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Developing the Attentive Brain: Contribution of Cognitive Neuroscience to a Theory of Attentional Development

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Abstract
Attention is a fundamental cognitive mechanism whose primary function is to regulate and organize the flow of perceptions and actions shaping our mental life. Early cognitive models have highlighted aspects of sustained, selective, and executive control as essential components of attention. These three broad aspects can be further subdivided into subordinate operations, depending on whether the particular function is mostly driven by external stimulation (bottom-up attention) or relies on endogenous processes such as voluntary intentions or expectations (top-down attention). After several decades of cognitive neuroscience research, these different functions have been associated with specific circuits of brain regions. Based on the cognitive neuroscience framework, this paper presents a theory of attention development and discusses behavioral and brain evidence regarding the development of attention function during the first years of life.

The brain is committed to process sensory signals in order to perceive and comprehend the world around us and launch the actions that enable us to interact with objects and people. The information reaching our senses is vast, and only a small portion is consciously perceived. In our interaction with the world, we combine responses that are established unconsciously and delivered automatically with others that are consciously elaborated in line with current or future goals. Within this framework, the brain is the body organ that serves as the interface where awareness of the world and consciousness of our desires and intentions intersect, and attention is a brain mechanism which primary role is regulating the flow of information by selecting the sensory input or internal line of thought that needs deeper processing on the one hand, and by inhibiting certain actions, and activating others, in close connection with the individual's internal goals, on the other hand. Information processed under the influence of attention attains the quality of conscious, and attended responses are mostly perceived by the individual as voluntary. Therefore, attention is a fundamental cognitive mechanism whose primary function is to regulate and organize the flow of perceptions and actions that shape our mental life, a mechanism that lies at the essence of two central subjective properties of our mind: consciousness and volition.

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In this paper, I will present a theory about the early development of attention and the brain processes that support this development. The remarkable advancements in neuroimaging over the past decades have sparked new insights into the longstanding inquiry about the relationship between mind and brain. These advancements have also greatly enriched the field of cognitive development. A wealth of new data concerning attentional development is currently being generated. Within this fertile landscape, existing theories must be reevaluated to accommodate the influx of new data. Moreover, in the context of extensive methodological possibilities, it is imperative that new research questions be guided more than ever by theoretical frameworks.

Building a Theory of Attention

Early Models

At the end of the XIXth century, William James dedicated a seminal and very insightful chapter to *Attention* in his book "The Principles of Psychology" (James, 1890), a manual that became foundational for the science of Psychology. In that chapter, he stated "*My experience is what I agree to attend to*" and provided an intuitive definition of attention as follows: "*It is the taking possession by the mind in clear and vivid form of one out of what seem several simultaneous objects or trains of thought.*" James' conceptions gave attention a very central role in the cognitive system, which main function was to coordinate the mental life and regulate the access to consciousness. Without attention, the state of the mind will be "*confused, dazed and scatter-brained*" (pp. 404). These ideas have since influenced the study of attention to these days.

During most of the first half of the 20th century, research on inner states and cognitive processes was for the most part neglected due to the emphasis on studying only direct, observable responses and its contingencies proposed by the behaviorism movement, as well as the lack of technology that could provide fine-grained measures of behavioral and brain processes linked to cognition. After World War II, the interest in studying mental processes was reinstituted, and most of James' ideas about attention were incorporated in the early theoretical accounts. For instance, Donald Hebb stated that every stimulation reaching our senses has two main effects. First, it produces a general burst of activation that is canalized by the reticular activating system. Changes in alertness are very much related to neural activity in regions of the brainstem, mostly the locus coeruleus (LC), that modulate the level of arousal of the cerebral cortex by means of noradrenergic modulators. The second effect is to initiate a sequence of processing computations along sensory pathways aimed to identify the location and nature of the stimulation to a more or less deep level of consciousness. Thus, the level of alertness reflects the disposition and/or preparation of the organism to process information (Hebb, 1949).

Influenced by the work of Hebb, early models of attention distinguished between intensive (activation) and selective aspects of attention. For instance, Broadbent (1958) conceptualized attention as a cognitive process of limited capacity whereby relevant information is selected for further processing while ignored information is filtered out. Several years later, Anne Treisman proposed that visual features were processed separately until attention bound them together into coherent objects. According to this theory, objects can only be differentiated based on particular combinations of features when they are attended (Treisman & Gelade, 1980). Around the same time, Michael Posner introduced an experimental task to study selective attention (Posner, 1980) and conducted a series of studies on the benefits of attentional selection for task performance.

Other coetaneous authors emphasized the role of attentional resources in managing actions. In his book "Attention and Effort," Daniel Kahneman introduced the concepts of attentional resources and mental effort (Kahneman, 1973). He argued that tasks vary in terms of the extent to which they demand attentional resources. Well-practiced tasks require little to no resources, thus becoming effortless, while tasks that demand a significant amount of attentional resources are perceived as effortful. Thus, depending on the amount of resources available, two or more tasks may or may not be performed concurrently. Posner and colleagues also discussed the role of attention in action monitoring, particularly when selection has to be achieved in a voluntary, effortful mode (Posner et al., 1975). They stated that attention is needed in a variety of situations in which automatic processing is either not available (e.g., responses are not well-learned) or is likely to produce inappropriate responses (e.g., in interference-rich contexts).

Posner's Attention Networks Model

By the end of the 20th century, the first brain's activation images of people performing cognitive tasks inside the PET and MRI scanners were available. It was then when Posner and Petersen (1990) presented their theory of attention, which was later revised after 20 years of

