimental measures of attention control. Fixation durations to static 2D stimuli also decrease with increasing age during the first year of life, although associations between fixation durations and experimental measures of attention control are inconsistent. For dynamic 2D stimuli, and 3D settings, the opposite pattern is generally observed. Longer look durations in later infancy are generally associated with better performance on experimental measures of attention control. However, no research has examined how fixation durations ('micro-level attention') to dynamic 2D stimuli and 3D settings change over time, or associate with performance on experimental measures of attention control.

In the sections that follow, we discuss how different contributions from different attentional subsystems may have given rise to these findings.

4. Attention shifting

In the next two sections we discuss behavioural, neural, and physiological research that has differentiated between various types of attention across different settings. Our aim is to build on the research described in Section 3, which examined average attention durations in real-world settings, by considering the multiple factors that interactively determine how long an individual attention episode lasts. We divide our discussion by structuring it into two sections, following Cohen and Richards (L. B. Cohen, 1972; Richards, 2010). In Section 4 we discuss attention shifting - i.e., the factors that might cause a new attention episode to be initiated. We consider first periodic attention shifting (Section 4.1) and aperiodic shifting (Section 4.2). Then, in Section 5, we discuss attention holding - i.e., the factors that might cause an attention episode to be maintained.

4.1. Periodic shifting

Animals sample periodically from their environment across a range

of sensory modalities, a phenomenon often described as foraging. For example, rats move their whiskers periodically (Kleinfeld et al., 2016), sniff periodically (Tsanov et al., 2014), and lick periodically (Amarante et al., 2017). Young (<3 month) human infants move their limbs periodically (Robertson, 1985, 1993). Eye movements, which also take place periodically, have been described as visual foraging, or "visual sniffing" (Kozma and Freeman, 2001).

Any plot of attention durations - whether of fixation durations ('micro-level attention') or look durations ('macro-level attention') (Richards and Anderson, 2004) shows fundamentally the same pattern. For fixation durations, for example, the modal fixation duration is generally somewhere between 300 ms and 500 ms (depending on age, viewing material and context) (Wass and Smith, 2014), indicating that participants tend to shift gaze most commonly about 3 times per second. Look durations tend to show the same pattern, with a clear preferred reorientation rate, but this varies more widely contingent on age, viewing material and context. Similar distributions are observed relatively consistently between infancy, later childhood, and adulthood, and across a range of different settings (Engbert et al., 2005; Henderson and Pierce, 2008; Henderson and Smith, 2009; Morrison, 1984; Nuthmann et al., 2010; Trukenbrod and Engbert, 2014); see also (McAuley et al., 1999)). Importantly, as we shall discuss in Section 5, the distribution is also asymmetric around the mode, indicating that the preferred reorientation rate is not the only factor affecting attention durations.

Fig. 1a, for example, shows look durations in 5-month-olds playing in a tabletop setting with toys, showing a preferred modal look duration of 500 ms. Fig. 1c shows the hazard function of this distribution (i.e. the likelihood of a look ending as a function of the look length), which peaks at c.500ms in 5-month-olds. Modal look durations observed in this setting, and at this age, are similar in duration to more fine-grained fixation durations (which are ~400ms in table-top settings at this age (Wass and Smith, 2014)). In other contexts, though, such as while viewing TV clips on screen, modal look durations are markedly higher (see, for example, Fig. 5 in (Richards and Anderson, 2004)). Another study looked at periodic fluctuations in children's looking behaviour to static pictures and found that children whose attention patterns more closely followed a preferred modal reorientation rate showed superior stimulus discrimination (Feldman and Mayes, 1999) (see also (Feldman et al., 1996)).

The most common explanation for why attention shifts take place periodically is to link them to fluctuations in endogenous neural activity (Buzsaki, 2006; Fries, 2023; Goel and Buonomano, 2014; Nobre and van Ede, 2023). Several specific mechanisms have been proposed to account for this link. For example, the ability to detect stimuli that are at the threshold of an individual's sensory sensitivity is thought to vary systematically with the phase of underlying oscillatory neural activity (Busch et al., 2009; Landau et al., 2015; Landau and Fries, 2012; VanRullen, 2016) (although this idea has recently been contested (Ruzzoli et al., 2019)); one possibility is that the tempo of self-generated eye movements may have evolved to match the tempo of these endogenous fluctuations in neural sensitivity (Otero-Millan et al., 2008), although this has been challenged (Dimigen et al., 2011). Another suggestion is that saccades play a role in generating periodic brain activity by resetting the phase of ongoing rhythms, particularly low-frequency components like theta (Fries, 2023). This may contribute to the role that low-frequency theta rhythms play in attentional selection between different internal competing representations (Fries, 2023). A final possible explanation for these findings is that, similar to mechanisms that are well understood at other levels of biological organisation (Gamble et al., 2014; Goldbeter, 2018; Winfree, 2001), periodic patterns of attention reorientation arise as a consequence of a trade-off between behaviours that increase systemic activity and those that decrease it, allowing for non-equilibrium steady-state self-organisation (Decroly and Goldbeter, 1987; Goldbeter, 2018).

