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PERSPECTIVE

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Attention: The grounds of self-regulated cognition

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Abstract

Everyone knows what *paying attention* is, yet not everybody knows what this means in cognitive and brain function terms. The attentive state can be defined as a state of optimal activation that allows selecting the sources of information and courses of action in order to optimize our interaction with the environment in accordance with either the saliency of the stimulation or internal goals and intentions. In this article we argue that paying attention consists in tuning the mind with the environment in a conscious and controlled mode in order to enable the strategic and flexible adaptation of responses in accordance with internal motivations and goals. We discuss the anatomy and neural mechanisms involved in attention functions and present a brief overview of the neurocognitive development of this seminal cognitive function on the grounds of self-regulated behavior.

This article is categorized under:

- Psychology > Attention (BEAB)
- Brain Function and Dysfunction (BEAC)
- Cognitive Development (BAAD)

KEYWORDS

activation, attention, development, executive attention, selection

1 | INTRODUCTION

When William James stated that everyone knows what attention is (James, 1890), he probably wanted to underlie the extended use of the term in many circumstances of daily life. But, what do we mean when we call somebody to *pay attention*? What is it that we are asking for in cognitive and brain function terms?

The body serves as the interface with the environment. The structure of the body (e.g., having two arms and hands instead of four) limits our interaction with objects and people. Likewise, the cognitive structure of our mind (and brain processes that enable it) imposes limits to the sensory inputs and trends of thoughts that can be consciously processed at a time. Therefore, a mechanism has evolved to help us regulate the information we process and decide how we want to respond to it. This mechanism is attention.

2 | THE ATTENTIVE STATE

Behavior, cognitive and physiological states change with attention (Posner, Rothbart, & Sheese, 2007a; Rueda et al., 2015). Stimulation reaching our senses produces two main effects in the brain (Hebb, 1949). On the one hand, the information is processed along sensory pathways in order to identify its nature and location with respect to the body. On the other hand, stimulation produces a general burst of activation canalized by the reticular activating system (RAS). From the seminal work of Donald Hebb, classical models of attention distinguished activation and selection aspects of attention (Broadbent, 1958; Kahneman, 1973). Along the sensory pathways, information undergoes extensive elaboration, and attentional modulation has been increasingly incorporated into the repertoire of human skills as evolution increased the spatial and temporal dilation of information processing within the functional architecture of the brain (Mesulam, 1998).

2.1 | Activation, selection, and control

Notions of activation, selection, and control have been associated to attention from early models (James, 1890; Posner & Petersen, 1990; see Figure 1). To be effective, attention requires a minimum level of activation of the nervous system. The optimal activation of the arousal system as well as the active representation of goals and information (either coming from sensory or memory systems) is an important part of the construct of attention. Alertness is very much related to regions of the brainstem that modulate the level of arousal of the cerebral cortex by means of noradrenergic neuromodulators (Coull et al., 2001). Warning signals produce a rapid change in the state of the brain for processing information (Posner, 2008), which results in faster reaction times, although it may also cause less accurate responses, as we describe below.

Conscious perception is highly modulated by attention. We perceive a highly edited version of the world that is filtered by our interests and intentions (i.e., top-down attention), as well as the features of the stimulation that configure the scene (i.e., stimulus-driven attention). Attentional selection is necessary to prioritize the processing of particular sensory inputs or internal representations according to their relevance or the voluntary desires of the individual. When we look at a scene, we have the subjective impression that all that it contains is perceived. However, much evidence has demonstrated that important changes in the scene can be missed if unattended, a phenomenon called *inattentional blindness* (Mack & Rock, 1998; Rensink et al., 1997).

When somebody calls you to pay attention to something, you may experience both the burst of activation and the orientation toward the particular source of information that usually accompanies attention. In this case, attention is driven by a change in the stimulation coming from the environment (the person's voice, in this particular example). When this happens, we call it *exogenous* or *stimulus-driven attention*. This type of attention is both anatomically and cognitively different from when we choose what and where to pay attention to because we have an expectation about the environment or an internally generated goal or intention (Corbetta & Shulman, 2002; see Figure 2). This other form of attention is referred to as *endogenous* or *goal-directed attention*.