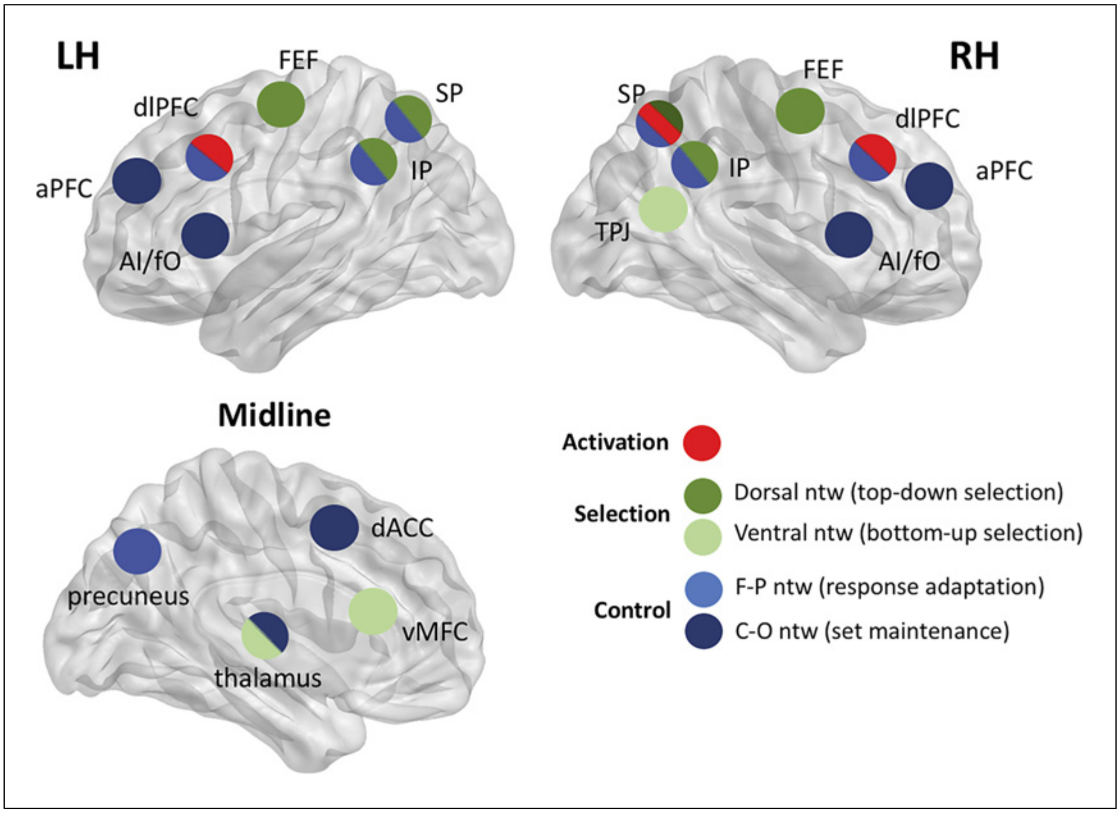

Fig. 1. Main nodes of the attention networks according to Posner's model (adapted from Petersen and Posner, 2012).

progress in neuroimaging research (Petersen & Posner, 2012). According to their model, the three functions of attention that had been studied in the past decades (alerting, selection and executive control) are related to partially independent networks of cortical and subcortical brain regions (see Fig. 1).

To be effective, attention requires an optimal level of activation of the nervous system. The attentional state of an individual varies in function of internal (e.g., internal activation of arousal systems related to circadian rhythms, level of fatigue, etc.) as well as external (e.g., level of stimulation present in the environment) conditions. Alerting is associated with the activation of norepinephrinergic neurons in the LC and their projections to frontal and parietal regions of the cortex. Neurons at the LC exhibit two modes of activity: phasic and tonic. The phasic mode works in a short timescale and promotes event-locked fast and efficient responses within the task at hand (exploitation of stable sources of reward), while the tonic mode increases the responsivity of neurons more broadly, promoting an exploration mode of attention (Aston-Jones & Cohen, 2005).

Two separate circuits control selective attention to prioritize the processing of salient stimulation, or stimulation that is relevant according to internal goals or expectations. Salient stimulation activates a right-lateralized ventral circuit including the temporoparietal junction and ventral frontal cortex, while goal-oriented selection involves the activation of a bilateral fronto-parietal circuit including the intraparietal sulcus and the frontal eye fields. These networks show a coordinated activity for controlling overt and covert shifts of attention across sensory domains.

Finally, the executive attention network has a main node in the anterior portion of the cingulate cortex (ACC), which works in connection with other prefrontal regions and the anterior insula, as well as areas of the superior parietal lobe, to determine goal-directed actions. Following the evidence presented by Dosenbach and colleagues with neuroimaging, the executive network is thought to be divided in two differentiated circuits (Dosenbach et al., 2007, 2008). The circuit comprising the ACC and the frontal operculum/anterior insula is mostly involved in representing and maintaining the goals that

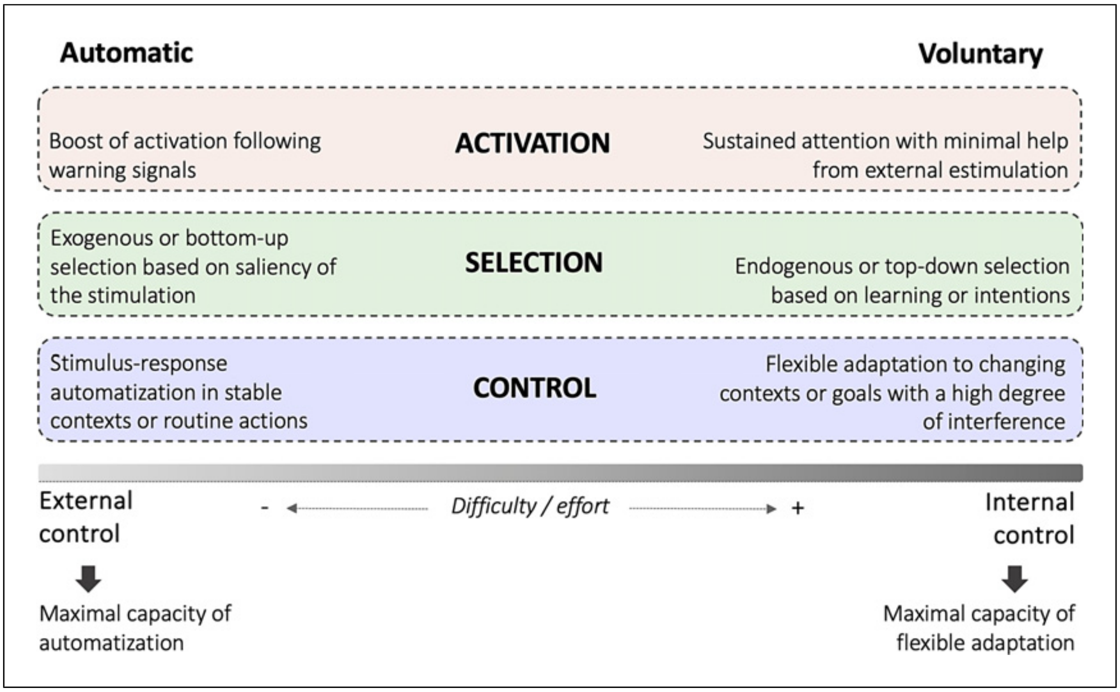

Fig. 2. Bottom-up (automatic) and top-down (voluntary) control within attention networks.

drive performance, whereas regions of the parietal cortex including the superior parietal, the intraparietal sulcus and precuneus in connection with the dorsolateral prefrontal cortex are involved in adjusting responses to changing goals or contextual conditions.

