CHAPTER

8

How an infant's active response to structured experience supports perceptual-cognitive development

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Abstract

Previous research on perceptual and cognitive development has predominantly focused on infants' passive response to experience. For example, if infants are exposed to acoustic patterns in the background while they are engaged in another activity, what are they able to learn? However, recent work in this area has revealed that even very young infants are also capable of active perceptual and cognitive responses to experience. Specifically, recent neuroimaging work showed that infants' perceptual systems predict upcoming sensory events and that learning to predict new events rapidly modulates the responses of their perceptual systems. In addition, there is new evidence that young infants have access to endogenous attention and their prediction and attention are rapidly and robustly modified through learning about patterns in the environment. In this chapter, we present a synthesis of the existing research on the impact of infants' active responses to experience and argue that this active engagement importantly supports infants' perceptual-cognitive development. To this end, we first define what a mechanism of active engagement is and examine how learning, selective attention, and prediction can be considered active mechanisms. Then, we argue that these active mechanisms become engaged in response to higher-order environmental structures, such as temporal, spatial, and relational patterns, and review both behavioral and neural evidence of infants' active responses to these structures or patterns. Finally, we discuss how this active engagement in infancy may give rise to the emergence of specialized perceptual-cognitive systems and highlight directions for future research.

Keywords

Attention, Learning, Prediction, Infancy, fNIRS, EEG, Active processing, Specialization, Cognitive development, Perceptual development

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1 Introduction

A common metaphor compares infants to "sponges" that absorb information. This description conveys a sense of *passiveness* and appears to suggest that infants are recipients who reflexively absorb or reflect the environment that they experience. Indeed, a key part of infant and early childhood development entails infants' adaptation to their environment. Given that infants have highly immature motor abilities, including language production, it is perhaps not surprising that their responses were traditionally considered to be passive. However, we question the notion that infants' adaptation to the environment arises from the passive unidirectional receiving of input. One reason is that adult responses to the environment can be active in the absence of overt motor responses. Thus, at minimum, we must evaluate whether these active mechanisms are available to human infants or emerge over development. While we do not doubt that some aspects of early development are passive, we review recent work to argue that infants also actively engage with their environment. We then argue that this active engagement directly influences the types of environmental inputs that infants process and are affected by.

In this chapter, we emphasize infant's active response to experience with *environmental patterns*. Environmental patterns are a key type of sensory input arising from the structures in the environment. We further review evidence that experience with environmental patterns can result in an infant's active engagement. It is important to note that environmental patterns are not the only type of input with which infants actively engage; other types of input (e.g., social contexts) can also elicit active engagement. However, we focus specifically on the infant response to environmental patterns in this chapter to lay the foundation for research on the infants' active engagement with the environment.

Examples of environmental patterns include *temporal structures*, which refer to statistical regularities within a sequence in auditory, tactile, visual, and other modalities; *spatial structures*, which refer to statistical regularities in the placement and arrangement of elements in the spatial organization; and *relational structures*, which refer to the statistical regularities in the relationship between two or more inputs. Research has found that even young infants are responsive to temporal (Basirat et al., 2014), spatial (Tummeltshammer and Amso, 2018), and relational patterns (Werchan et al., 2016). In order to interact with and comprehend a noisy environment, infants likely need to extract these types of regularities. It has been long known that the detection of these patterns, which can be as simple as a highly repeated stimulus (e.g., checkerboards shown repeatedly in Cohen, 1972), results in the rapid and robust modification of attention allocation (Rose et al., 1982). This modification of attention already provides some evidence that infants are, in some way, actively engaging with environmental patterns. In this chapter, we expand on this body of evidence and examine how experience with temporal, spatial, and relational patterns result in the active engagement of attention, prediction, and learning mechanisms starting in infancy.

In summary, this chapter focuses on infants' responses to the different types of environmental patterns to lay out the evidence that infants are actively engaging with their environmental input and that this active engagement significantly shapes infants' internal systems and representations. We argue that this cyclical relationship between input and active response in infancy is a key component in the developmental trajectory that gradually leads to the specialization of perceptual-cognitive systems.