Neuroimaging research has helped to elucidate the brain circuits underlying both top-down and stimulus-driven attentional selection, mostly in the visual domain (Corbetta & Shulman, 2002). Much evidence has shown that attention enhances the representation of task-relevant features of stimulation (e.g., color, shape, movement, etc.) as well as spatial locations where something relevant is expected to occur (Müller et al., 2006; Polk et al., 2008; Posner et al., 1980; Treisman & Gelade, 1980). Top-down or endogenous attentional modulation is characterized by top-down feedback

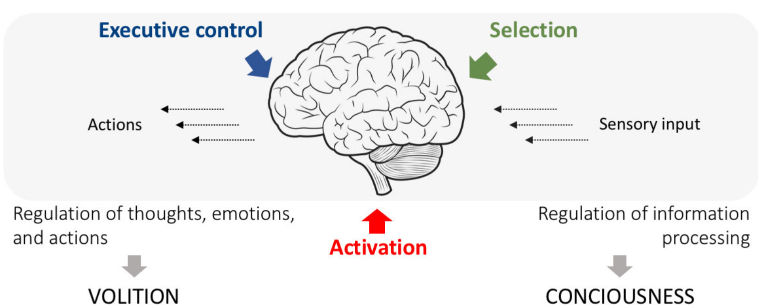

FIGURE 1 Attention is a mechanisms for canalizing information processing toward the conscious and voluntary regulation of actions, thoughts and emotions. Notions of activation, selection, and control are involved in this function

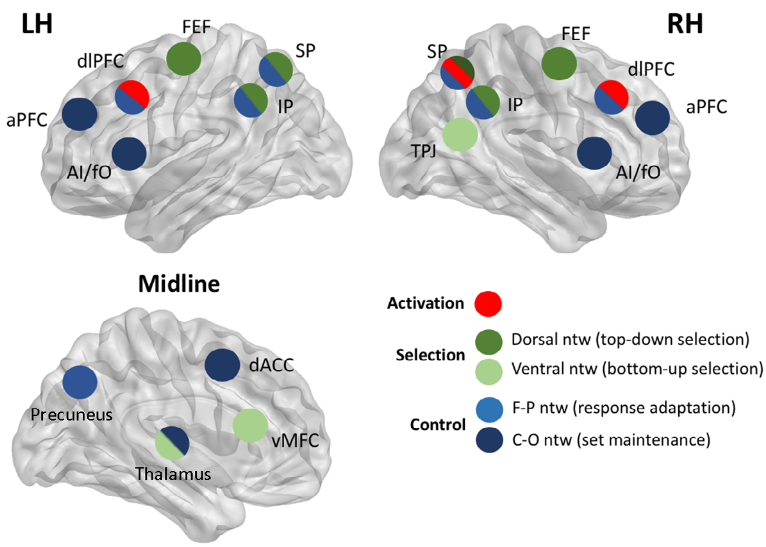

FIGURE 2 Graphical representation of the brain networks involved in activation (red), selection (green), and control (blue). Nodes of the activation network are located in the dorsolateral prefrontal cortex (dlPFC) and the superior parietal lobe (SP). Two separate networks have been involved in attentional selection (Corbetta et al., 2008), the ventral network includes the temporoparietal junction (TPJ), thalamus and ventromedial prefrontal cortex (vMFC); the dorsal network includes the frontal eye-fields (FEF) and the intraparietal sulcus/superior parietal lobe (IP/SP). Finally, executive attention is associated with two distinct circuits: The cingulo-opercular (C-O) network, involved in representing goals and intentions, which includes the dorsal anterior cingulate cortex (dACC), anterior prefrontal cortex (aPFC) and the anterior insula/ frontal operculum (AI/fO); and the fronto-parietal (F-P) network involved in adjusting responses in relation to changes in the stimulation, and includes the precuneus, dlPFC, and the SP/IP brain regions

signals that originate in frontoparietal regions (Baldauf & Desimone, 2014; Buschman & Miller, 2007) and show functional connectivity with dorsal parietal regions of both hemispheres (Corbetta & Shulman, 2002). In addition, a set of ventral frontal and parietal regions of the right hemisphere respond to the saliency of events (e.g., infrequent or unexpected events that are relevant). These dorsal and ventral circuits are involved in biasing competition among neurons processing the sensory input, which results in a much rich processing of the selected object (Baldauf & Desimone, 2014; Bichot et al., 2015). Patients with damage to those parietal and frontal regions, mostly to the right hemisphere, suffer the drama of inattentional blindness to stimulation occurring on the left visual field, sometimes also to the left side of focused objects, and in some cases, they also show neglect to perceiving or acting toward the left side of their own body (Kerkhoff, 2001). These patients also miss the left side of information that is retrieved from memory, suggesting the domain-general nature of attentional selection, which acts on spatial-based and object-based processing of current inputs, as well as on memory representations.