Bottom-Up (Exogenous) versus Top-Down (Endogenous) Attention

These three broad aspects of attention (i.e., activation, selection, and control) can in turn be subdivided in subordinate functions or operations in relation to whether the particular function is mostly driven by external stimulation or else relies on endogenous processes such as voluntary intentions or expectations (see Fig. 2). In the scope of selectivity, attention can be oriented to an object or space automatically because of an abrupt change in stimulation occurring there. This happens, for instance, when somebody says your name out loud in a quiet room or a bright light starts flashing in a dark background. Parameters of saliency (contextual distinctiveness) and relevance (connection to potentially important outcomes) of the stimulation determine its capacity to capture attention automatically, without the need of an expressed intention to pay attention to it. On the contrary, attention can also be directed to an object because of its relevance to our current goals. If I search for a friend in a crowd of people and I know that she is wearing a green cap, attention will bias the visual system toward the detection of green objects. These two modes of guiding attention are, respectively, referred to as exogenous or stimulus-driven (bottom-up) and endogenous or goal-directed (top-down) orienting of attention (Corbetta & Shulman, 2002).

Likewise, the alerting state of the individual can be varied endogenously, for example, because of a change in motivation (e.g., I gained interest in the plot of a movie) which facilitates sustaining attention over longer periods of time. Or else, the level of activation can be varied exogenously because of a sudden change in stimulation (e.g., the sound of an alarm while I was feeling drowsy). Very often sustained or tonic attention relies on voluntary processes while phasic preparation is automatic and linked to changes in stimulation.

Finally, the exogenous versus endogenous division can be also applied to control processes. While attention control processes have been conventionally considered voluntary and endogenous by definition (Kane & Engle, 2002; Norman & Shallice, 1986), some authors argue that certain processes contributing to executive control such as facilitation of processing due to repetition (i.e., priming and conflict adaptation) or associative learning can be carried out automatically (Abrahamse et al., 2016;

D'Angelo et al., 2013). This happens when the context presents regularities (e.g., stable stimulus-response contingencies) that allow for the establishment of action schemas or routines that can be unfolded with low levels of supervision. Nonetheless, executive processes such as inhibitory control, cognitive flexibility, conflict detection, and working memory have been largely considered of attentional nature (Baddeley, 1996; Botvinick et al., 2001; Kane & Engle, 2002) because they require an active state of mind that is necessary for making conscious and deliberated decisions. Attended information can be processed to a deeper level usually leading to awareness of its features and meaning, can be reasoned upon, and hold active in mind for an extended period of time, which may exceed its physical presence (Posner, 2012). This conveys attention a domain-general role in cognition, being involved in many other cognitive functions, such as learning, reasoning, and the regulation of actions (Rueda et al., 2023).

Optimal performance demands a fine balance between the activation of well-learned, automatic pathways, and the control processes that regulate them. In stable, non-changing contexts, routines are easily established and the opportunity for automatization of behavior is maximal. However, in a changing context, or when automatic responses conflict with goals and intentions, executive control is necessary. A flexible adaptation to rules and goals requires the regulation of automatic response tendencies. Thus, conscious and deliberated decisions, particularly when made in contexts that are rich in interference between what is dominant (e.g., I feel an urge to smoke a cigarrette) and what is desired (e.g., I want to stay healthy), cannot be made by applying well-learned action schemas, and rather need the executive control of attention. For this reason, consciousness and volition have been largely linked to attention (Posner & Rothbart, 1998).

In sum, attention can be defined as a multidimensional construct that refers to a state in which we have an optimal level of activation that allows selecting the information we want to prioritize in order to control the course of our actions. Moreover, the attentive state can be primarily driven from external stimulation or be under the voluntary control of the individual.

Neural Mechanisms of Attention

A relevant question is how attentional functions are implemented in the brain. Cognitive neuroscience research has made significant contributions to answer this question. A wealth of evidence indicates that biased competitions during perceptual and response selection processes is a basic mechanism of attention (Desimone & Duncan, 1995; Kastner & Ungerleider, 2001). Biased competition involves increased neural activity related to the processing of attended stimulation compared to the activity associated with non-attended stimuli (Desimone, 1998). This way, attention can modulate perceptual experiences by enhancing the processing of salient stimulation (bottom-up) and/or prioritizing the processing of stimulation that is relevant to our goals (top-down).

For instance, biasing of neural competition has been observed along the hierarchy of areas in the visual cortex, with larger and earlier effects in V4 compared to V2 and V1, suggesting that attentional mechanisms operate via feedback projections from higher to lower order sensory processing regions (Buffalo et al., 2010). Additional research has shown that the attentional modulation of sensory processing areas is associated to enhanced activity coupling between frontal regions involved in attentional orienting, such as the frontal eye fields or the inferior frontal junction, and regions of the visual cortex processing the relevant object or location (Baldauf & Desimone, 2014; Gregoriou et al., 2009). Interestingly, the communication appears to be initiated in the anterior regions under top-down control conditions (i.e., search for a particular visual feature), whereas the activation of posterior parietal regions precedes that of frontal areas under bottom-up (i.e., pop-out of salient features) attention (Buschman & Miller, 2007). Likewise, biased competition is involved in executive control processes necessary for response selection. Action-rules are represented by neurons of the prefrontal cortex following a caudal to rostral axis in function of increased complexity (Bunge & Zelazo, 2006). Using multivariate decoding analyses with fMRI data, it has been shown that neurons in both ventrolateral frontal and lateral parietal regions code complex rules by combining simpler ones (Reverberi et al., 2012). Based on these representations, fronto-striatal circuits involving the basal ganglia and prefrontal regions bias processing in the premotor cortex where the appropriate action according to current rules or goals is selected (Chatham & Badre, 2015).

Thus, by leveraging the intricate circuitry of feedforward stimulus-driven projections and feedback goal-driven connections in the brain, attention operates across the cortex at multiple levels of abstraction. This ranges from sensory representations of features, objects and locations in posterior brain regions to increasingly abstract representations of rules and goals in the frontal cortex (Lynn & Amso, 2023). Within this circuitry, neural activity related to a particular feature or response is amplified when attention is directed toward it and less when directed to a non-preferred stimulus, thereby reflecting the basic biased competition principle (Desimone, 1998).

A Theory of Attention Development

Viewing attention as an organ system associated with brain mechanisms and circuits involved in alerting, selection and executive control provides a grounded outline for a theory of attention development. The framework of attention presented in Figure 2 combines the Posner's structure of attention functions with two modes of control (i.e., stimulus-driven or automatic vs. goal-directed or voluntary) largely established in both behavioral and neuroimaging research. This general framework suggests the existence of two principles of attention development. The first developmental principle is that maturation is to follow a timeline from an early evolving capacity of exogenous or stimulus-driven control toward a later emerging capacity for endogenous or goal-directed control of attention. The second one indicates that development proceeds along a hierarchy of attention functions from control of activation to control of selection to executive control.