2 Mechanisms of active engagement: Definitions

This chapter presents convergent evidence that infants actively engage with the environmental patterns that they receive from their environment. The idea that *learning from the environment is active* is not a new one. For example, in 1975, Eleanor Gibson argued that perceptual learning is active: "We use our receptor systems—our hands, eyes and ears—to explore, to search for useful information [in our sensory input]" (Gibson and Levin, 1975). Here, Gibson is arguing for a definition of "active" that is motor-based. In the next section, we will review evidence from eye movements that infants are active in this way and argue that this is evidence for the active engagement of attention. However, we expand the definition to include other types of active engagement that do not involve a motor component including learning and prediction. Our overall definition of *an active mechanism is a mechanism that, when engaged, results in short-term differential processing of sensory input in the service of information-gathering and/or modifies internal representations of the environment to enable more efficient processing of sensory input*. Using this overarching definition of an active mechanism, we now consider how attention, learning and prediction can be considered active mechanisms.

2.1 Attention

We present attention as our first example of an active mechanism. In previous literature, attention has been largely categorized into two interrelated but distinct concepts of endogenous and exogenous attention. With exogenous attention, attention is automatically directed to a certain stimulus due to the bottom-up characteristics of the stimulus (e.g., visual salience). With endogenous attention, attention is directed to a certain stimulus due to the internal or top-down effects of factors such as previous experiences. Endogenous attention enables infants to be active directors of their attention, rather than passive recipients of externally guided attentional processes.

We specifically highlight selective attention as an endogenous attention mechanism of active engagement. Selective attention refers to attending to a certain stimulus (or part of a stimulus) in the presence of multiple options presented simultaneously. Importantly, what an infant voluntarily and selectively attends has a powerful effect on the sensory input that the infant experiences, and evidence strongly shows that infants use selective attention to gather information. In other words, infants can intentionally direct attention and alter the environment to obtain different information about the environment. This ability makes infants the active agents in determining their sensory experiences.

Infants' selective attention can be observed through a number of behaviors. Two of the most readily observed methods that infants use to allocate attention are eye movements and multimodal exploration. As infants develop the ability to control their eye movements, they become increasingly able to determine what they see by directing their eye gaze (for review, see Amso and Scerif, 2015). The control over their visual input enables infants to govern the information they receive and process. From around 4 or 5 months of age (Gibson, 1988), infants also begin to systematically reach for and explore specific items of interest. With this development, infants can voluntarily and selectively choose the information they receive by exploring a particular object. At first glance, this complex motor behavior may appear to be drastically different from allocating attention via small eye movements we discussed earlier. However, consider that both eye gaze shifts and multimodal exploration of a specific object are caused by an infant's active directing of their attention to a specific stimulus or aspect of a stimulus over other distracting stimuli. From this perspective, both eye movements and more overt motor explorations enable infants to gather information about the selected stimulus, and thus both can be considered active mechanisms. We will discuss research that has looked to eye gaze and grasp-based multimodal exploration to test infant attention in more detail in a later section.

The reason that we discuss attention as an important form of active mechanism is that the information that infants selectively obtain has a profound impact as the infant detects, explores, and understands the world (Cohen, 1972). For example, research showed that visually attended stimuli affected infant word learning more than unattended stimuli (Yu and Smith, 2011). This view is also convergent with previous findings that infants' attentional processes affect other important functions such as perception and memory (for review, see Amso and Scerif, 2015). In this regard, attention is a powerful mechanism that not only enables active and intentional selection of information, but also greatly influences other functions essential for perceptual and cognitive development. We will discuss the impact of attentional processes on the specialization of perceptual-cognitive systems later in this chapter.

2.2 Learning

Learning is the process in which internal representations of the environment are modified following experience. Importantly, the creation of these internal representations comprises an active process because (1) internal representations can result in differential processing of future sensory input, and (2) internal representations can serve to more efficiently process this input. For example, when engaging in statistical learning, an infant learns that some stimuli occur together and uses that information to form a unit, chunk, or combined representation of those stimuli. In later sections, we will review evidence that the formation of these new representations results in better cognitive processing.

Moreover, there is a variety of evidence that learning does not simply arise from a low-level or passive response to environmental patterns. First, under some circumstances, learning can create representations that are not merely copies of environmental patterns. These cases suggest that there is some kind of a higher-level or constructive process that uses experience to produce these representations. Indeed, recent neuroimaging studies have also found that exposure to environmental stimuli result in the engagement of higher-level cortices such as the frontal cortex even in very young infants (Sakatani et al., 1999; Taga et al., 2003). The engagement of these higher-level cortices, similarly, suggests that there is an active component to learning where representations are constructed rather than passively received from sensory input.

