

Studying the developing brain in real-world contexts: moving from castles in the air to castles on the ground.

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Abstract

Most current research in cognitive neuroscience uses reductionist, standardised experimental simulacra to study the developing brain. But these approaches do a poor job of mimicking the real-world, and thus can only provide a distorted picture of how cognitive operations and brain development unfold outside of the lab. Here we consider future research avenues which may lead to a better appreciation of how developing brains dynamically interact with a complex real-world environment, and how cognition develops over time. We raise several problems faced by current mainstream methods in the field, before briefly reviewing novel promising approaches that alleviate some of these issues. First, we consider research that examines passive perception by measuring entrainment between brain activity and temporal patterns in the environment. Second, we consider research that examines our ability to parse our continuous experience into discrete events, and how this ability develops over time. Third, we consider the role of children as active agents in selecting what they sample from the environment from one moment to the next. Fourth, we consider the potential of new approaches to measure how mutual influences between children and others are instantiated in suprapersonal brain networks. Finally, we discuss how we may reduce adult biases when designing developmental studies. Together, these approaches have great potential to further our understanding of how the developing brain learns to process information, and to control complex real-world behaviours.

Keywords: neuroimaging, development, entrainment, environment, real-world, naturalistic, EEG, fNIRS, fMRI, hyperscanning, child, infant.

Looking at brain function using non-ecological, non-interactive paradigms intended to mimic real-world cognitive operations

“Problem-level assumptions set the course for the entire research programme” (Edelman, 2016)

“There is more pleasure to building castles in the air than on the ground” (Gibbon, 1788)

Psychologists and (more recently) cognitive neuroscientists often use standardised simulacra intended to mimic real-world cognitive operations (Danziger, 1994; Hatfield, 2002). From the start, we have been aware that this approach has intrinsic limitations (Aanstoos, 1991; Anderson et al., 1999; Bronfenbrenner, 1977; Shamay-Tsoory & Mendelsohn, 2019; Sonkusare et al., 2019) (although see (Holleman et al., 2020)). But it is, nevertheless, always worth reminding ourselves what some of the inherent assumptions underlying this approach are – particularly when it comes to studying brain function *in vivo*, and during development.

The first problem is that experimental simulacra often differ in a number of ways from the real-world that they are intended to mimic (Shamay-Tsoory & Mendelsohn, 2019), and can therefore only provide a distorted picture of cognitive operations. For example, visual event-related potentials are typically measured relative to the sudden appearance and disappearance of objects, and relative to the repeated presentation of exact sequences of events that reoccur – both of which rarely if ever occur in the real world. Similarly, although auditory evoked potentials are typically measured relative to the presentation of single nouns, real-world language comprehension critically requires parsing single words out of a dynamic stimulus.

In particular, one general assumption underlying experimental simulacra is that both the events themselves, and their exact timings, tend to be decided by the experimenter, and not the participant. In the real world, though, behaviour does not happen just through passive, serial-order responses to external stimuli (Edelman, 2016; Kolodny & Edelman, 2015; Marr, 1985; Phillips, 1971; Smith & Gasser, 2005; Spivey & Dale, 2006; Yu & Smith, 2013). As Dewey first noted over hundred years ago “[w]hat 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).

Beyond perception-action continuities at the personal level, for example, at the subpersonal level our world is also heavily shaped by social partners. This is especially true for babies whose perceptual access often depends on caregivers’ decisions (e.g., babies will not have the same visual access to a scene if they are sitting in a reclined chair as opposed to an opaque crib). In the lab, researchers present infants with standardised simulacra whose specific features depend on their own (adult, expert in child development) understanding of what infants may or may not be able to discriminate. These assumptions may sometimes match caregivers’ assumptions, and thus partially match what infants are given perceptual access to in their daily lives; but it can also critically differ, for instance when experimenters have a strong theory-driven bias, or when they have different beliefs about infants’ cognition than the caregivers.