These proposed directions of attention development are consistent with well-established general principles of brain maturation. Much evidence indicates that brain development proceeds in subcortical to cortical and posterior to anterior axes of maturation in which the prefrontal cortex shows the most protracted developmental trajectory (Bethlehem et al., 2022). This is coherent with the involvement of subcortical regions (generally LC, for alerting, superior colliculus for orienting, and basal ganglia for executive attention) in establishing initial and primarily routinary forms of attention control (Petersen & Posner, 2012). These evolve toward more endogenous forms of control with the functional incorporation of cortical regions building progressively sturdier subcortico-cortical circuits (Hendry et al., 2019). The caudal to rostral neural maturation is also consistent with a hypothetical hierarchy of attention functions. Perceptual selection operates fundamentally in posterior parietal regions in connection with sensory cortices and frontal regions involved in the motor control of eyes and body (Corbetta & Shulman, 2002; Petersen & Posner, 2012). In turn, the selection of responses is preferentially associated with anterior regions in connection with a myriad of brain areas involved in almost any other aspect of behavior in order to regulate motor responses, cognitive processes involved in learning and memory, and the regulation of thoughts and emotions (Posner & Rothbart, 2009).

In terms of neural mechanisms, competition among relevant locations or objects necessarily requires a minimal capacity of representation of these features in the cortex. Therefore, attention emerges only when those features are represented robustly enough in sensory cortices and the structure of neuronal interactions within and across brain regions allow for competition to be implemented at the neuronal realm. Thus, following the biased competition framework, Lynn and Amso (2023) claim that the emergence and efficiency of attention across development should be shaped by the quality of sensory processing via local cortical architecture and feedforward-feedback information flow. A similar prediction stands up for response regulation processes in prefrontal regions. Bunge and Zelazo presented a hierarchical model of rule representation in the lateral prefrontal cortex in which increasing rule complexity is represented in more rostral regions of the frontal cortex. They pointed to evidence showing that the age-related changes improvements in children's use of the different rule types, from simple stimulus-reward associations to high-order stimulus-response rules that vary depending on the task set, corresponds to the order in which each of the implicated brain regions matures (Bunge & Zelazo, 2006).

In addition to particular predictions about the developmental process of building the attentive brain, interdisciplinarity of developmental cognitive neuroscience research provides a sound context for connecting anatomy and neural mechanisms of attention to relevant biochemical and molecular processes. Much evidence has linked the function of attention networks to the modulatory effects of particular neurotransmitters: norepinephrine for alerting, acetylcholine for orienting, and dopamine and serotonin for executive attention (Fossella et al., 2002). This information has greatly helped understand the genetic origins of attention networks by studying the genes that influence the expression and function of those particular neuromodulators and their impact on individual differences in efficacy at the behavioral and brain function levels in both children and adults (Posner et al., 2007; Rueda et al., 2015). This information is extremely valuable to address the long-lasting fundamental question of human development: that of its origins. To this matter, a great bulk of research is shedding light into the complex Gene × Experiences interaction equation that is necessary to explain individual differences in attention along and across development (Musso et al., 2022; Rueda et al., 2005). Thus, the cognitive neuroscience approach provides a platform for connecting different levels or analysis, all the way from molecular to social, into an integral explanation of attention development.

Theory-Grounded Research: The Cognitive Neuroscience Approach Applied to Developmental Studies

Theories provide conceptual frameworks that help generating new ideas and constraint the experiments to test them. The theory of attention outlined above integrates data that have been generated over decades with experimental protocols that were carefully designed to measure particular mental operations. A good example of a task designed from a theoretical model is the Attention Network Task (ANT (Fan et al., 2002); and its child-friendly version (Rueda et al., 2004). This task includes experimental conditions that serve to measure alerting, orienting, and executive control effects by, respectively, manipulating the presence (vs. absence) of warning cues, the validity of orienting cues, and the presence of incongruent (vs. congruent) distracting flankers (Fig. 3). The use of these experimental conditions with diverse behavioral and brain imaging methods has provided a wealth of information about different processes involved in a particular cognitive function, travelling all the way from behavior to molecular biology. All these different levels of analyses are connected by the theory-grounded experimental conditions utilized to generate the data. As an example, in the realm of executive attention, the contrast between incongruent and congruent distractors using the flanker task provides a behavioral effect (i.e., slower response for incongruent compared to congruent trials). Using EEG with the same experimental protocol, we can test the timing of brain processes underlying this flanker effect, and with fMRI it is possible to examine the regions that modulate the activation level associated to the contrast between the congruency conditions. Information about anatomy helps, in turn, to understand the neurotransmitters that are likely involved in modulating the activation of those regions, which can be confirmed with neuropharmacological studies (see Fig. 3).

In the field of Cognitive Neuroscience, theories are key to the interpretation of results. Generating brain imaging data without a clear hypothesis of what mental process is being carried out inside the scanner is useless because of the difficulty of interpretation or, even worse, because of the risk of inverse inferences (i.e., interpreting what the individual was doing/feeling from the observed pattern of activations). Safe and rigorous science should go from theory to optimal experimental designs that allow the confirmation or rejections of generated hypothesis, rather than the blind search of new data.

Many of the experimental conditions that have been used in attention research with adults are amenable to developmental studies. Table 1 provides a list of examples of experimental conditions that have been used with a wide range of developmental populations, from infants and toddlers to older children, adolescents, and adults.

Convergent Evidence from Behavioral and Brain Research on the Development of Attention

All three functions of attention emerge along the first year of life and seem much more interdependent in the early stages of development (Rothbart et al., 2011). Then, from about the second year of age, attention shows a three-factor structure corresponding to the alerting, orienting and executive attention networks of the Posner's model (de Jong et al., 2016). Among these networks, executive attention undergoes the largest development during this period. Projections connecting the thalamus, cingulate cortex and prefrontal structures grow and consolidate as a differentiated neural network, the development of which predicts cognitive achievements during the first years of age (Alcauter et al., 2014). An overview of the early development of attention networks in presented in Figure 4.