In addition, learning depends on factors that affect other active mechanisms. Since learning and engagement of other active mechanisms are both contingent on the same factors and are mostly measured using similar tools and under similar circumstances, we argue that, in its essence, learning is an active process. Here, we focus on the links between predictability and learning (see more on prediction as an active mechanism below). For example, learning requires more than a mere exposure to a stream of sensory information: The information to be learned should be relatively predictable (i.e., not random), but not too predictable or too easy to learn. Operationalizing this idea, infants' preference is drawn toward moderately predictable streams of events, rather than toward fully predictable or fully unpredictable streams of events (Kidd et al., 2012). This sensitivity of preference toward moderate predictability streams is readily available from birth (Bulf et al., 2011) and dynamically changes with age during infancy (Johnson et al., 2009). Predictability also reflects the difficulty in processing the stream of information. In this framing, the effect of moderate predictability is tightly related to a child's engagement with the stimuli, and the engagement is likely strongly linked to endogenous attention as we discussed earlier. Tasks that are moderately difficult preferentially engage attention compared to trivially easy or highly difficult tasks (Hunter and Ames, 1988). Thus, conditions that produce good learning outcomes are conditions that are particularly beneficial for the two other active mechanisms covered in this chapter, predictability and attention. Since learning outcomes are linked to other active mechanism, we argue that that learning itself is an active process.

2.3 Prediction

Prediction-based processes (prediction and prediction error) are a key feature of cognition and development. For example, in a game of peak-a-boo, an infant will experience seeing hands followed by a face in a repeating pattern. After a few repetitions of experiencing this pattern, they likely begin to predict seeing the face upon seeing the hands. However, if the adult waits a particularly long interval before revealing their face, the infant likely experiences a prediction error. Prediction is the process or ability by which previous experience affects the internal likelihood of upcoming events and produces corresponding changes in processing these events based on their likelihood. Prediction error is the difference between the predicted event and the actual event that was experienced. Prediction error also has impacts on processing as well as in updating the internal likelihood of upcoming events. Computationally, prediction and prediction error facilitate engagement between cognition and the environment; prediction uses internal representations of the likelihood of different events (i.e., cognition) directly alter processing of sensory input (i.e., the environment). Relatedly, prediction is an important link between what has been learned and the processing of future sensory input.

Prediction occurs through numerous related sub-processes, many of which can be considered active. The first sub-process is forming a prediction about an upcoming sensory input; the second sub-process is processing sensory input relative to the prediction and possibly producing a prediction error; and the third sub-process is updating the internal models or representations of the environment based on the prediction error. Each sub-process of predictive processes can be considered active according to our definition, as the formation of a prediction changes the processing of upcoming information by processing it relative to an internal state and prediction results in updating internal representations of the environment. For example, after visual stimuli were consistently preceded with auditory cues, the presentation of an auditory cue elicits prediction about this specific upcoming visual presentation. When this visual stimulus is omitted, a prediction error is calculated and the following prediction is updated (Jaffe-Dax et al., 2020).

Recent theories of prediction suggest that the entire brain may be involved in this type of active processing. The focus on prediction and prediction error in learning and updating internal representations was first formalized in the Rescorla-Wagner reinforcement learning model (Rescorla and Wagner, 1972). A more recent expansion on the theoretically purported role of prediction in neural processing and behavior is the theory of predictive coding (Friston, 2005; Rao and Ballard, 1999). Predictive coding posits that top-down or feedback neural signals in the cortex communicate prediction, and bottom-up neural signals communicate prediction error. According to this view, it is more efficient for sensory processes to convey prediction error rather than continuous flow of sensory input. Coding for prediction error, a comparison between prediction and sensory input facilitates the extraction of meaningful information from the environment starting from the earliest sensory cortices. In later sections, we will review evidence that the infant brain is also engaging in this type of predictive processing similar to what would be posited by the predictive coding theory. In this way, the entire cortex and perceptual system would be engaged in prediction and, thus, active processing.

Overall, prediction is a mechanism of active engagement with the environment because it involves modifying internal representations following experience and changing sensory processes relative to internal states in order to gather information or process future sensory input relative to past experiences.

2.4 Interrelationships among these three mechanisms

As mentioned earlier, the three mechanisms of active engagement we discuss—attention, learning, and prediction—are closely interrelated concepts that greatly affect one another. For example, the level of infants' attention to a given stimulus is affected by what they learn and predict (Doherty et al., 2005), and infants attend to events that violate their expectations (e.g., Baillargeon, 1987). What infants learn is affected by what they attend to (Johnson et al., 2004; Pereira et al., 2014), and learning affects what infants predict (Romberg and Saffran, 2013). As stated in a previous section on learning, infants' attention is drawn toward moderately predictable events rather than toward fully predictable or entirely unpredictable events (Kidd et al., 2012) and toward moderately difficult tasks than trivially easy or notoriously difficult tasks (Hunter and Ames, 1988). Thus, research readily shows that these three mechanisms relate to each other.