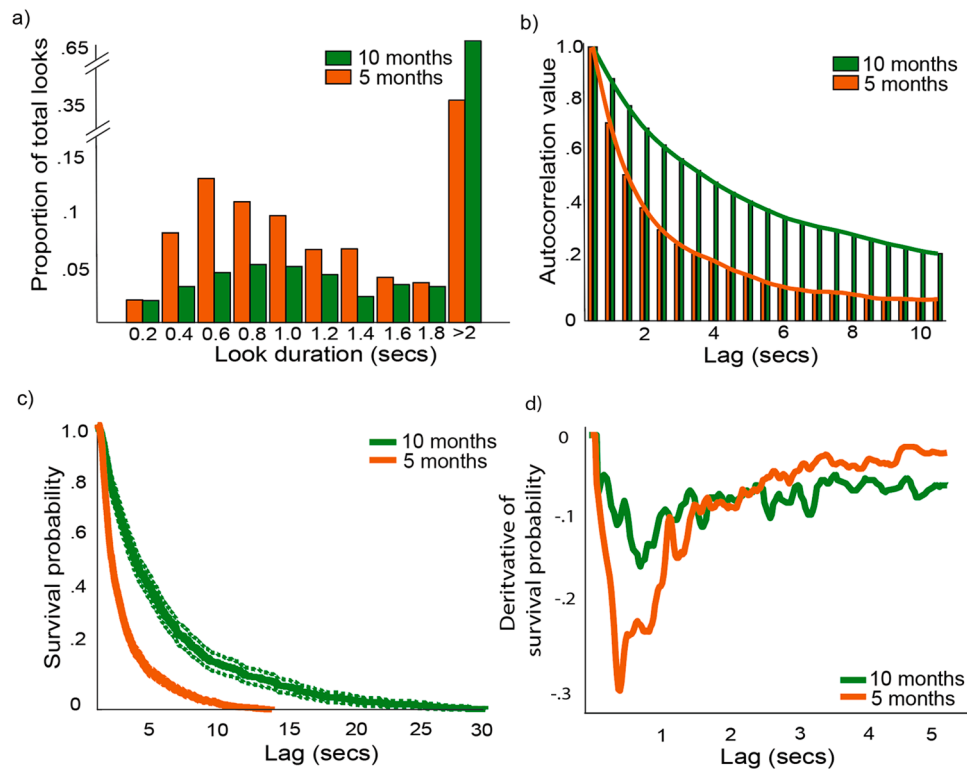


Fig. 1. a) Histogram. The distribution of look durations while 5-month-old infants (orange) and 10-month-old infants (green) were playing alone at a tabletop with toys (redrawn with permission from [Amadó et al., 2023](#), further details available there). Both distributions show a clear mode (at 0.6 seconds in 5-month-olds, and 0.8 seconds in 10-month-olds), and both distributions show a strong positive skew, which is more pronounced in 10-month-olds. b) Autocorrelation. These measure how predictive looking behaviour at one moment in time is of looking behaviour before and after. Looking behaviours are faster changing (i.e. less stable over time) in 5-month-olds. c) Survival analysis. These show the probability that a look will end at a given time lag after its onset. Looks are overall longer lasting in 10-month-olds (consistent with the stronger skew shown in [Fig. 1a](#)). d) Derivative of the Survival Probability at 5 months and 10 months, showing only the 0–5 seconds period. A stronger peak at around 0.5 s is seen in 5-month-olds, consistent with the stronger modal look durations at 5 months shown in [Fig. 1a](#).

4.2. Aperiodic shifting

Because all attention durations are not of exactly equal length, a preferred mean reorientation rate cannot be the sole influence on attention durations. In this section, we consider a range of different factors that might cause aperiodic attention shifting. First, we consider reflexive, and then stochastic, attention shifting ([Section 4.2.1](#)). Finally, we consider several lines of research that point, indirectly, to the emergence of the capacity for endogenous attention control over the timing of attention shifts ([Section 4.2.2](#)).

4.2.1. Reflexive and stochastic drivers of aperiodic shifting

The first category of aperiodic attention shifting is reflexive shifts triggered by changes in our external environment. Exogenous drivers of attention (collectively termed ‘salience’) have been extensively studied in adults both using 2D arrays ([Itti and Baldi, 2009](#); [Mital et al., 2010](#)) and in 3D settings ([Land B., 2009](#); [B. Tatler and Vincent, 2008](#)). For example, unexpected luminance changes within our visual field are likely to trigger an attention reorientation towards the area that has changed ([Itti and Baldi, 2009](#)). Van Renswoude and colleagues found that, when infants aged 3–15 months viewed 2D arrays, their gaze behaviour can be partially predicted based on adult salience metrics, suggesting that infants also make reflexive, gaze shifts based on similar salience criteria to adults ([M. Jing et al., 2023](#); [van Renswoude et al., 2020](#)).

Aperiodic gaze shifts also take place, however, in settings where shifts cannot be driven directly by changes in salience. For example, Robertson and colleagues observed young infants’ attention patterns while viewing toys hung up against a cloth background and built generative models to recreate the patterns of attention shifting observed.

The model contained just two components: a stochastic component (which randomly determined the likelihood of an attention reorientation occurring at a given moment in time) and hysteresis, or an ‘attention stickiness’ component (which we discuss further in [Section 5](#)) ([Robertson, 2004, 2014](#)). Importantly, the model did not include any representation of the content being fixated on (see [Section 5](#)). This model successfully recreated attention patterns in 1-month-olds but was less successful with data from 3-month-old infants.

4.2.2. Endogenous drives of aperiodic shifting

In addition to this purely stochastic causation of attention shifts, as development progresses an increasing number of aperiodic but predictable causes of attention shifting start to develop as well. For example, when a single 2D array is presented repeatedly across discrete but contiguous trials, look durations tend to decrease over time ([Colombo and Mitchell, 2009](#); [Fantz, 1964](#)), which seemingly indicates that some type of stored mental representations of objects must be influencing infants’ looking behaviour ([Colombo and Mitchell, 2009](#); [Sokolov, 1963](#)). More recent research has indicated several other, more subtle markers of cognitive influence on infants’ looking ([Forest and Amso, 2023](#); [Oakes, 2023b](#)); for example, patterns of looking towards and away from a 2D dynamic array in 8-month-old infants can be understood in terms of the changing informativeness of the array ([Kidd et al., 2012](#); [Poli et al., 2020](#)). Importantly, these gaze behaviours are driven not just by the immediate low-level salience of the array, but by the history of what they have seen before: infants monitor and continually update the predictability/surprise of an array and tailor their attention to maximise learning ([Kidd et al., 2012](#); [Oudeyer and Smith, 2016](#); [Poli et al., 2020](#)).

In 3D environments, older infants who are crawling and walking

have been shown to perform various types of saccade ((Franchak and Yu, 2022); see Fig. 2), similar to those documented in adults – which for some types of movements include “look ahead” fixations based either on predictions, learnt knowledge about the statistical properties of scenes, or working memory (B. Tatler and Vincent, 2008) (Hayhoe & Lerch, 2022). As well as influencing their own gaze behaviour when they are actively moving, these “look ahead” fixations also influence their gaze behaviour when passively observing others looking. For example, when viewing actors performing action sequences, infants from as young as 6 months of age can in some circumstances shift their attention to an actor’s goal target before the action is completed (Cannon and Woodward, 2012; Falck-Ytter et al., 2006; Hunniss and Bekkering, 2010; Kanakogi and Itakura, 2011; Ossmy and Adolph, 2020).

Other studies have recorded infants’ brain activity to study how the relationship between attention shifting and cortical brain activity changes over time. For example, a series of studies concurrently measured attention durations and cortical brain activity during free-flowing real-world attention and examined how fluctuations in cortical neural activity - in particular theta power (3–6 Hz in infants), considered a marker of endogenous cognitive engagement (Orekhova et al., 1999; Xie et al., 2019) - relate to fluctuations in attention. The aim of this research is to understand whether fluctuations in neural engagement take place before attention shifts, or after them (see Fig. 3).

Cross-correlation analyses show that, by 12 months, theta activity forward-predicts attention (Wass, Noreika, et al., 2018), such that the strongest relationship between cortical activity and behaviour is observed between cortical activity at time t and behaviour 1500msecs after time t (Fig. 3b). At 10 months, cortical activity does not forwards-predict behaviour, but associations are observed between behaviour and concurrent neural activity (Fig. 3d); at 5 months, no associations are observed between attention and cortical activity ((Amadó et al., 2023); see also (Xie et al., 2018)) (Fig. 3d). Similar findings come from analyses that use linear mixed effects models to examine the relationship between cortical neural activity during different time windows relative to the onset of a look and the subsequent duration of that look (Figs. 3c, 3e). The same approach has been used to examine the relationship between neural activity and heart rate, which is well studied as a physiological correlate of attention in infancy. At 10 months, neural activity forwards-predicts heart rate decelerations; at 5 months, the same relationship is absent (Amadó et al., 2023).

In summary, these results suggest that forwards-predictive relationships, through which cortical neural activity predicts future changes in behaviour, gradually emerge over development. The behavioural research described above, which examines gaze behaviour during both the passive viewing of 2-D arrays and during free locomotion, also suggests that, by later infancy, the timing of attention shifts is at least partially under endogenous control.