For the purpose of this paper, I will primarily focus on research underlying the development of attention in the first years of life; however, much research has demonstrated a protracted and heterochronous process of development of the attention functions (Rueda, 2013; Rueda & Conejero, 2020). Attention over time varies from transient bursts of alerting to external stimuli to sustained attention over prolonged periods. Newborns dedicate most of the time to sleep, but by 3 months of age infants' awaken time increases from an initial average of about 4 h to about 6 h a day (Figueiredo et al., 2016). The alerting system (involving subcortical structures such as the brainstem) is functional enough at birth, so that the newborn infant is sensitive to physical changes in the environment (Arditi et al., 2006). At first, attention episodes are mostly controlled by the caregiver, but the ability to maintain optimal arousal levels for increasingly prolonged periods of time develops rapidly during

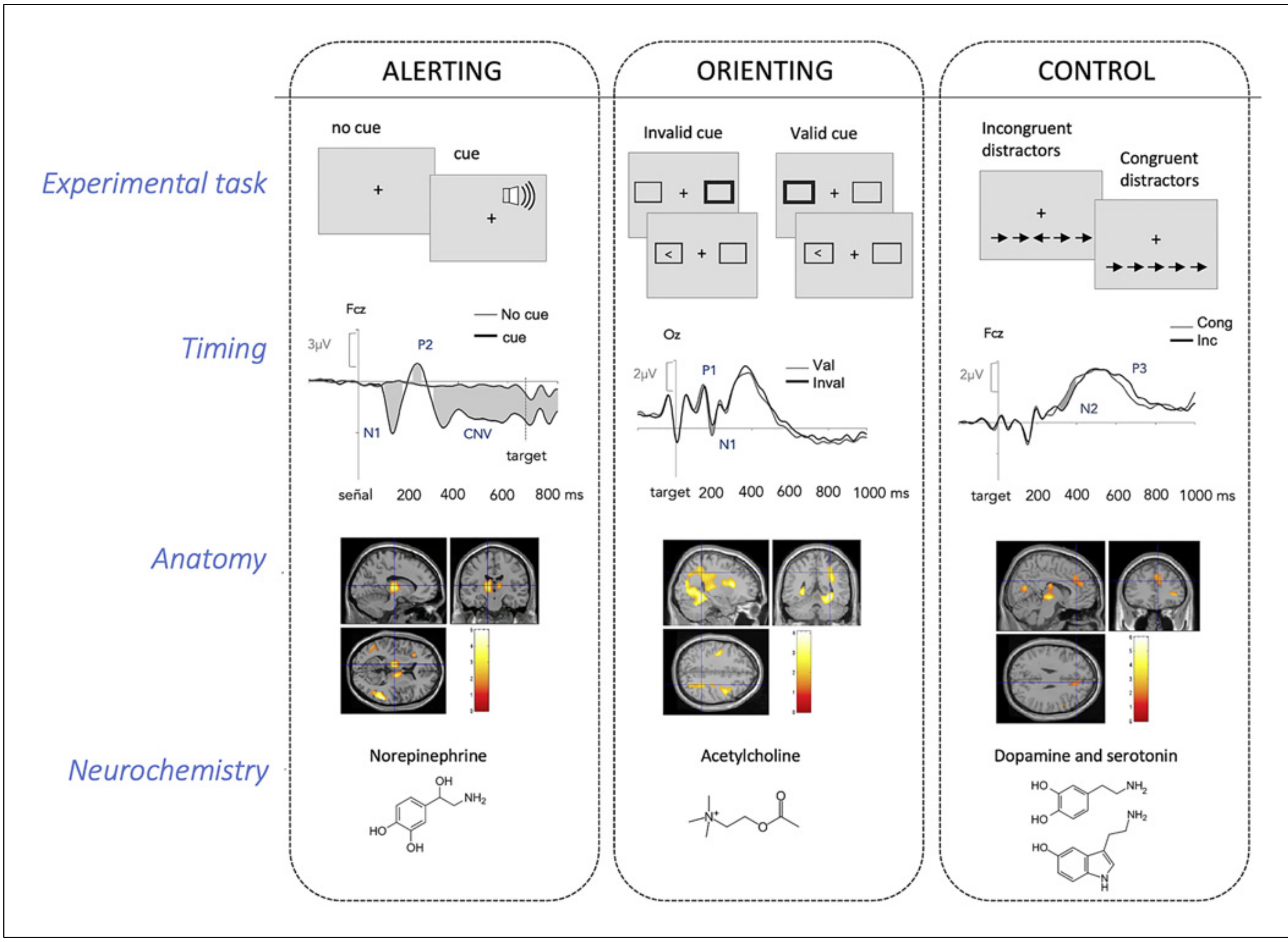

Fig. 3. Representation of multiple levels of analysis of attention functions following theory-grounded experimental design. Represented data are adapted from (Abundis-Gutiérrez et al., 2014) for timing (Fan et al., 2005); for neuroanatomy; and (Marrocco & Davidson, 1998) for neurochemistry.

infancy. Changes in sustained attention during infancy differ depending on the complexity of stimulation. As young infants grow up, they lose interest on simple stimuli such as geometric figures or static images of human faces. Conversely, the time infants spend looking to more complex stimuli such as dynamic video clips of child-friendly characters increases exponentially (Reynolds et al., 2010). Also, changes in arousal levels influence individual patterns of sustained attention during the first months of life. Increases in arousal level relate to infants' shorter look durations to objects whereas low arousal levels relate to longer looking times (de Barbaro et al., 2017). Thus, from very early on, changes in activation are likely to serve as an initial mechanism of modulating sustained attention some time before other more complex forms of endogenous control of attention are sufficiently developed. High arousal levels may act by enhancing sensitivity to incoming inputs, whereas low arousal may help focus attention longer in a certain stimulus by reducing reactivity to potential distractors. Later on, from about 7 to 9 months of age the ability to maintain focused attention appears to be further braced by the emergence of endogenous control mechanisms supported by the functional incorporation of cortical regions involved in top-down orientation and executive attention.

In the domain of attentional selectivity, a rough form of exogenous orientation (i.e., head orientation toward external stimulation) is present from birth or even before (Reid et al., 2017), whereas the capacity for endogenous control of attention progressively emerges from about 4 to 6 months of age and shows great maturation in the

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Table 1. Examples of experimental conditions associated with particular attention functions that are amenable to participants of all ages and can be used with brain imaging technology

	Bottom-up or exogenous	Top-down or endogenous
ALERTING	Warning cues Attentional capture	Looking duration Sustained attention
ORIENTING	Reactive looks Orienting to valid cues Attentional engagement Pop-out/saliency tasks	Anticipatory looks Orienting to invalid cues Attentional disengagement Visual search tasks
EXECUTIVE	Following response tendencies Low levels of interference Routinary actions/Stable task sets	Inhibiting response tendencies High levels of interference Switching task/mental sets Error detection