Relatedly, it should be noted that the distinctness of these three mechanisms is not always clear. It is difficult to differentiate the three mechanisms in empirical designs because researchers often manipulate one to investigate another mechanism. For example, Kidd et al. (2012) manipulated the predictability of events to measure attention, while Hunter and Ames (1988) manipulated the learnability of a task to investigate attention allocation. In these cases, it is difficult to distinguish the individual effect of each active mechanism. In addition, whether prediction can be separated from attention at all is a hotly debated topic in itself, as some researchers argue that predictions are a type of top-down attention while some argue that they are distinct constructs (for a review, see Clark, 2013). Similarly, whether learning can be separated from prediction is also unclear; there is somewhat of a chicken-or-egg problem, as it is difficult to conceive of predictions arising without some kind of learning, and it is also possible that predictions are an essential component of learning. However, despite the difficulty with determining the boundaries and independence of these mechanisms, we maintain the main focus of the current chapter: Infants actively engage with the environmental patterns and this active engagement supports their perceptual-cognitive development.

3 Evidence of active engagement with environmental patterns

So far, we have both laid out a definition of active engagement and made the argument that attention, learning, and prediction are mechanisms of active engagement. Now, we present existing behavioral and neural evidence that infants engage these active mechanisms in response to environmental patterns.

3.1 Attention

The engagement of selective attention allows infants to change their sensory input and shape the temporal, spatial and relational information they acquire from the environment. As described earlier in this chapter, we define selective attention as a form of active engagement, because attending to a certain stimulus out of multiple options determines the sensory input that the infant receives, and this change in sensory input is a result of the information-gathering of the infant. In this section, we describe previous research showing that infants' active engagement via selective attention begins early and grows substantially throughout infancy.

Different motor abilities can assist with attention-guiding processes throughout the stages of development. By 3 months of age, infants are capable of attention-guided oculomotor control (Amso and Johnson, 2006) and their primary visual cortex is mature enough to support this function (Johnson, 1990). Oculomotor-controlled attentional allocation allows infants to selectively attend to input based on factors such as knowledge acquired from statistical regularities in the stimuli (by 6 months of age: Tummeltshammer and Amso, 2018), informational complexity (Kidd et al., 2012), and predictability (Kinney and Kagan, 1976), as well as short-term (Hurley and Oakes, 2018) and long-term (Kirkham et al., 2007; Tummeltshammer and Amso, 2018; Wentworth et al., 2002) exposure to environmental patterns and novel experiences. It was also found that a brief training can improve selective attention in 11-month-old infants, such that infants exhibit trending changes in spontaneous looking during free play after training (Wass et al., 2011). Combined, research suggests that infants modify their sensory input by actively manipulating oculomotor control in the service of information-gathering.

By 5 or 6 months of age, the ability to selectively attend becomes substantially strengthened as infants acquire the ability to systematically reach for and grab objects with their hands, which enables the multimodal exploration of objects (Needham et al., 2002). Infants can use these motor abilities to explore specific objects out of multiple options. In this way, this ability functions similarly to selective attention as measured using eye movements. For example, Stahl and Feigenson (2015) exposed 11-month-old infants to expectation-violating and expectation-consistent objects and found that infants preferentially attended to expectation-violating toys using their grasp, as a younger infant would attend to the same toys with their eye gaze. In addition, infants multimodally manipulated the expectation-violating objects in a way that was specific to the types of violations they witnessed (e.g., dropping the toy that previously appeared to defy the principle of object support). Thus, infants selectively explored these objects based on their recent experience. The grasp-based combination of visual, manual, and oral exploration facilitate a richer collection of multimodal information (Rochat, 1989) about a specific object and has long-term effects on the infants' object exploration (Wiesen et al., 2016). These studies show that infants continue to develop more complex methods of selective attention allocation as they age, and become increasingly sophisticated at actively directing their information-gathering processes.

Investigations of the neural systems supporting the development of endogenous or selective attention provides convergent neuroimaging evidence for the early availability and rapid growth of selective attention in infancy. The areas of particular interest here are the frontal and parietal lobes, which have been implicated in selective and endogenous attention in adults (Kastner and Ungerleider, 2000).