5. Attention holding

When 10-month-old infants are playing with toys in a tabletop setting, the modal look duration is 600 ms (Fig. 1b); but nearly 40 % of looks last over 5000 msecs. In 5-month-olds, the modal look duration is similar, but only 10 % of looks exceed 5000 msecs (Fig. 1a). In this section, we shift away from considering the factors that might cause an attention shift to be initiated, to emphasise instead the factors that might cause an attention episode to be maintained.

One possible explanation for this is that an attention episode is maintained because that individual is unable to shift their attention away from where they are looking (‘sticky fixation’ – see Section 2) (Hood and Atkinson, 1993). Traditionally, this is linked to development of the posterior attention network that is thought to be involved in disengaging attention (see Section 2) (Hendry et al., 2019). For example, one study suggested that, in younger infants (1.5 months), fixations landing on the edge of a static 2D object boundary last longer than those that do not (G. W. Bronson, 1994). Another suggested that, in 0.5–3-month-old infants, static stimuli that flicker on and off elicit longer fixations than those that do not (G. W. Bronson, 1990b).

Over time, though, as posterior attention networks develop, it becomes easier to disengage from salient stimuli (Hendry et al., 2019). During this period, the likelihood of an attention episode being prolonged actually increases, in multiple settings (Richards and Anderson, 2004). And what is more, as development progresses, attention episodes begin to take on a self-sustaining character: the longer an attention episode lasts, the more its likelihood of ending during the next successive time interval diminishes (D. R. Anderson et al., 1979; D. R. Anderson and Lorch, 1983; Richards and Anderson, 2004; Robertson, 2004). This phenomenon is known as ‘attention inertia’ (Richards and Anderson, 2004) or ‘attention hysteresis’ (Robertson, 2004). Inertial states are indicated by a negatively accelerating hazard function (Fig. 1d). The effect has been observed in a variety of real-world settings, including during free play (Choi and Anderson, 1991; Oakes et al., 2004), reading (Imai et al., 1992) and looking towards a screen (Richards and Anderson, 2004).

Although researchers commonly refer to these extended periods of real-world looking by using the term ‘sustained attention’, there is a crucial point of difference here between real-world attention and experimental measures of sustained attention. Experimental tasks normally use the Continuous Performance Task, or a variant thereof, which is a ‘maximum performance test’ to measure sustained attention (Manly et al., 2001). But performance on these experimental tasks declines over time; and increasing the difficulty or duration of a task associates with subsequent performance decrements (Huang et al., 2023). This leads to a theoretical approach that treats endogenous control over attention as a resource that can become temporarily diminished, or ‘depleted’ (Fortenbaugh et al., 2017; Huang et al., 2023). But, over medium

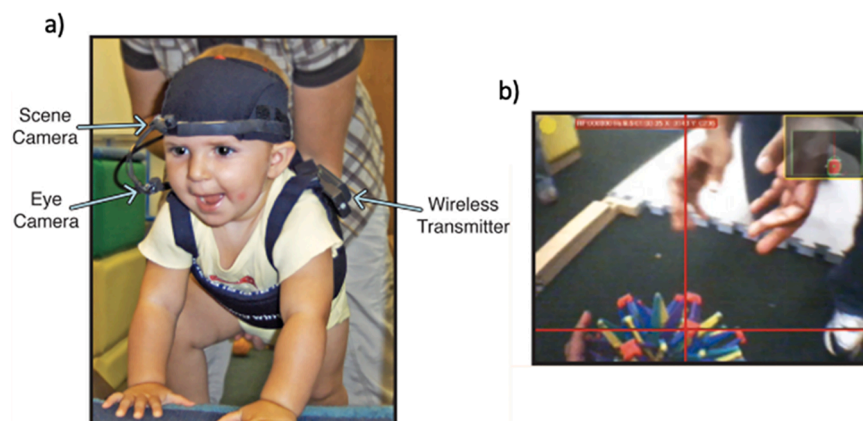


Fig. 2. Illustrations of head-mounted eyetrackers tracking eye movements during free behaviour in naturalistic settings, from (Franchak and Adolph, 2010).