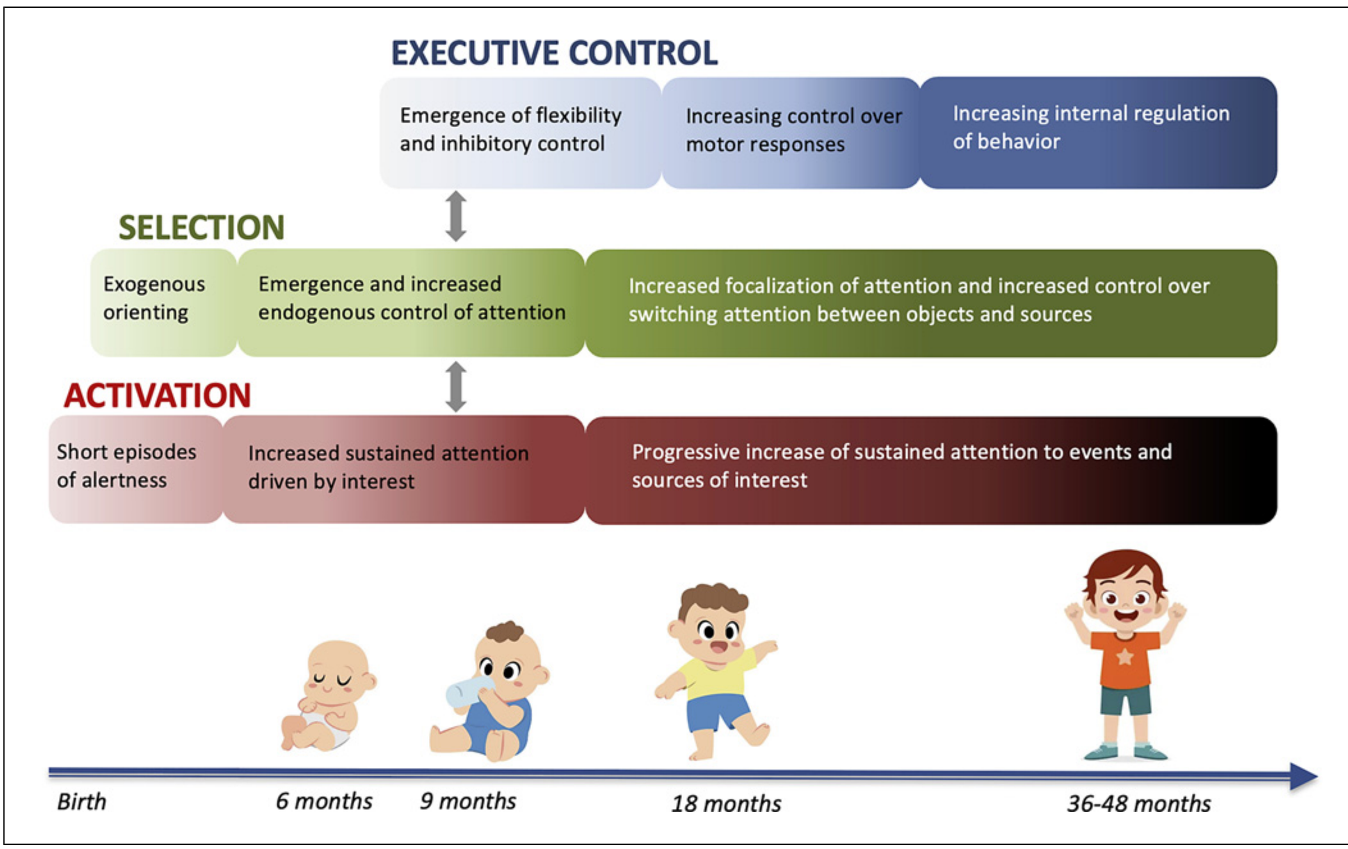

Fig. 4. Picture representation of the early development of attention networks.

following years (Hendry et al., 2019). Newborns direct their head and gaze toward new stimuli, showing a preference for certain types of stimuli, such as faces or moving objects (Courage et al., 2006). As for adults, infants' orienting of attention speeds up after the presentation of a valid cue indicating the target location (Johnson & Tucker, 1996). However, in the first months of life, orienting of attention mainly relay on external characteristics of stimuli (saliency) and is controlled by external events with a predominant role of caregivers.

Infants automatically shift their attention toward objects with attractive colors that make funny sounds or what caregivers encourage them to look at. First signs of endogenous orienting can be observed at about 4 months of age. A way to prove this is by presenting babies with a sequence of events that repeats itself (e.g., one attractive picture appearing on the left followed by a second one presented on the right side of a screen). After a few repetitions of the sequence, 4-month-olds are able to anticipate gaze toward the expected location in which the upcoming stimulus will appear, proving that they learned the regularity and that they are able to orient attention accordingly (Clohessy et al., 2001). This endogenous orienting of attention precedes the voluntary control of attention by the executive network. Infant that young are only able to learn simple unambiguous sequences (e.g., 1-2-1-2. . .; each number being a particular location on the screen). Learning more complex structures in which the sequence can continue in two possible directions after a certain stimulus (e.g., 1-2-1-3-1-2-1-3. . .; where location 1 can be followed by location 2 or location 3 depending on the previous location) will not be possible for children until toddlerhood as it requires monitoring the context, and therefore, some degree of maturation of the lateral prefrontal cortex (Clohessy et al., 2001; Moyano et al., 2022).

Likewise, disengaging attention from a focused stimulus is a hard task before the third month of life. Attention disengagement implies an effortful intent to terminate attention to an object or event in order to allocate it to a different one, and thus constitutes an early form of endogenous attention (Johnson et al., 1991). Young infants find it very difficult to move attention away from a stimulus they are focused on, even after it becomes boring or uninteresting, and redirect attention to a new one, a phenomenon that has been referred to as "*obligatory attention*" (Colombo, 2001). Using the Gap-Overlap task, a classic marker task to study attentional disengagement in infants, it has been shown that 1–2 months old infants are very slow to disengage from a central stimulus to orient to a peripheral target and often fail to disengage unless the central stimulus disappears (Hood & Atkinson, 1993). However, by 3–4 months of age, the ability to disengage from a central stimulus improves substantially even when the central object remains on the screen (overlap condition), and the latency to orient to the peripheral stimulus decreases significantly during the following months (Holmboe et al., 2018; Moyano et al., 2023).

The different developmental trajectories of attentional engagement and disengagement in this early period of life have to do with the maturation of particular brain structures (Hendry et al., 2019). While attentional shifting and engagement have been associated with early developing subcortical structures of the brain, such as the pulvinar and superior colliculus in the thalamus, disengaging visual attention from an object or location has been associated with the function of cortical regions of the dorsal orienting network (Özyurt & Greenlee, 2011), which take some more time to be functionally active. In a recent fMRI study with awake infants performing a version of the Posner's orienting task, activation in a number of frontal regions, including the ACC and anterior portions of the dorsal fronto-parietal circuit (inferior frontal and medial frontal gyrus), was observed in conditions that required reorienting attention to the target location following invalid cues (Ellis et al., 2021).