The second general problem is that these approaches rely on the assumption that cognitive operations *can* be abstracted and encapsulated by stable and context independent mental state concepts such as “attention” or “cognitive control” (Pessoa et al., 2022) – i.e. that, for example, cognitive control measured at one time and using one paradigm relates

meaningfully to cognitive control measured using a different type of paradigm (Broadbent, 1993; Campbell, 1957; Kingstone et al., 2003, 2008; Neisser, 1977), and cognitive control as it is deployed in ecological contexts. In fact, the claim that the experimental simulacra do actually mimic the real-world cognitive operation that they were designed to imitate is rarely, if ever, tested (Sonkusare et al., 2019). And research suggests that both individual differences (Awh et al., 2007; Neisser, 1977) and transfer effects following cognitive training (Holmes et al., 2019) are remarkably specific to minor details of the experimental paradigm used.

Indeed, such abstract concepts may rarely – if ever – strictly correspond to distinct neural structures (e.g., there is no strict boundary at the neural level between “emotions” and “cognition”) (Pessoa et al., 2022); rather, neural architectures appear to be geared towards solving specific problems that depend on the characteristics of the world that cognitive agents live and develop in (Pessoa et al., 2022). In other words, although mental state concepts constitute useful shortcuts to talk about cognitive operations, understanding how neural systems support behaviour requires research that documents how cognitive agents solve specific real-world problems.

In the following, we review recent developments in how we study brain function across adult and developmental cognitive neuroscience, and we discuss possible new future research directions, that we hope will in future allow us to alleviate some of these problems.

Our discussion is in four sections. In Part 1, we examine studies that examine the passive perception of complex, naturalistic stimuli. In Part 2, we consider research which examines our ability to parse our continuous experience into discrete events, and how this ability develops over time. In Part 3, we consider the role of children as active agents in selecting

what they sample from the environment one moment to the next. In Part 4 we consider the potential of new approaches to measure how mutual influences between children and others are instantiated in the brain. Finally, we discuss research strategies that may enable us to limit the influence of experimenters' own beliefs when designing experiments, which appears especially important given the discussion developed in the preceding sections.

Section 1 – the passive perception of complex, naturalistic stimuli

In the real world we virtually never encounter a stimulus that flashes on and off, in isolation, out of the black – despite the ongoing popularity of this type of stimulus in neuroimaging studies (Shamay-Tsoory & Mendelsohn, 2019). Rather, the real world is a complex, dense, continuous mishmash of electromagnetic information, through which our sensory systems have developed to navigate. Reflecting this, an increasing number of studies have started to measure brain responses during the passive perception of complex, naturalistic stimuli that approach the complexity of real-world stimuli. Practically these normally take the form of audio and video recordings that are presented identically to multiple participants.

A large body of research has looked at how temporal activation patterns in our brain respond to periodic and aperiodic temporal structures in our everyday environments (Haegens & Golumbic, 2018; Lakatos et al., 2019; Rimmele et al., 2018). Of this, the largest body of evidence looks at temporal structures in everyday natural speech (Doelling et al., 2019; Giraud & Poeppel, 2012; Poeppel & Assaneo, 2020). Several recent papers have used EEG and fNIRS to demonstrate that infants show dynamic neural tracking to visual information (Jessen et al., 2019) and natural speech (Attaheri et al., 2021; Barajas et al., 2021; Jessen et al., 2019; Kalashnikova et al., 2018; Liu et al., 2017; Menn et al., 2022) in pre-recorded

videos. These studies have mainly used variants of the Temporal Response Function (Jessen et al., 2021), which essentially regresses the stimulus (e.g. the auditory envelope of speech) onto the neural activity (or vice-versa).