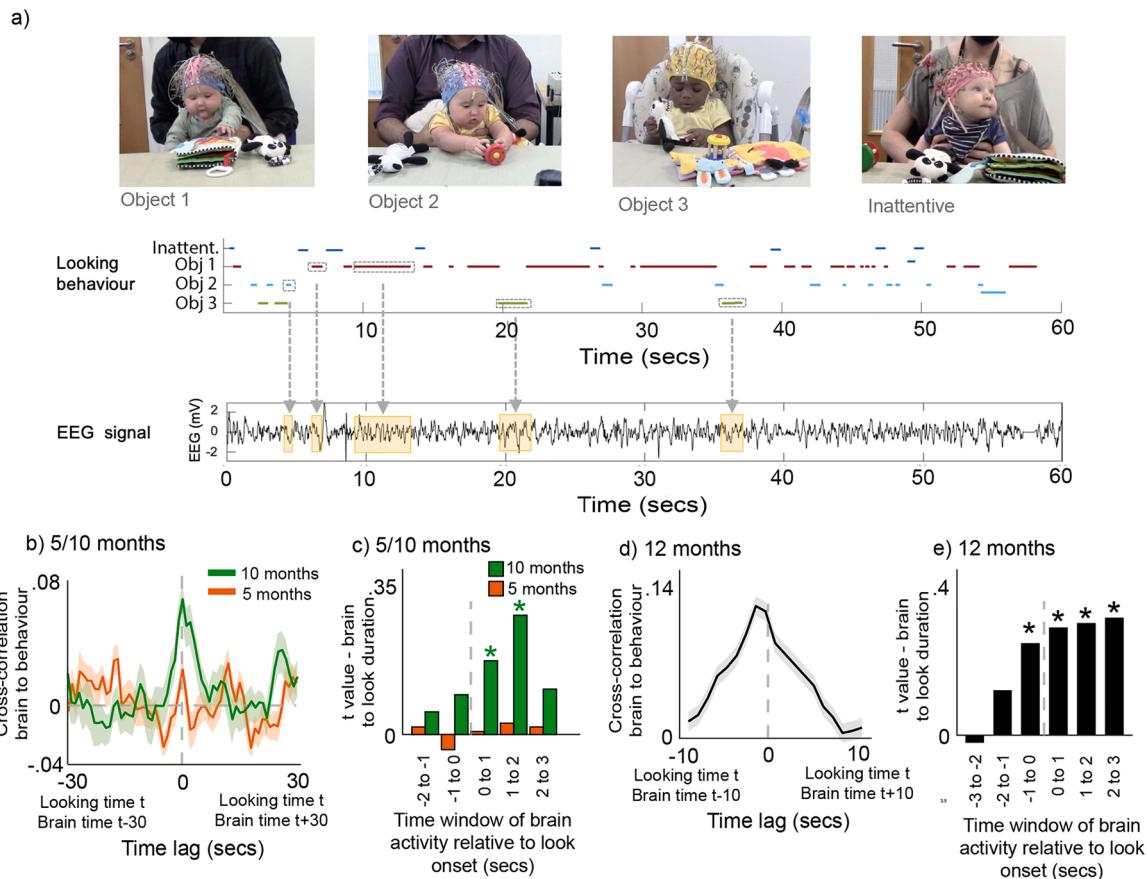


Fig. 3. a) Schematic illustrating a sample of raw data. Brain activity was recorded while infants played alone at a tabletop with toys, and time-series analyses examined the associations between brain activity and behaviour before, during and after the look. b) Cross-correlation between cortical activity (theta (3–6 Hz) power) and attention, in 5- and 10-month-old infants (from [Amadó et al., 2023](#)). At 5 months, no associations are seen between behaviour and cortical activity; but at 10 months, there is an association. c) Linear mixed effects models examining the relationship between theta activity at different time windows relative to the onset of a look and the duration of that look, in 5- and 10-month-old infants ([Amadó et al., 2023](#)). At 5 months, there was no relationship between cortical activity and look duration. At 10 months, cortical activity after the onset of a look predicted the duration of that look. All asterisks (*) indicate p values < .05. d) Same as 3b - Cross-correlation between brain activity in the theta (3–6 Hz range) and attention, but in 12-month-old infants (from [Wass, Noreika, et al., 2018](#)). In contrast to the 10 month data shown in 3b (where the strongest association is between brain activity and concurrent attention), the strongest association shown at 12 months is forwards-predictive (i.e., between cortical activity at time t and behaviour 1500msecs after time t). e) Same as 3c - linear mixed effects models examining the relationship between cortical theta activity at different time windows relative to the onset of a look and the duration of that look in 12-month-olds ([Wass, Noreika, et al., 2018](#)). In contrast to the 10 month data shown in 3c (where cortical activity after the onset of a look predicted the duration of that look), at 12 months theta power during the period –1000–0 msecs before the onset of a look predicted subsequent look durations.

time-frames at least (e.g., an hour-long play session), real-world attention inertia indicates the opposite pattern: increased attention predicts subsequent *increases* in attention.

5.1. Attention episodes show inertial dynamics

In this section, we consider the factors that can cause a micro- or macro-level attention episode to become prolonged. Naturally these factors will differ depending on whether information at the point fixated is constantly changing (as, for example, during TV viewing), or static (as, for example, during tabletop play in a real-world setting). We shall consider these two settings in turn.

Our aim for this [Section \(5.1\)](#) is to advance the idea that, while viewing both 2D (static and dynamic) and 3D scenes, transient attention episodes can develop which show inertial dynamics.

5.1.1. TV viewing

Numerous empirical studies which examined attention patterns during TV viewing have found that, the longer a fixation or look lasts, the lower the likelihood of it ending (L. B. [Cohen, 1972](#); [Richards and Anderson, 2004](#); [Richards and Gibson, 1997](#)). Inertial patterns increase

with age ([Richards and Anderson, 2004](#)) and are lower in children with ADHD ([Lorch et al., 2004](#)). We know that, by 12 months, looks are preceded by increases in cortical engagement (see [Section 4.2](#)). But what drives the finding that, the longer a look continues, the more its likelihood of ending decreases?

Behavioural work has shown that these periods of extended attention periods are marked by temporary reductions in distractibility (D. R. [Anderson et al., 1987](#); [Lansink and Richards, 1997](#); [Mallin and Richards, 2012](#); [Oakes et al., 2004](#)). For example, a study with 6–12-month-old infants examined visual attention patterns during toy play, whilst recording concurrent heart rate and measuring response latencies to a peripheral distractor. They found that, during periods of extended visual fixation, heart rate decelerations occur, together with transient increases in distraction latencies ([Casey and Richards, 1988](#); [Lansink and Richards, 1997](#)). Consistent with this, neural work has shown that evoked neural responses to unattended objects transiently decrease during extended attention episodes ([Richards, 2010](#)). Other behavioural evidence has also indicated that infants' ability to subsequently recognise information is also greater when that information was presented during an episode of extended visual attention ([Frick and Richards, 2001](#); [Richards, 2011](#)).

Other research has shown that periods of extended visual attention are greater for comprehensible over incomprehensible stimuli (Burris and Brown, 2014). For example, one study looked at the effects of making a television program unintelligible by reordering the order of the shots or reversing the speech. No effects were observed on looking behaviour in 6- and 12-month-olds; but for 18- and 24-month-olds, looking times increased for comprehensible stimuli (Pempek et al., 2010). Other research has suggested, possibly consistent with this, that older children are more likely to look away from a screen around the semantic boundaries (i.e., shifts in topic, or between different strands of a story) (Hawkins et al., 2015; Lorch et al., 2006; Richards and Anderson, 2004) (see also (H. Jing et al., 2022)); and that presenting the same TV clip repeatedly also increases viewing time in younger viewers (Barr et al., 2007).

These findings, which look at the timing of attention episodes, can be compared with other studies which examine where children look whilst freely viewing TV clips and videos. Children's gaze behaviour tends to be more scattered than adults', but becomes less so over repeated viewings (Kirkorian et al., 2012; Kirkorian and Anderson, 2018). Presenting television programs rendered unintelligible by reordered the scenes makes low-level salience more influential on gaze location (M. Jing et al., 2023).

Both of these sets of behavioural findings have been interpreted, consistent with the evidence reviewed in Section 4.2.2, as providing evidence that eye movements during TV viewing come increasingly under endogenous control across development (Kirkorian and Anderson, 2018). One important potential driver of this is prediction (Clark, 2013; Henderson, 2017; Köster et al., 2020): whilst free viewing dynamic stimuli, children are thought to generate moment-by-moment predictions which drives gaze behaviour based on semantic and contextual factors (i.e., not just based on salience) and facilitates sustained attention.

Recent research with adult neuroimaging is shedding light on the neural mechanisms that drive these predictions during the free viewing of complex dynamic stimuli (Buschman and Kastner, 2015; Rabinovich et al., 2015). These studies suggest that the human brain relies on a chain of hierarchically organised areas with increasing temporal receptive windows to process temporally evolving, nested structures (Caucheteux et al., 2023; Heilbron et al., 2022a). For example, studies have manipulated the temporal coherence of naturalistic narratives to measure how the presence of higher order semantic and contextual information, which is present in temporally ordered narrative structures but not those in which the temporal order has been destroyed, affects how brains track content (Hasson et al., 2008a; Lerner et al., 2011). Other studies have, similarly, used large language models to quantify the predictability of language across multiple scales - from parts of speech to words, to higher-order contextual factors - to measure how brains differentially track information across multiple, hierarchically nested scales (Caucheteux et al., 2023; Heilbron et al., 2022b). These studies have reported a fixed temporal sequence of response lags - starting in early auditory areas, followed by language areas and lastly the default mode network - corresponding to different hierarchically organised layers of predictions (Chang et al., 2022; Stawarczyk et al., 2011b). However, questions about how these hierarchically organised layers of prediction change over developmental time remain under-explored - such as for example, whether low-level predictions are more influential in guiding attention allocation in younger viewers, and higher-order contextual factors become increasingly influential over development (Berger and Posner, 2023; Köster et al., 2020; Sim and Xu, 2019; Truzzi and Cusack, 2023; Yates et al., 2022).