Although both frontal and parietal lobes exist at birth, they structurally and functionally change drastically in early infancy (for review, see Amso and Scerif, 2015; Colombo and Cheatham, 2006). The frontoparietal pathway undergoes rapid structural maturation and myelination in early infancy (Deoni et al., 2011) and functional connectivity is present by as early as 39–42 weeks after birth (Fransson et al., 2011), with long-range functional connectivity networks developing in the first 2 years of life (Gao et al., 2017). These findings show that the brain areas and connections necessary for endogenous attention both exist and continue to exponentially grow during infancy. This neural evidence converges with the behavioral evidence for selective attention in early infancy and rapid development and growth.

Together, neural and behavioral research reveal that infants employ various motors abilities and neural mechanisms to actively engage with their sensory input by selectively allocating attention. In this way, selective attention forms an integral part of the bidirectional and active relationship between the infant and their environment.

3.2 Learning

Learning is the process in which experience modifies the internal representations of sensory input. This process of creating or modifying representations can be considered active because (a) learning creates representations that are not mere reflections of sensory input; (b) these representations facilitate future perceptual and cognitive processing; and (c) it engages higher-level cortices like the frontal lobe.

The representations that are created as a result of learning are not simply reflections of the environment, but ways to organize and understand sensory input, which in turn facilitate perceptual and cognitive processing. For instance, in statistical learning, exposure to a consistent stream of individual stimuli results in learning of representations that span beyond the individual stimuli. To illustrate with a simple example, if infants experience *A* is followed by *B* which is followed by *C*, they may form a single, higher-order *ABC* representation. These higher-order representations are often referred to as chunks or new units composed of smaller units (Saffran et al., 1996; Saffran and Kirkham, 2018). Importantly, these chunks are not reflections of the statistics of sensory input but are constructed higher-order representations. For example, even though the statistics are uniform between each of the individual stimuli of the chunk, infants only recognize the complete chunk (i.e., do not recognize subcomponents of the chunk), suggesting that infants have formed a new representation based on the statistics (Orbán et al., 2008; Slone and Johnson, 2018). Moreover, forming these chunks has been found to facilitate subsequent processing. For example, Graf-Estes and colleagues found that forming chunks from a stream of syllables facilitated infants' subsequent association of these speech sounds as labels for objects (Estes et al., 2007). Thus, the representations that are formed as a result of learning create higher-order representations that are not mere reflections of the environment and in turn, these representations facilitate future processing of sensory input.

Recent neuroimaging studies have found that learning engages higher-level cortices, which suggests active engagement. Higher-level cortices are regions of the brain that are more likely to engage in active construction of new representations. Let us briefly return to the example of creating a representation of *ABC* following experience with *A* followed by *B* followed by *C*. In order for this higher-order representation to be created, regions of the brain have to hold information about these three discrete events (*A*, *B*, *C*) in memory. Given that these events are distinct in their initial representations, they need to be bound together or linked in some way to create a single *ABC* representation. Lower-level cortices (e.g., perceptual cortices) are not believed to be capable of these types of computations. As lower-level cortices are highly sensitive to the current sensory input, they are not able to process items that are no longer present. Thus, they would not have simultaneous access to A, B, and C. Given these limitations of lower-level cortices, higher-level cortices like the frontal lobe are thought to be necessary for these computations, and thus are crucial for the creation of higher-order representations. For these reasons, the engagement of higher-level cortices during suggests that the brain is engaging in active processing.

There have been a myriad of studies showing that the frontal lobe is involved in learning and novelty detection starting from very early in infancy. A recent EEG study investigating sequences in 3-month-old infants revealed that the frontal lobe is involved in learning sequences of stimuli (Basirat et al., 2014). More specifically, Basirat and colleagues found that in early infancy the left frontal lobe attenuates its response to a deviant stimulus when it is in a learned sequence. This finding dovetails with other work demonstrating that the infant frontal lobe is involved in processing of familiarity and novelty (Nakano et al., 2008), rule learning (Gervain et al., 2008; Werchan et al., 2016), and audiovisual associations (Kersey and Emberson, 2017) starting early in life. There are also broader proposals that the infant frontal lobe is available to contribute to infant cognition and learning at early infancy (Dehaene-Lambertz and Spelke, 2015; Grossmann et al., 2013). Overall, there is convergent evidence that learning in infancy engages the frontal lobe, suggesting that infant learning is an active process of cognitively constructing representations rather than passively processing them. While it is likely that other higher-level cortices are also involved in infant learning, we focus on the frontal lobe because of the large number of studies reporting its involvement and the easy of recording with this region of the brain in both EEG and fNIRS.