It remains to be seen, though, how mechanistically the developing brain processes the environment. A particularly important question is whether dynamic stimulus processing is driven by oscillatory entrainment (endogenous oscillatory activity in the brain becoming coupled with oscillatory activity in the stimulus) or by contingent responding (the brain showing an evoked response whenever a stimulus occurs) during early development (Wass et al., 2021). It also remains to be seen how endogenous attention, and the comprehensibility of this stimulus, affect neural tracking (see (Barajas et al., 2021; vander Ghinst et al., 2019)).

Section 2 - learning to parse our continuous experience of the real-world into discrete events.

Our experience of the real world is dynamic and continuous. But when we are paying attention to real-world events, Event Segmentation Theory (EST) (Kurby & Zacks, 2008; Zacks, 2020; Zacks et al., 2001, 2010) states that we segment events hierarchically on a coarse-fine spectrum so as to make prediction of the near future easier; we use ‘event models’ stored in working memory to match expectations with what we are currently observing, and we update these models at event boundaries when such a model is no longer accurately predicting what we see. Evidence of maintaining event models comes from research demonstrating that we can predict what happens before an event boundary with ease but have difficulty predicting what happens after the boundary (Zacks, 2020). EST gives a

parsimonious account of what mental representations underlie sustained attention. In traditional views of sustained attention, working memory (WM) is thought to be key for holding task-relevant information in mind.

For young infants, WM capacity is thought to be low to non-existent (Colombo & Cheatham, 2006). Based on Event Segmentation Theory, therefore, we might infer that infants lack any hierarchical structure to their play; their exploration of new objects is fragmented and is not segmented into discrete events. Intuitively, this prediction seems correct but it has not, to our knowledge, been tested. We could also examine whether infants show behavioural and neural entrainment to the events generated by a social partner during play (e.g. the movements and gestures that a parent makes while playing with a child). Here, we predict that that degree of entrainment shown by the child to the hierarchical structures of events might increase over time. Again, though, this prediction is untested.

Another open question is: *how* does the ability to parse continuous experience into discrete, meaningful events develop over time? Even during early infancy (3-months-old in linguistic studies), statistical learning of co-occurrences can guide our predictions about what we are seeing and hearing (Baldwin et al., 2008; Saffran, 2003; Saffran & Kirkham, 2018; Stahl & Feigenson, 2015). There is evidence that word learning – which requires singling out specific words and objects - is supported by the cross-situational statistics that learners can draw from multiple encounters with word-object associations across varying contexts (Bergelson & Aslin, 2017; Smith & Yu, 2008). Similarly, it has been suggested that statistical learning abilities may enable the child to parse their continuous everyday experience into meaningful event subunits (Conway, 2020; Levine et al., 2017). However, this idea also remains currently untested.

Section 3 – children actively sampling from the environment.

The research discussed above looks at how we passively process sensory information. But, as we discussed above, the real world is interactive. Behaviour does not happen just through passive, serial-order responses to external stimuli; rather, the response determines the stimulus just as truly as *vice versa* (Dewey, 1896; Phillips, 1971).

In this section we consider: what can neuroscience tell us about how we dynamically control our behaviour, moment-by-moment, ‘on the fly’? This question builds on research that looks at early foraging behaviours, in humans and animals. For example, modelling work has shown that just two parameters – stochastic gaze shifts and hysteresis (the intrinsic ‘stickiness’ of attention states) – can accurately model gaze behaviours in younger (1-month-old) infants, but are less accurate for older (3-month-old) infants (Robertson, 2004, 2014). Similarly, attention allocation fluctuates more periodically over time during early compared with later infancy (Feldman & Mayes, 1999). One interpretation of these findings is that early orienting behaviours are relatively more determined by factors internal to the infant in a bottom-up fashion during early life; during later infancy, orienting behaviours start to become relatively more influenced by the external properties of the environment in which the infant is located.