5.1.2. Tabletop play with toys

3D environments are interactive, in contrast to 2D environments which (at least in the case of TV) are largely passive. Because of this, other factors need to be accounted for while considering children's patterns of attention, such as their physical position relative to people

and objects around them (Clark, 1999). When young children play with toys they interact with them - for example, by reaching out towards an object to pull it closer (McQuillan et al., 2020; Smith et al., 2011). These interactions affect the salience of objects - for example, by creating a salience bias in which one object is more salient from the child's perspective (E. M. Anderson et al., 2022; Méndez et al., 2021; Schroer and Yu, 2021). Thus, an initial increase in attention engagement with an object might lead to changes in the child's immediate physical environment which in turn makes it easier to maintain engagement (see Fig. 4c).

In other ways, though, there are similarities between the hierarchical, nested structures of events contained in a TV clip and those that develop during free-flowing tabletop play with toys. We know that, when adults perform everyday actions, these naturally fall into event structures with hierarchically nested events (e.g., if my higher-order goal is to cook spaghetti, then my lower-order goals are to get out the pan, boil the water, put the spaghetti in the pan, etc) (Zacks, 2020). Event boundaries associate with transient increases in prediction error (Zacks et al., 2011), and correspond to how information is encoded into and retrieved from storage in the brain at specific moments and integrated across time-scales (Hasson et al., 2008b, 2015a).

When children engage in spontaneous play, they presumably also self-generate hierarchically nested goals, whether building structures out of Duplo (Schroer and Yu, 2021) or acting out scenes with dolls. Previous research examining infants' toy selections has suggested that infants generate intrinsically-motivated yet predictable routines (F. Kaplan and Oudeyer, 2007; Karmazyn-Raz and Smith, 2023). During early development, low-level predictability is high, and hierarchical goals seem to be absent: for example, 30-month-olds when invited to play with Duplo often build a simple, vertical tower using the same type of bricks over and over (B. E. Kaplan et al., 2022). In a study that involved giving children instructions to build a Duplo house, 3-year-olds were just as effective at building the walls (simple uniform towers) as 5-year-olds, but the older children were more effective at bringing the walls and roof (the sub-goals) together to complete a house (the main goal) (Schröer et al., 2021). This may reflect that 3-year-olds created highly predictable structures, whereas 5-year-olds created structures that were less predictable overall, but more hierarchically organised.

Over the course of development, it is likely that higher-order goals which act over longer timescales increasingly allow for the integration of nested sub-goals over shorter timescales (Duncan, 2013; Hasson et al., 2015b). Once initiated, these higher-order goals may serve to prolong a play episode longer than it would have lasted in the absence of a goal, possibly through similar mechanisms to those discussed in Section 5.1.1; however, this remains almost completely unexplored (see Section 6).

5.1.3. Understanding inertial dynamics

In the previous two sections we reviewed evidence that, both during the passive perception of TV clips, and during active tabletop play with toys, hierarchically nested event structures develop. These nested event structures align with adult neuroimaging evidence which suggests that hierarchically organised brain areas with increasing temporal receptive windows are present, and likely emerge over the course of development.

These findings are important for understanding how attention inertia emerges as a product of transient and mutually self-sustaining interactions between visual engagement, comprehension, prediction and selective attention (Buschman and Kastner, 2015; Rabinovich et al., 2015) (Fig. 4a). When hierarchically linked areas are simultaneously active, global representation of information through recurrent processing is strengthened (Singer, 2021; van Kempen et al., 2021). Evidence from fMRI shows that this process is also driven by increased functional system segregation lower down the sensorimotor association axis (Keller et al., 2022), which other studies have shown to associate with better comprehension (Just and Varma, 2007; Lee et al., 2009). At the more fine-grained cellular level, recurrent dynamics in the cerebral cortex drive the integration of sensory evidence with stored knowledge (Singer,

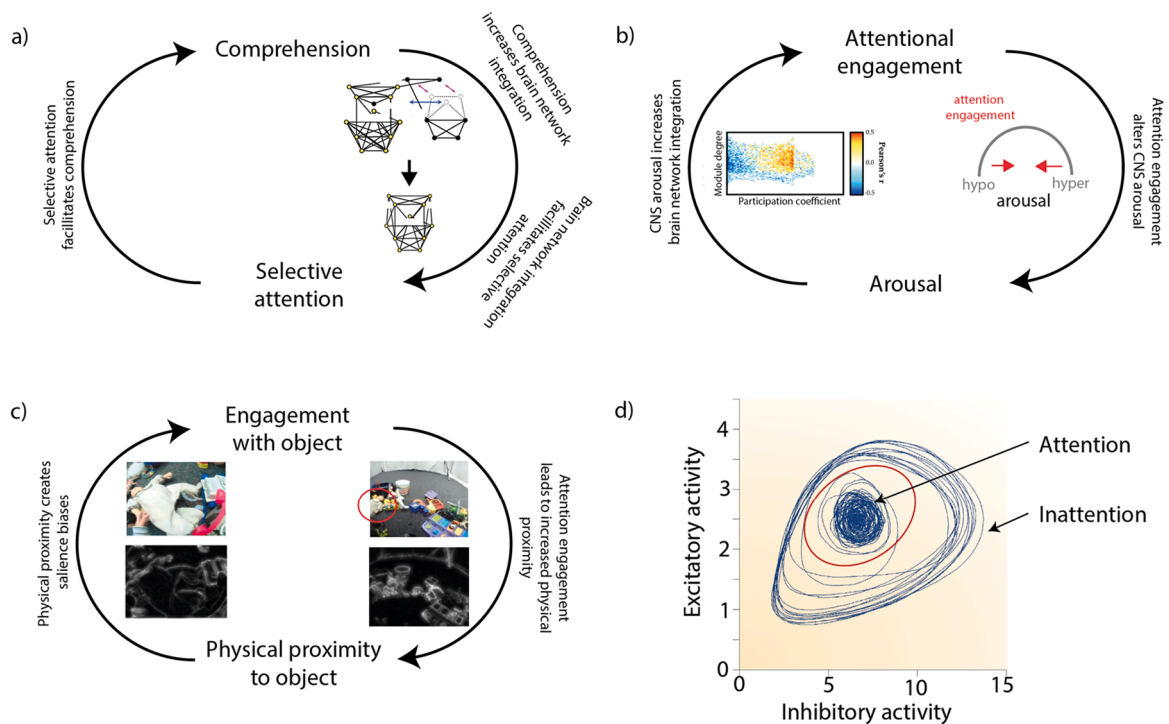


Fig. 4. a-c) Schematics showing three levels at which mutually amplifying self-sustaining interactions can develop during periods of attention engagement between a child and their environment. a) – interactions between comprehension and distractibility, mediated by brain network segregation and integration, discussed in Section 5.1.3. b) – interactions between attentional engagement and arousal, discussed in Section 5.1.3. c) – interactions between object engagement and physical proximity to that object, discussed in Section 5.1.2. d) schematic illustration of attractors – a phase space portrait (Afraimovich et al., 2011; Rabinovich et al., 2015) showing how both attention and inattention can develop as transient, self-sustaining states.