Taken together, these findings show that infant learning is an active process. Starting from the first few months of age, infants engage higher-level cortices like the frontal lobe during learning and related processes, infant learning results in the construction of higher-order representations, and these higher-order representations facilitate future perceptual and cognitive processing.

3.3 Prediction

Prediction is a process in which internally calculated probabilities of sensory input modify the internal representations and the subsequent perceptual processing of sensory input (e.g., predicted vs less predicted). Prediction is active because the perceiver applies their estimated prediction on the environment to their sensory input and modifies the way it is perceived in a way that uncovers information about the environment that is relevant to the infant's experience. Here, we present evidence that the infant brain is highly predictive and may follow similar principles to the theory of predictive coding.

Based on the framework of predictive coding (Friston, 2005; Rao and Ballard, 1999), many regions of the cortex, from higher-level cortices to sensory cortices, are involved in prediction. As explained above, predictive coding framework posits that the cortex communicates top-down prediction and bottom-up prediction error. One expected observation from this framework is that sensory cortices exhibit neural responses for predicted events compared to less predicted events (e.g., Summerfield et al., 2008; Summerfield and De Lange, 2014).

While there are relatively extensive findings that the adult brain is predictive, recent research in infants has suggested this adult ability does not rely on extensive experience and maturation of the cortex. By contrast, this ability to form predictions is readily available in early infancy. In young infants, the impact of predictability was first demonstrated using neuroimaging and recording sensory responses when unexpected omissions of stimuli (cued from different sensory modalities) continued to result in sensory cortex responses (Emberson et al., 2015). Relatedly, when sensory input from a particular modality is correctly predicted (cued again from a different sensory modality), infants modulate their sensory processing compared to incorrectly predicted stimulus (Kouider et al., 2015). Xiao and Emberson (2019) similarly found that infants can show increases in their face perception abilities when they are able to predict upcoming faces. Recent work has suggested that predictability may also reflect the processing of repeated stimuli (Emberson et al., 2019) following the results from Summerfield et al. (2008). Thus, there is emerging evidence that the infant brain is highly predictive and that prediction affects the processing of sensory input and the activity of perceptual systems starting in infancy.

In addition, there is much evidence that prediction results in updating representations. First, infants and toddlers experiencing a prediction error resulted in allocating more time to learn about those objects. In an example we mentioned earlier, when infants observed ordinary events (e.g., a ball hitting a wall) vs highly unlikely events (e.g., a ball passing through a wall), infants learned more about the object that violated their expectations and behaved against their prediction (Stahl and Feigenson, 2015). Second, a series of studies by Kayhan and colleagues established that infants and toddlers update their internal models of stimuli based on prediction errors (Kayhan et al., 2019a; Kayhan et al., 2019b; Kayhan et al., 2019c). Finally, the processes supporting prediction errors may represent a continuous ability that guides development from infancy to adulthood: Using pupillometry—a method that can measure infants and adults comparably—we found that the learning trajectory of cross-modal association was similar in 6-month-old infants and adults (Zhang et al., 2019).

Taken together, these findings elucidate the early availability of prediction, a process which actively affects their perceptual processing of these stimuli and their formations of future representations.

4 Active engagement shapes perceptual and cognitive development starting in infancy

In the previous sections, we have defined active mechanisms, identified three examples of active mechanisms (attention, learning and prediction) that are available early in development, and provided evidence that these active mechanisms are readily engaged when infants experience environmental patterns. The evidence we have already cited indicates that these active mechanisms can affect perception and cognition in a number of ways: (1) Attending to different aspects of the environment changes the sensory input and affects learning; (2) Learning can result in the creation of internal representations that have downstream consequences for perceptual and cognitive processing; and (3) Predictive processes modulate neural responses to sensory input, and this neural modulation can have downstream consequences for learning and memory. Thus, young infants have active responses to their experiences, and these active mechanisms have consequences on perception and cognition.

While findings that infants actively respond to their experiences imply that active mechanisms can shape the development of perception and cognition, evidence is not sufficient to make a definitive link. In particular, the bulk of these studies focus on the short-term outcomes of active mechanisms, with the effects tested seconds or minutes after attention, learning, or prediction is engaged. This short-term focus is readily attributable to the methodological difficulties of investigating the consequences of laboratory tasks days after an experimental manipulation in young infants. However, it is necessary to build upon the short-term findings and also ask whether these active mechanisms result in meaningful medium and long-term changes in infant perception and cognition and, moreover, to link these mechanisms to broader developmental trajectories.