Further, developmental neuroscience research has shown that the development of feedforward and feedback connections between the hierarchy of visual areas emerge shortly after birth, with forward connections preceding feedback ones (Burkhalter, 1993). Also, neurons in the visual cortex develop early after birth (Huttenlocher & de Courten, 1987). In the following few years, substantial refinements in receptive fields take place across the ventral visual stream (the pathway where objects are represented). In agreement with the biased competition outline, changes in the representational properties in this pathway predict patterns of selective attention across development. For instance, it is well known that ventro-occipital regions specialize to process particular types of visual objects such as words and faces. Along childhood, receptive fields of the neurons in those regions increase the foveal coverage bias for faces in the RH and for words in the LH. Moreover, these neurophysiological changes are related to developmental changes in patterns of fixations on words and faces as observed with eye-tracking devices (Gomez et al., 2018). Likewise, suppression of neural activity for unattended stimuli is observed in the visual cortex, being modulated by age-related changes in the receptive fields properties of visual neurons. This competitive interaction mechanism shows a prolonged period of maturation along childhood because only appears to be adult-like in children above 8 years of age (Kim et al., 2021).

The circuitry of brain regions of the executive attention network appears to be in place even several weeks before birth, as observed in patterns of functional connectivity at rest in preterm infants (Doria et al., 2010). However, evidence of the functional activation of this network is hard to observe before the second half of the first year of life. For instance, detecting errors and reacting to the violation of expectations is a function attributed to the ACC, a principal node of the executive attention network. There is evidence that babies below 1 year of age show differential patterns of attention and behavior (i.e., increased attentional focus and looking duration) when observing unexpected events such as simple incorrect mathematical operations (Wynn, 1992) or the violation of physical laws (Stahl & Feigenson, 2015). Further evidence demonstrates that from about 7 to 9 months of age babies show an error-related brain activation in the mid-frontal line that is similar to that shown by adults, except for being delayed by several hundreds of milliseconds (Berger et al., 2006). Toddlers also show a frontal midline response linked to the observation of the unexpected completion of animal figures with which they have just been familiarized with (Conejero et al., 2018). In both adults and babies, this error-related brain response is associated with a burst of activity in theta frequency. The importance of theta activation for executive control has been largely evidenced (Cavanagh & Frank, 2014). Increased functional connectivity between core regions of the executive attention network in theta frequency has been linked with individual differences in executive control and the performance of conflict monitoring tasks in adults (Smit et al., 2023). Therefore, the activation of the executive attention network when observing contextual irregularities may be on the basis of the proneness that babies show to learn from objects that behave in unexpected ways. Stahl and Feigenson (2015) demonstrated that 10 months old babies show better learning of new properties of toys that were previously seen violating a physical law (e.g., running through a solid wall) as compared to toys that behaved naturally. Thus, we can tackle the emergence of this attention-based learning mechanisms by observing patterns of looking in babies and know about the brain mechanisms underlying this development by utilizing neuroimaging tools with the same experimental protocols. Results so far indicate that the executive attention network functionally emerges during the first year of life, allowing the increasingly endogenous regulation of attentional orientation first, and the regulation of actions later on, starting at about the last trimester of the first year.

At about 9 months of age, infants are able to inhibit attention to irrelevant distractors and remain focusing on an interesting stimulus (Holmboe et al., 2008). Between 9 and 12 months, infants also show the capacity to stop searching for a toy in the location where it has been initially hidden to successfully retrieve it from a new location (A-not B task; Diamond, 1990). Moreover, performance of the A-not B task is correlated with infants' ability to ignore distractors (Holmboe et al., 2018) suggesting a common underlying neural system involved in inhibitory control. Action control is also observed at this age with the Early Childhood Inhibitory Touchscreen Task (ECITT), a task in which babies must inhibit touching a tablet screen in a frequently rewarded position (i.e., prepotent location) in trials in which the target is presented at the opposite, less frequent, location. In the transition from infancy to toddlerhood, babies are increasingly able to flexibly switching responses from the prepotent to the inhibitory location with less inhibition errors; although, despite the progress, inhibition performance during this early stage is still far from stable (Hendry et al., 2022). Further research with infants' friendly imaging technology such as fNIRS has shown higher levels of activation in right prefrontal and parietal cortices linked to inhibition (Fiske et al., 2022). In addition, performance of trials that involved switching attention between prepotent and non-prepotent locations was associated with increased oscillatory activity in alpha band (6–9 Hz), a rhythm that is associated with attention in older children and adults, in frontal channels (Rico-Picó et al., 2024).

During the second and third year of life, a substantial development of attention neural networks takes place. In parallel with the highest rate of growth of white matter volume (Bethlehem et al., 2022), the process of myelination shows an uppermost peak about the second year of life (Deoni et al., 2015). These structural changes in white matter bring about the enhancement of neural connections, which become more efficient and reorganized into modular networks (Hagmann et al., 2010). These changes translate in behaviorally observable changes in young children's executive attention abilities. There is a considerable progress in executive attention skills throughout the second and third years of life. Cohesion and consistency among diverse executive attention measures also improve with age during this period (Hendry et al., 2022). Between 18 months and 3 years of age performance in simple inhibitory control tasks in which children are required to withhold a motor response also experience major development (Garon et al., 2008). The same applies to a simplified, child-friendly version of the Dimension Card-Sorting Task (DCST) which can hardly be performed by children below 3 years of age, who tend to make too many perseverative errors or show an inconsistent sorting strategy (Blakey et al., 2016). Also, consistently with the anatomy of executive attention, children with better scores in the DCST activate prefrontal areas during performance of the task to a greater extent than those performing poorer (Moriguchi & Hiraki, 2013).

In summary, during the first years of life there is an extraordinary development of the brain networks supporting the functions of attention. Age-related gains in behavioral and brain function efficiency are most likely related to changes in structural and functional connectivity observed with neuroimaging techniques. There is increased evidence that attentional performance is associated with greater efficiency of information transfer in the brain, which is characterized by the involvement of distributed brain nodes and shorter length of paths connecting such nodes (Gießing et al., 2013). Beyond the preschool years, changes in functional connectivity of brain regions involved in attention continues. Compared to adults, attention networks appear to be more integrated in childhood (Fair et al., 2007), and children exhibit many short (local) connections instead of the long distance connections involving frontal and parietal regions exhibited by adults (Dosenbach et al., 2010). Consistently, attention-related executive processes show great changes in the preschool period and a protracted developmental course extending up to late adolescence (Rueda, 2013).