2021). Priors and expectations drive the flexible reconfiguration of feed-forward and recurrent connections (Kreiter and Singer, 1996), enabling a high-dimensional resting state to collapse into a lower-dimensional substate (Lazar et al., 2009; Singer and Lazar, 2016), facilitating processing efficiency (Singer, 2021).

One additional, related mechanism that may subserve these bidirectional associations is between attention engagement and arousal, defined as activity within brainstem reticular activating systems (Aston-Jones and Cohen, 2005; Shine et al., 2016; Wass, 2021b). As we discussed in Section 2, ample evidence suggests that showing attention-eliciting, comprehensible stimuli can lead to changes in physiological arousal (Graham and Clifton, 1966; Richards, 2010; Sechenov, 1965). But changes in arousal also cause changes in attention: arousal changes associate with alterations in ascending neuromodulatory input to the cortex and subcortex, which associate in turn with global fluctuations in network structure over time, which mediate increases in connectivity between otherwise segregated regions of the brain through the modulation of neural gain (Pfeffer et al., 2022; Shine et al., 2016) (Fig. 4b).

Consistent with behavioural evidence that attention inertia gets stronger with increasing age (see Section 5.1.1), these putative neural mechanisms would also suggest that, as learning drives refinement in the weights of neural networks that allow feed-forward and recurrent connections to be flexibly recombined (Singer, 1993), these bidirectional associations between comprehension and distractibility ought to become progressively stronger over developmental time. This is also consistent with the evidence we discussed in Section 4.2, where we found that, in 10-month-olds, changes in attention forwards-predicted changes in cortical theta power (a marker of cortical engagement) and changes in cortical engagement forwards-predicted changes in arousal; but both of these relationships – between attention and cortical engagement, and between cortical engagement and arousal - were absent at 5 months (Amadó et al., 2023) (see also (Richards, 2010, 2011)).

5.2. Multi-stable attention states

In the previous section, we discussed amplifying interactions between engagement, comprehension and distractibility that can cause attention episodes to develop as stable states that persist over time. In this section, we speculate that attentional engagement may not be the only state in which a system is stable. We discuss how attention disengagement, which occurs during both hypo- and hyper-arousal, may also develop self-sustaining attractor dynamics driven by amplifying child-environment interactions, leading to ‘multi-stable’ attention (see Fig. 5). This idea, that behavioural states can be multi-stable, is already well developed for understanding emotions (Afraimovich et al., 2011; Cole et al., 2020; Hollenstein, 2015). In neuroscience, our understanding of multi-stable brain states is also well developed (Flavell et al., 2022; Giesbrecht et al., 2024; Greene et al., 2023; Meer et al., 2020; Rabinovich et al., 2015; Shine et al., 2016; Tang et al., 2012). In physiology, the concept has also been developed to explain how stress states develop and persist (Brooks et al., 2021). Other research has investigated how multi-stable states can develop in psychopathology, whether internally, as persistent mental states in conditions such as Obsessive Compulsive Disorder (Rabinovich et al., 2010), or externally, as persistent oppositional interpersonal interactions (Granic and Patterson, 2006; Hollenstein et al., 2004; Wass et al., 2024) or shared dyadic states of anxiety (Perlman et al., 2022). Here, we draw on some of these ideas to explore how attention disengagement, which can occur during both hypo- and hyper-arousal, may also develop self-sustaining attractor dynamics driven by amplifying interactions between a child their environment (see Fig. 5). This can lead to ‘multi-stable’ attention states (Flavell et al., 2022).

5.2.1. Hypo-arousal

Previous research has examined episodes of extended looking towards a particular object that co-occur with the decoupling of overt and

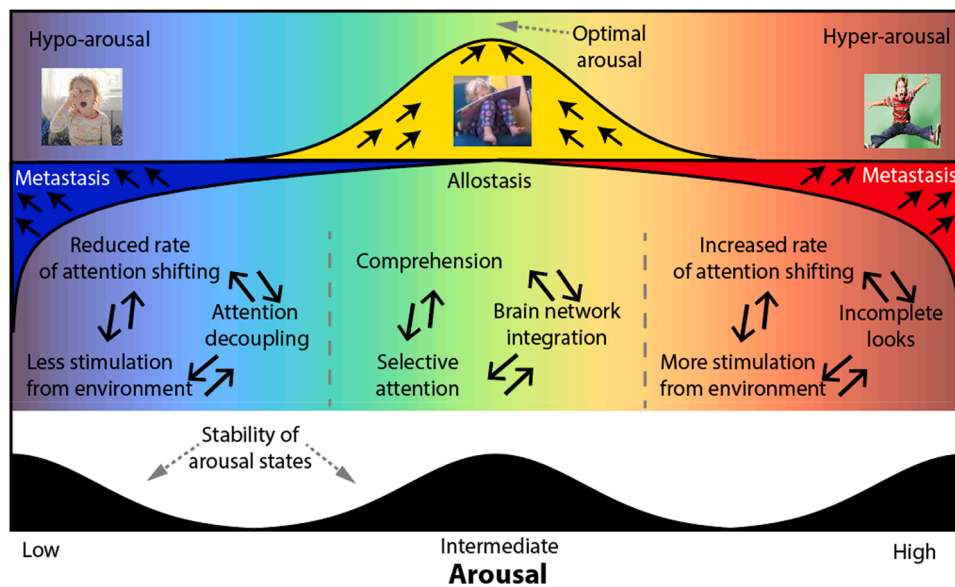


Fig. 5. schematic illustrating the possible multi-stable attention and arousal attractor states described in Section 5.

covert attention (known as mind-wandering) (M. R. Cohen and Maunsell, 2011; Keulers and Jonkman, 2019; Smallwood et al., 2011; Unsworth and Robison, 2017). When viewing a 2D static array, infants typically show most fixations in the 0–1000ms range, but with a substantial tail of > 1000 ms fixations (see Fig. 1a). These extended fixations often occur during hypo-arousal – for example, when a child is in the process of falling asleep (Brazelton, 1991). An early study noted, for example, that when fixations in 2-to 14-week-old infants remained centred on a single feature, 24 % were of relatively long duration, whereas when infants were scanning between the features the incidence dropped to 11 % (G. W. Bronson, 1990b).

Although it is hard to identify when mind-wandering occurs in infants and young children, several studies have tried. First, some studies have differentiated between different types of extended look using video coding. These studies have suggested that attention engagement (i.e., the coupling of covert and overt attention) is accompanied by serious facial expression, reduction of vocalisation and extraneous motor activity, close approach to an object, and looking while fingering and rotating an object (known as focused attention); whereas attention disengagement is characterised by extended looking in the absence of these concomitant behaviours (known as casual attention) (Lawson and Ruff, 2004; Ruff and Capozzoli, 2003; Ruff and Lawson, 1990; Ruff and Rothbart, 1996).