Recent research with adults has examined entropy production in the human brain, by quantifying detailed balance – i.e. the balance of likelihood between one possible transition (state A \rightarrow state B) and the opposite transition (B \rightarrow A) (Lynn et al., 2021). Adult brains nearly

obey detailed balance at rest (Lynn et al., 2021). Given the intrinsic instability of younger brains, it seems plausible to predict that resting state entropy in younger brains ought to be lower, and that detailed balance is less likely to be maintained; however, this prediction is untested.

Research with adults has also examined the differences in the energetic state of the brain between a resting and an attentive state. Generally, the resting state is associated with near-critical dynamics, in which a high dynamic range and a large repertoire of brain states may be advantageous; whereas, a task-active (attentive) state induces subcritical dynamics, which is associated with a lower dynamic range, which in turn may reduce elements of interference affecting task performance (Fagerholm et al., 2015; Hellyer et al., 2014; Lynn et al., 2021; Plenz et al., 2021). According to the free energy minimisation principle, biological systems must resist the second law of thermodynamics (i.e., a tendency to disorder), so that they do not decay to equilibrium (K. Friston, 2010; K. J. Friston & Stephan, 2007); one mechanism that they might use to do this is through sampling the environment, to actively minimise the surprise of each successive sensory sample (Schwartenbeck et al., 2019; Sengupta et al., 2016). Behavioural evidence in adults (Oudeyer et al., 2016; Ten et al., 2021) and children (Begus & Southgate, 2018; Kidd et al., 2012; Poli et al., 2020) has shown that attentional allocation and information seeking reflect how predictable and informative stimuli are to them. In adults, we know that neural representations of subjective confidence and surprise are related to information-seeking (Desender et al., 2019; Ligneul et al., 2018). But whether similar neural representations guide infants' attention allocation and exploration remains unclear (though see Meyer et al., 2022). One further prediction – which again is untested - is that the degree of energetic change (quantified as criticality) between a resting and attentive state should increase over developmental time.

Section 4 – examining mutual influences between children and others

What infants perceive is not only determined by how they actively sample the world, but also by their caregiver's decisions and actions. Babies spend most of their awake time with other people – e.g., caregivers. It seems critical, then, to understand how caregivers and infants *together* shape infant's sensory inputs (Feldman, 2007; Vygotsky et al., 1994). This is not a unidirectional process, as caregivers' actions are also largely dependent on their infants' behaviour, so it is essential to understand how attentional and affective states are shared between children and other people, and how children and their caregivers mutually affect one another's actions and perceptions during social interaction.

Extensive behavioural research has been dedicated to this issue (Feldman, 2007; Jaffe et al., 2001; Wass et al., 2018; Yu & Smith, 2016), but only recently has there been an equivalent shift away from studying how our brains process a one-way flow of information – e.g. from senders to receivers - towards approaches that examine bidirectional information exchanges between multiple brains during social interaction (Fan et al., 2021; Holroyd, 2022; Osborne-Crowley, 2020; Redcay & Schilbach, 2019; Risko et al., 2016; Wass et al., 2020). In the developmental literature, a growing number of studies have started to investigate interpersonal brain couplings (IBC) in interacting adult-child dyads (Hoehl & Markova, 2018; Markova et al., 2019; Piazza et al., 2020; Wass et al., 2020).

Unsurprisingly, given the recentness of this work, and the wide-ranging and fundamental differences between the paradigms and analyses used in two-brain neuroimaging recordings

compared with traditional one-brain recordings, there are currently numerous fundamental disagreements between researchers in how paradigms should be designed, and what measures and analyses should be used (Hamilton, 2021; Holroyd, 2022). An important step forward will be to better understand how coupled brain states relate to behavioural and physiological coupling. IBC is typically measured in situations where partners also have a common perceptual access to a shared environment (Hamilton, 2021). Without parsing out the contribution of the shared environment on each partners' neural activity it remains difficult to interpret IBC's functional significance (Holroyd, 2022). Moving in this direction probably requires event-locked approaches whereby IBC is examined with respect to specific 'edges' that naturally occur during social interactions - such as the occurrence of mutual gaze, parental emphasis during speech, bursts of infant vocalizations, gaze shifts towards a joint focus, etc (Haresign et al., 2022). Alternatively, joint measurements of behavioural, physiological and neural coupling and multiple regression approaches can also shed light on this issue (Nguyen et al., 2020; Piazza et al., 2020; Reindl et al., 2022). This will be important to reach a mechanistic understanding of how individual brains support collective behaviours such as joint attention and joint action that are thought to be crucial for early learning.