In this section, we review several studies that provide initial evidence to this end and argue that these active mechanisms are highly likely to have influences on longer-term developmental trajectories. We present evidence that active mechanisms shape the development of face perception and are involved in language development. All three of the active mechanisms considered (attention, learning and prediction) have been linked to development in these domains.

Recent work has linked the engagement of selective attention with the development of face perception in infancy. Markant et al. (2016) found that attentional mechanisms are differentially applied to own vs. other-race faces, and results in the differential face perception in these groups that has typically been considered to arise from differences in perceptual representations alone. Following up on these findings, Markant and Scott (2018) published a theoretical position piece linking attentional mechanisms and the emergence of perceptual specialization for familiar/own-race faces. Overall, this line of work suggests that differences in the active engagement of attention ultimately results in both reflexively applied differences in attention to different types of faces and the emergence of perceptual representations for faces.

Other lines of research have used individual differences to make links between the engagement of active mechanisms and broader developmental trajectories. Kannass and Oakes (2008) found a relationship between measures of endogenous attention at 9 months of age and measures of language development years later (vocabulary size at 31 months). Reuter et al. (2018) found that differences in prediction from 12 to 24 months also relate to language development (vocabulary size measured concurrently). Lany et al. (2018) found that differences in statistical learning abilities related to real-time language processing at 15 months. These studies of individual differences provide evidence for the broader developmental consequences of an infant's abilities to engage these active mechanisms. However, there are some important methodological limitations to the existing literature. For example, the test-retest validity of the measures of these active mechanisms have not been established (see papers by Siegelman, Frost, Christiansen and colleagues concerning the measuring of individual differences in statistical learning; e.g., Siegelman et al. (2017) for adults and Arnon, 2019 for children). Test-retest validity is important for measuring stable, reliable individual differences in these mechanisms. Moreover, the specificity of these findings is unclear. Since "positive" aspects of development often develop together, it is unclear whether these correlations simply reflect generally better development in some individuals whether it reflects more direct links between these active mechanisms and development. While approaching the investigation of the long-term consequences of these active mechanisms using an individual differences approach has yielded early positive results and is methodologically tractable, this approach has substantial limitations that need to be addressed in future work.

Finally, one of the most compelling lines of evidence that active mechanisms are involved in long-term changes in perceptual and cognitive development comes from the work by Lisa Scott and colleagues, who used training studies to examine the impact of verbal labeling on perceptual narrowing. In their seminal work, Scott and Monesson (2009) provided infants with one of three types of exposures to nonhuman primate faces while controlling for the bottom-up exposure to the faces. Infants were exposed to the faces without labels, faces with general labels (i.e., "monkey"), or faces with specific labels (i.e., "Boris"). Researchers found that infants showed significant alteration of their developmental trajectory in perceptual narrowing only in the specific label condition. Scott (2011) also extended this finding to another category of stimuli (strollers) and similarly found that the specific label affected perceptual narrowing. A follow-up investigated the impact of this training several years later and found that infants who had received specific label training in their first postnatal year showed differential neural responses to faces when they were 5 years old (Hadley et al., 2014). Following this compelling series of studies, we suggest that long-term training studies are important avenues for future investigation of the long-term consequences of active mechanisms.

However, the studies that use long-term training also have limitations that need to be addressed in future work. Considering the studies by Scott and colleagues, the exact active mechanisms involved in Scott and Monesson's (2009) intervention are not known. While these findings suggest that it is not only the mere sensory input of these faces, but also the context in which this input, that matters for an infant's perceptual development, it does not reveal what mechanisms are engaged through this contextual manipulation. An additional caveat is that Scott and Monesson (2009) did not directly quantify the sensory input that infants received. They relied on parental report, which may be limited, and there could be differences in the sensory input that infants received.

In sum, this section reviewed the current, albeit limited, evidence that the engagement of active mechanisms has consequences for the long-term development of perception and cognition. The findings in this section are scattered and some have notable limitations, but these findings provide an important foundation for linking the short-term effects of these active mechanisms to longer-term developmental trajectories. Given the recent focus on these active mechanisms, we propose that a key future direction for the field is to start to make stronger links between these short-term effects and longer-term developmental consequences of these mechanisms.