Other studies have measured the physiological correlates of attention, to differentiate between attention episodes that are accompanied by physiological changes (heart rate decelerations) and those that are not (Richards, 2010). Attention episodes accompanied by short-term physiological changes (e.g., heart rate decreases during a look) are thought to be more commonly observed at intermediate levels of tonic arousal; at both hypo- and hyper-tonic arousal, short-term attention-related changes are less likely to occur (Aston-Jones and Cohen, 2005; Wass, 2021b). During attention episodes accompanied by short-term reductions in heart rate, children show larger evoked neural responses to attended stimuli (Richards, 2003), superior recognition memory (Richards, 2010), and are less likely to respond to peripheral stimuli (Lansink and Richards, 1997; Richards, 1997). Attention episodes accompanied by heart rate decelerations show changes in cortical activity (increased theta and decrease alpha) during a look, in 10- and 12-month-olds but not 6- and 8-month-olds (Xie et al., 2018, 2019).

Extended visual fixation periods accompanied by hypo-arousal and the decoupling of overt and covert attention might also associate with transient problems in disengaging from salient stimuli (Frick et al.,

1999; Hood and Atkinson, 1993; Hunnius, 2007; Stechler and Latz, 1966). For example, when stimuli were flickering, the incidence of long fixations was 23 % compared to only 13 % during steady illumination (G. W. Bronson, 1990b). In 6–13-week-old infants, long fixations were only observed when the area fixated contained a stimulus contour (G. W. Bronson, 1994). Reductions in arousal may associate, therefore, with a reduced rate of re-foveation (Brazelton, 1991) and to the decoupling of overt and covert attention, resulting in a reduced rate of uptake of new information (see Fig. 5). Because arousal changes take place in response to external stimulation (Aston-Jones and Cohen, 2005), this reduced rate of information uptake could be both a consequence of hypo-arousal, and a cause of it – creating self-sustaining dynamics similar to those we discussed in Section 5.1 (see Fig. 5, left side). This may, for example, drive inattention in some cases of ADHD, where cases of hypo-arousal have been observed (Bellato et al., 2020).

5.2.2. Hyper-arousal

Similar self-sustaining dynamic may also develop during attention disengagement through hyper-arousal, although little research has investigated this thus far. During hyper-arousal reorientation rates increase (de Barbaro et al., 2011), which presumably leads to an increased rate of information uptake, which may cause further hyper-arousal (see Fig. 5, right side). If proven, this would be a similar type of self-sustaining dynamic to that discussed above: hyper-arousal is both a cause of increased information uptake, and a consequence of it (Wass, 2021a).

There is also another possible route through which episodes of hyper-arousal may become self-sustaining: it is also possible (although again under-researched) that hyper-aroused children may alter their physical environment in a way which makes it harder to focus on single individual objects (e.g. by scattering their toys all over the floor) (Gould et al., 2018). This is the opposite of the pattern we described in Section 5.1.2, where children engaged with objects create salience biases to make it easier to maintain attention. By altering their environments to make it harder to focus on individual objects and toys, this might cause further hyper-arousal.

6. Conclusions, practical implications, and directions for future work

From the first moment that we open our eyes until the last, our sensory organs are bombarded by a constant, complex mishmash of

electromagnetic information (Metzinger, 2010). In real-world settings we organise our visual behaviours into discrete periods of attention engagement and disengagement (Nakamura et al., 2007). These patterns of engagement and disengagement can be seen across multiple spatio-temporal scales, from micro-level reorientations occurring several times a second through to macro-level behaviours. This process, of choosing what we sample from the environment and when, is crucial. Through it, we determine not just what we experience from the world, but also the state that we are in when each new piece of information reaches us. It is tempting to think of our experience of reality as a passive process - like viewing the outside world through a window. But this is wrong (Clark, 1999). It is an active process: where we look, and when, determines what information we receive. Behaviours generate experiences.

In this article we have reviewed evidence for how the timings of attention shifting change over development, during the period when experimental evidence suggests that the capacity for endogenous control is beginning to emerge. In Section 4 we concentrated on the factors that might cause a new attention episode to be initiated; in Section 5, we concentrated on the factors that might cause an existing attention episode to be prolonged. The two are of course inextricably intertwined, and we have followed this distinction purely for emphasis.

In Section 4 we presented evidence that, even from early development, shifts of overt visual attention are triggered both periodically, and aperiodically. We discussed multiple sources of evidence that the timings of spontaneous attention reorientations become progressively more endogenously controlled during early life. These included studies that examined behaviour while children passively view 2D arrays on screen, those that view active gaze behaviour during free locomotion, and those that measure the fine-grained associations between cortical neural activity and behaviour.

In Section 5, we examined the factors that might cause an attention episode to be prolonged. First, we examined the mechanisms that might drive 'attention inertia' - i.e., the finding that, the longer an attention episode lasts, the more the likelihood increases that the episode will be prolonged. We argued that, both during the passive perception of TV clips, and during free, self-generated behaviour (e.g. tabletop play), transient, mutually self-amplificatory interactions develop between engagement, comprehension, prediction and distractibility. We pointed to evidence from adult neuroscience which suggests that these may be instantiated through hierarchically nested structures that operate across multiple brain systems. Second, we speculated that multi-stable attention states may also develop, through which both hypo-arousal and hyper-arousal can also develop as stable states that persist over time.

6.1. Directions for future work

6.1.1. Studying attention across different spatiotemporal scales

Attention behaviours can be studied across multiple spatiotemporal scales; here, we differentiated between fixation durations ('micro-level attention') and look durations ('macro-level attention'), but there are even larger-scale patterns of engagement and disengagement (e.g., daily cycles) that we have not studied, because observation studies are lacking. We know that similar organisational principles guide attention across different scales, such as the relationship between the power (i.e., the size of an attention shift) and the frequency (i.e., how often shifts occur) (Stallworthy et al., 2020). And we know that energetic principles underpin real-world attention behaviours - such that we are less likely to perform attention reorientations that require greater energy (e.g., spatial shifts of attention involving both head and eye movements) (Ballard et al., 1995; Hayhoe and Lerch, 2022).

But there is a lot that we do not understand about how attention behaviours are coordinated across timescales. For example, classical theoretical approaches such as comparator theory state that, when children look at an object, they are collecting information to build a mental representation of it, and when they look away, they have

completed the representation (Colombo and Mitchell, 2009; de Barbaro et al., 2011; Sokolov, 1963). These models were developed to account for individual differences in behaviour on a habituation protocol (Colombo and Mitchell, 2009; de Barbaro et al., 2011). But individual differences in fixation durations are not always stable as measures of individual difference and across contexts (Section 3.1); the relationship between average attention reorientation frequencies and long-term outcomes differs between contexts and as a function of developmental time (Section 3); and extended visual fixation durations can arise from both attention coupling and decoupling (Section 5). Because of this it is unclear whether, and if so how, these models of individual differences can account for the complexity of real-world attention. Relatedly, it is also unclear whether, for example, an individual's preferred mean reorientation is consistent across micro- and macro-level attention, and, if so, why.

6.1.2. Attention control, arousal and real-world attention behaviours - part 1 - rhythms and extrinsic self-regulation

In Section 4.1 we also discussed the possibility that shifting attention at regularly spaced time intervals may help maintain non-equilibrium state-state self-organisation, by maintaining a balance between behaviours that increase the level of activity and those that reduce it. This was motivated, for example, by findings that children whose patterns of engagement and disengagement were more periodic, exhibited better attention and learning (Section 4.1). To test this hypothesis would require the observation of fine-grained arousal and attention fluctuations, using a high-resolution measure of arousal such as pupil size or cortical arousal, to measure how periodic patterns of attention and inattention associate with changes in arousal.