Conclusion – picking one stream from many: experimenter's lenses and distorted pictures.

In this paper, we considered how our brains respond to isolated streams of sensory information in our environment (section 1) and how the ability to parse continuous streams of sensory information into discrete events may develop over time (section 2). We then discussed how from early on in development, children's experiences are largely determined

by how they actively sample their environment (section 3), and how others respond to them (section 4). Studying these four elements is crucial because, in the real world, we are bombarded by a polyphony of different types of dynamic information from different sources. When experimenters investigate child development in the lab, however, they typically decide to present specific stimulus in a specific context and order. And even when they decide to observe children's environment, they use a specific lens to analyse their data, and select specific variables of interest. In other words, in most cases, the decision about what to look at is decided *a priori* by the experimenter.

Recent research illustrates the type of problems that this can raise: while initial investigations suggested that children from low-socioeconomic status (SES) households hear far less words than children from higher SES households (the infamous '30-million word gap', (Hart & Risley, 1995; Hirsh-Pasek et al., 2015; Huttenlocher et al., 2007)), later work suggested that this picture was in fact due in part to the experimenters' decisions about what to look for – for example, by focusing on words that are directed to the child by the primary caregiver, rather than extending the word count to bystanders (Dailey & Bergelson, 2021; Sperry et al., 2019). Other researchers have made the comparable point that Western researchers may overemphasise the role eye contact in early social development – which is more important in Western parent-child interactions (where babies spend more time seated, and face-to-face) than in other cultures (where infants often spend more time carried, and facing in the same direction as their parents) (Akhtar & Gernsbacher, 2008; Feldman et al., 2006). Clearly, there is a similar risk in designing developmental neuroscience studies that the experimenter's adult preconceptions may influence design and analysis decisions about what aspects of the naturalistic environment are most developmentally relevant to infants, and children.

One way to circumvent this is to look at how stimuli are distributed in diverse naturalistic data, and to conduct cross-linguistic and cross-cultural studies. This approach is increasingly popular in adult research (e.g. (Urassa et al., 2021)), but it seems important for developmental neuroscience, too - as the examples above illustrate. Arguably, diversity has the potential to lead to more neutral experimental designs, because the relativity of each experimenters' culturally situated beliefs should become obvious when they exchange ideas to design their studies.

Data-driven approaches have also been developed to mitigate some of these problems. Instead of positing specific categories beforehand – which can create confirmation biases and demand effects – reverse-correlation approaches rely on the presentation of several naturally or pseudo-naturally occurring variations (Burred et al., 2019; Jack et al., 2012). Participants' categorical or dimensional responses to this large corpus are then used to reconstruct the mental models that drove their judgements in a data-driven, rather than experimenter-driven, fashion. These methods have recently started to be applied to developmental neuroscience, where they allow researchers to measure children's neural responses to stimulus categories determined in a data-driven, rather than experimenter-driven way (Kamps et al., 2021; Richardson et al., 2018).

We started this article with a quotation from Edward Gibbon, suggesting that using non-ecological neuroimaging paradigms to study purely internal mental constructs is like 'building castles in the sky'. Taken together, the various approaches discussed in this paper have the potential to allow us to reach a better understanding of how human minds develop by learning to select information from complex and continuously evolving streams of information in the real-world environment. As Henry David Thoreau put it: "If you have built

castles in the air, your work need not be lost; there is where they should be. Now put foundations under them” (Thoreau, 1854).

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