5 Outstanding questions

The goal of this chapter is to push the boundaries of the field's thinking *vis-a-vis* active mechanisms and their role in early development. There has been a growing interest in these mechanisms, and how they are engaged in response to different types of experience (e.g., environmental patterns, which was the focus on this chapter). While the term "active" has been increasingly used in relation to these mechanisms, this chapter provides a definition of an active mechanism and makes a direct argument for why these mechanisms are active. Building on seminal demonstrations that these active mechanisms are available to infants, important avenues of future work involve uncovering the interrelationship between these active mechanisms, investigating the experiential conditions in which these mechanisms are engaged, and, particularly for learning and prediction, considering the developmental emergence of these active mechanisms or whether they are available in an invariant form from birth. Relatedly, do these mechanisms operate similarly across domains (i.e., are domain-general) or do they exhibit specialization for specific stimuli? It has been argued that there is specialization of attention (e.g., Markant and Scott, 2018 for different types of faces) but this work needed to be extended to consider other domains and types of active mechanisms as well.

In addition, we argue that it is essential for the field to continue investigating how the active mechanisms, engaged in the moment, ultimately contribute to broader developmental trajectories. Answering this question will involve tackling a number of difficult outstanding questions, including uncovering the means by which short-term effects relate to long-term effects. To highlight an example where it is important, but difficult, to understand the relationship between short-term effects of active mechanisms and broader developmental changes, we turn to auditory development. Sussman and colleagues have argued that the engagement of selective attention to stimuli may be linked to developmental changes in auditory processing. Passive responses of the auditory system to odd-ball stimuli show a developmental trajectory in which there is increased sensitivity of the auditory system to different auditory features (e.g., frequency and intensity). It was previously thought that these passive responses reflect the fixed capacity of the auditory system. Indeed, odd-ball responses are usually measured under passive conditions (e.g., with a stream of auditory stimuli presented in the background with the participant engaged with another stimulus like a video). However, when children are encouraged to actively engage with an odd-ball task, they show sensitivity to these auditory features that cannot been seen using passive paradigms (Sussman and Steinschneider, 2011). Thus, active engagement appears to push the boundaries of the capacities of the system at a given age. While this is a compelling finding and strongly suggests that there is a link between active engagement at a particular age or point in development with the emergence of developmental capacities later, this isn't directly demonstrated. Moreover, it is unclear *how* these active mechanisms translate into changes in perceptual capacities.

Following from this example from Sussman and colleagues, it is clear that future work is needed to link between the differential processing enabled by an active vs. passive comparison at a given age and developmental capacities or the lack of a need for active processing at a later age. Key questions in this line of thinking include:

- Does active processing engaged at some point in development lead to better passive processing later? The trajectory movements from active to passive follows from the example from Sussman and colleagues above but there are examples in other domains and periods of development (e.g., face perception and selective attention, Markant and Scott, 2018). More work is needed to establish this shift from active to passive more directly. Once/if that shift is established, it will then be necessary to determine how and why this happens. In other words, what is active processing doing in the short-term that reduces the need for active processing in the future?
- Presuming that these individual active mechanisms (attention, prediction, learning) can be isolated, do different active mechanisms result in different long-term changes or do they all exhibit similar effects?
- What developmental changes are found in these active mechanisms? Does their operation change across to individual domains or are they uniform across domains (domain-general)?
- Finally, a key question that is largely unexplored is as follows: How are these mechanisms are affected in at-risk populations or how do they manifest differently in atypical developmental trajectories?

6 Summary and conclusions

Although traditionally considered passive "sponges" that absorb information, we argue that infants play a more active role in using their experience to support their neural and cognitive development. In this chapter, we presented an overview of existing research and argued that infants are actively engaging in their experiences even without overt motor responses. To do so, we first defined an active mechanism as a mechanism that results in short-term differential processing of sensory input in the service of information-gathering and/or modifying internal representations of the environment to enable more efficient processing of sensory input. Using this definition, we have argued that attention, learning, and prediction are significant examples of active mechanisms. Specifically, all of these mechanisms give an infant the ability to gather information and modify internal representations to support better processing of their sensory input. We then presented behavioral and neural evidence that infants engage these active mechanisms in response to higher-order environmental structures, including spatial, temporal, and relational patterns. Despite the obvious short-term effects of these active engagements, however, the long-term consequences of active engagement are not yet clear. We reviewed some research that begins to answer how active engagement may shape broader trajectories of perceptual and cognitive development. In future work, it will be necessary to shed light on the developmental changes in the engagement of active mechanisms, the roles of these active mechanisms on the long-term developmental trajectories, and their impact in atypically developing populations. This field of research can help us gain an understanding about how the bidirectional relationship between infants' active engagement and the environmental patterns that we have discussed in this chapter ultimately affect the developmental trajectory that results the specialization of perceptual-cognitive systems.

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