These early-developing periodic attention shifting behaviours are internally triggered: we reorient attention periodically, even in the absence of external triggers. But, because they happen periodically, they are not habitually included into traditional definitions of attention control, as we have defined it here ('choosing what we pay attention to and what we ignore').

More problematic for traditional definitions of attention control is that periodic orientations can also be triggered extrinsically (see Section 4.2). By controlling the temporal properties of a visual stimulus (e.g. how information content in a video is structured over time), we can trigger periodic patterns of attention shifting, which may extrinsically regulate arousal and maximise information uptake. This would, in some ways, be a visual analogue of how communicative behaviours with children (patterns of eye gaze, touch, turn-taking vocal behaviours, and volume fluctuations in child-directed speech) also contain predictable periodic structures (Choisdealbha et al., 2023; Leong et al., 2017; Wass et al., 2021) (see also Labendzki, n.d.). Studying this area may in future be useful for understanding how the optimal rate of engagement and disengagement differs between different atypical individuals; and for understanding individual differences in attention in individuals (such as children with autism, ADHD etc), who would benefit from more extrinsic regulation.

6.1.3. Attention control, arousal and real-world attention behaviours - part 2 - endogenous attention shifting

In Section 4.2 we discussed evidence from computational modelling and neuroimaging that suggests that patterns of attention shifting may be largely stochastic during early infancy. During the first year of life, though, an increasing number of sources suggest that the timings of attention shifts come under endogenous control (Section 4.1.2).

We still understand relatively little, though, about how we use this endogenous control to maintain stability within a complex and changing environment - a process known as allostasis. We know, for example, that even newborns will close their eyes when over-stimulated (Brazelton, 1983), and that infants are more likely to show gaze aversion following experimenter-administered toy removal, which upregulates arousal (Kopp, 1982). Some experimental studies have also shown that young

infants dynamically recalibrate their attentional behaviours to down-regulate their own arousal when it is high, and to upregulate it when it is low (Gardner and Karmel, 1984, 1995). But beyond that we understand virtually nothing about how we use attention ‘on the fly’ to gate what information we receive from the environment, and when – either from the perspective of low-level information content (movement/volume) or informational content. Studying this would help us understand how arousal and attention are coordinated on a moment-by-moment basis, and how this ability changes and develops over time.

6.1.4. Attention control, arousal and real-world attention behaviours – part 3 – attention engagement

At the start of Section 5 we discussed an important difference between experimental measures of sustained attention, which show decrements in performance over time, and real-world attention which shows the opposite pattern: the longer an attention episode lasts, the more its likelihood of ending during the next successive time interval diminishes. This may be because experimental tasks (such as the Continuous Performance Task; Flanker task; Attention Network Test, etc) strip away the requirement to integrate successively encountered information, hence are very different to the types of situations in which we usually sustain attention (such as a conversation, play with DUPLO, reading a story book, etc) (see Section 5.1.2).

Real-world attention is not a finite resource over time (at least over the timescale of minutes/hours). But, importantly, it is a finite resource in the moment: paying more attention to one thing decreases the attention that we can pay elsewhere (Richards, 2000). In Section 5.1 we discussed several different possible pathways through which transient engagement between an observer and their environment might develop self-sustaining dynamics.

Importantly, these relationships emerge during an attention episode, and possibly irrespective of whether that attention episode was endogenously initiated (as discussed in the previous statement). This leads to a shift away from an approach that views selective attention *purely* as a trait-like property of individuals (i.e., whether one child has a better selective attention capacity than another). Instead, it emphasises how selective attention also operates as a trait-like property, that varies transiently as a function of our engagement with people and objects around us (cf Woods, 2016).

This shift of emphasis is relevant, for example, for our attempts to use cognitive training to improve children’s attention by targeting their attention control capacity (see e.g., (Klingberg, 2010; Rueda et al., 2005; Wass et al., 2011)). Now, these studies measure the effect of attention training either by administering an experimental test battery, or by averaging attention behaviours across a short naturalistic observation period. Both approaches implicitly treat attention it as a trait-like feature of individual differences. An alternative approach designed to measure the state-like variability of selective attention based on engagement, may be a fruitful avenue to pursue in future work.

6.1.5. Attention control, arousal and real-world attention behaviours – part 4 – attention dysregulation

In Section 5.2 we discussed the possible existence of ‘metastatic’ processes (Wass et al., 2021) through which small initial increases and decreases in arousal can be progressively amplified over time through actor-environment interactions, leading to multi-stable attention states.

From a practical perspective, hyper-arousal is relatively easy to identify (for example, in educational settings). Hypo-arousal, though, can be much harder to identify (Hinshaw et al., 2022). Hypo-arousal often manifests as attention decoupling (mind-wandering) (see Section 5.2.1). From the outside, these episodes can be hard to identify (Ruff and Capozzoli, 2003; Ruff and Lawson, 1990). From a practical perspective, though, understanding hypo-arousal is vital, as it is a potentially important but hard-to-spot driver of under-performance in academic settings (Moldavsky et al., 2013). Improving our ability to identify hypo-arousal would allow us to trial interventions to reduce their

frequency. For example, studies have shown that simply playing a regular tone to stroke patients can cause their attention patterns to become more like those of neurotypicals (Manly, 2002). It is possible that similar techniques may be effective with hypo-aroused children.

6.1.6. Attention control, arousal and real-world attention behaviours – part 5 – long-term interactions

At the moment, we also understand very little about the longer-term relationships between environmental stimulation, arousal and attention. The short-term mechanisms that we described above explain how initial increases and decreases in arousal are progressively amplified over time (Wass, 2021a). But do the opposite of these – i.e., allostatic, or negative feedback processes – emerge later in development? In other words, if I am used to spending time in hyper-stimulating environments, do I progressively become desensitised, such that a given level of stimulation elicits progressively less arousal over time? And does my long-term ‘optimal’ arousal state (i.e. the ‘centre point’, which I use allostatic mechanisms to maintain) vary between individuals – such that a given level of stimulation might elicit down-regulatory behaviours in one individual, but up-regulatory behaviours in another? Again, answering this question is essential from a practical perspective, as it will allow us to optimise how we design learning settings to be tailored for the needs of different individual children.

7. Conclusion

Evidence from experimental studies suggests that the capacity for attention control emerges over the early years of life. But how do we define attention control in real-world contexts, and what implications does this have for how we understand its development? In this article, have reviewed evidence which suggests that the capacity to choose when we shift attention emerges through early life. But this is only part of the picture. Irrespective of what initiated the episode in the first place, transient bidirectional, mutually amplificatory interactions between an observer and their environment develop during the course of the episode, and determine how long that episode lasts. Attention control is not just a cause of our engagement with our environments, but also a consequence of it.

Ethics approval

Not applicable (review article)

Consent to participate

Not applicable (review article)

Consent for publication

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Code availability

Not applicable (review article)

Authors’ contributions: SW conceptualised and wrote manuscript. MPA, TN, IMH and EP read the draft and gave comments.

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Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

Data availability

No data was used for the research described in the article.

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