Concluding Remarks

Piaget's constructivism theory of cognitive development moved the focus of the scientific community toward the active role of the child in interaction with the environment on the process of developing a mental model of the world. While growing, the child learns in a complex dynamic interaction with the surrounding environment. Decades later, an impressive wealth of technical advancements allows the investigation of brain mechanisms underlying cognitive development and the learning of mental skills. The emphasis on brain-based constraints of cognitive development gives rise to the idea of neuroconstructivism (Karmiloff-Smith, 2006). According to this framework, representations in the brain emerge within the context of multiple interacting levels: molecular, cellular, bodily, and social events interact and constrain the development of cognitive representations. Thus, cognitive development is construed in terms of multiple brain-based constraints due to the timing of brain changes in the micro (e.g., synaptogenesis, myelination, synaptic pruning, etc.) and macrostructure (e.g., formation of processing circuits based on structural and functional connectivity) of the cortex. The process of growing is complex because it does not happen in isolation or according exclusively to biological instructions, no matter how complex those might be. Growing is an interactive process that involves biology and socialization.

Following this conceptualization, developmental research should not only provide an understanding of the mechanisms underlying the evolution of children's capacities, something for which the framework of Cognitive Neuroscience is crucial. In addition to this, the field of Developmental Cognitive Neuroscience should put an emphasis on when and under what circumstances children use their capacities. Thus, it is important to study the environmental conditions in which children grow and how these factors impact the myriad of processes taking place between brain and behavior, in an effort to understand and acknowledge individual differences in the process of growing into an idiosyncratic human being.

Developing an Attentive Brain

Attention serves as a mechanism for regulating the processing of information in the brain. Exogenous attention is an early evolving mechanism developed to prioritize information processing according to the saliency and relevance of surrounding stimulation. This mechanism is complemented by a later evolving capacity to regulate the flow of information processing, at both perceptual and executive levels, according to strategic goals and intentions, the so-called endogenous or top-down attention control. Three main networks of brain areas contribute to the functions of attention, namely, (1) subserving an optimal level of activation, (2) selecting and prioritizing the processing of relevant information, and (3) regulating responses at multiple levels, including cognitive processes such as learning and memory, motor responses and the regulation of thoughts and emotions.

Developing an attentive brain begins early in life, with significant milestones in attention control emerging during infancy and toddlerhood. One of the first cognitive challenges that a baby faces is learning to control their attention. This ability is crucial for learning from others and from the world around us. Therefore, the capacity to sustain attention sufficiently to learn about the properties of objects, as well as the ability to flexibly shift attention to explore the environment when necessary, is vital for learning. In a world full of stimulation, the capacity to regulate the flow of information processing according to rules (from simple E-R to complex ones that can be permeable to culture) and intentions (from those based in short-term to those based on long-term sought outcomes) sets human babies on a path of cognitive growth that is beyond the reach of other species. The regulation of mental processes provides humans with an extraordinary capacity for flexibility and adaptation, allowing them to exhibit different courses of actions in similar situations or, conversely, to behave similarly in a diversity of circumstances.

Early forms of exogenous control of attention in the activation and orientation domains are in place at birth. However, early signs of endogenous control over sustained attention and visual orientation emerge around 3–4 months of age. This emerging capacity requires a minimal level of maturation of subcortico-cortical pathways involving connecting regions of brainstem and the thalamus with areas of the parietal and frontal cortex involved in the control of attention. Later on, by the end of the first year of life, the circuitry of frontoparietal connections necessary for action-regulation begins to show their first signs of activity, as evidenced by brain responses to errors or the performance of inhibitory control tasks. Thus, between 9 and 18 months of age executive control undergoes important development. Oscillatory brain activity in the alpha frequency range also shows significant development during the first years of life (Rico-Picó et al., 2023), which is closely associated with the maturation of endogenous attentional control (Whedon et al., 2020). Moreover, efficient functional connectivity in the alpha frequency range may serve as a brain marker for the early development of attention, highlighting its importance in cognitive development during infancy and toddlerhood. This early development is foundational to the subsequent development of more complex forms of executive control and self-regulation in the years to come.

Future Directions and Challenges

For the times to come, more studies looking to reveal causal mechanisms, and not just neural correlates of emerging skills, must be designed. To this matter, it would be important to increase the number of studies aimed at analyzing the impact of educational, societal, or clinical interventions on the diverse mechanisms affecting development, from gene-expression to brain function.

An important challenge for developmental science that has started to be faced and will certainly continue in the near future is the joint collection of data from multiple laboratories. These efforts bring about large data sets extending the power and possibilities for statistical analyses. Hopefully, these efforts will include a diversity of populations and cultures from around the world.

Using artificial intelligence computational modelling with big data sets including brain, behavioral, and societal variables will help uncovering the key biological, individual, and educational/cultural factors predicting developmental outcomes. The use of neural networks and machine learning modelling may be particularly effective when it comes to analyze data sets that include multiple variables with complex intercorrelations among them. The information provided by the use of this methodology has the extraordinary potential of informing the design of health and educational policies that could potentially optimize the lives of children and their families. However, despite the huge potential of AI modelling for developmental research, an important concern is that the use of this methodology may not automatically result in understanding the development of complex human skills. To this respect, it is again worth noticing that confirmatory (i.e., theory-driven questions) rather than exploratory science will lead to stronger findings.

From Theory to Research and Back to Theory

Cognitive theory serves as a guiding framework for neuroscience research, facilitating the design of meaningful and interpretable experimental protocols. By integrating data from multiple levels of analysis, including cognition/behavior, brain function, genetics, and more, researchers can develop more comprehensive and robust theories. According to Mark Johnson (Johnson, 2020), a good developmental cognitive neuroscience theory should (1) incorporate an explanation about mechanisms of change and (2) relate evidence from different levels of observation in terms of one level of explanation. With the advent of new imaging technology and advanced methods of analysis, a wealth of new data is being generated. These new data provide valuable insights that can be integrated into theoretical models, leading to the refinement of existing theories and the generation of new hypotheses. Importantly, the cognitive neuroscience approach not only enhances our understanding of typical development but also provides a framework for understanding developmental disorders. By elucidating the underlying mechanisms, this approach facilitates the design of targeted interventions aimed at addressing these disorders, thus bridging the gap between theory and practice in developmental psychology and cognitive neuroscience.

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Statement of Ethics

Refer to cited publications in order to find information about ethical approval of protocols and consent of participants in the numerous studies discussed in this paper.

Conflict of Interest Statement

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