In addition to activation and selection, attention is also associated with the control of thoughts and actions (Norman & Shallice, 1986; Posner & Snyder, 1975). It is well-established that attention is necessary for regulating responses in situations that require a careful, deliberated, control of actions, as opposed to acting in the context of frequent and well-learned conditions (Posner & DiGirolamo, 1998; Posner & Rothbart, 1998). Executive control is associated with the activation of particular circuits of frontal and parietal structures involved in both representing and maintaining goals and intentions (i.e., cingulo-opercular network) and adjusting responses to accomplishing these goals (i.e., fronto-parietal network; Dosenbach et al., 2008). Most of the nodes of these circuits are considered *hubs* in the functional organization of the brain, meaning that they are regions with a high degree of centrality given their large number of interconnections with other regions (C. Gratton et al., 2018). When tasks require the attentive-control mode, executive circuits show enhanced functional integration, and interact with the brain regions in charge of processing the information that is relevant for the task at hand in order to adjust their function to current goals (C. Gratton et al., 2016).

Thus, the attentive state can be defined as a state of optimal activation that allows selecting the sources of information and courses of action in order to optimize our interaction with the environment in accordance with either goals and intentions or the saliency of the stimulation. A picture of the main regions of the brain involved in activation, selection, and control of perception and action is presented in Figure 2.

Working in an attentive state brings about costs in terms of resources but also some fundamental advantages. Attention has been linked to goal-driven, self-regulated behavior, given its role in executive control. Different terms are

TABLE 1 Taxonomy of executive processes

Term	Definition	References	Root field
Executive attention	Set of mechanisms that underlie our awareness of the world and the voluntary regulation of thoughts, feelings, and actions. Involves mechanisms of detection (target detection/error detection), conflict, and cognitive control (inhibition and switching/ flexibility).	Posner and DiGirolamo (1998); Petersen and Posner (2012); Kane and Engle (2002); Rueda et al. (2005)	Attention and cognitive psychology
Executive control/ cognitive control	Attention-based goal-directed bias over habitual responses. Form of action selection and monitoring that involves deliberate and voluntary adjustments in perceptual selection, response biasing, and online maintenance of contextual information.	Norman and Shallice (1986); Cohen et al. (1990); Botvinick et al. (2001)	Cognitive psychology
Self-regulation	Many processes by which the human psyche exercises control over its functions, states, and inner processes, being essential for transforming the inner animal nature into a civilized human being.	Vohs and Baumeister (2004)	Individual differences
Executive functions	Collection of top-down control processes used when going on automatic or relying on instinct or intuition would be ill-advised, insufficient, or impossible. Involves self-control, flexibility, and working memory.	Diamond (2013); Miyake et al. (2000)	Neuropsychology

frequently used to refer to the voluntary regulation of behavior. Very often, these terms are used as synonyms, although differences, sometimes subtle, can be acknowledged. The different terms are engrained in diverse research traditions in the field of Psychology and Neuroscience (see Table 1). Although there is also evidence that associative learning mechanisms can contribute to executive control in particular contexts (see Abrahamse et al., 2016), executive processes such as inhibitory control, cognitive flexibility, and working memory are fundamentally of attentional nature (Baddeley, 1996, 1993; Kane & Engle, 2002; Rueda et al., 2011). Also, there is a strong connection between attention and consciousness. Attended information can be processed to a deeper level, usually reaching a state of awareness of its features and meaning, can be reasoned upon, and hold active in mind for a longer period of time (Posner, 2012). This gives attention a domain-general role in cognition, being involved in many other cognitive functions, such as learning, reasoning and the regulation of actions, thoughts, and emotions. In the next sections, we focus on the fundamental role that attention plays in self-regulated behavior.

3 | EXECUTIVE ATTENTION: A SYSTEM FOR BALANCING EFFICACY AND ADAPTABILITY

Exogenous attention is crucial to survival and thus is an early evolving mechanism that we share with many other species. In fact, parameters of saliency (contextual distinctiveness) and relevance (connection to negative or positive outcomes) of the stimulation determine its capacity to capture attention automatically, without the need of an expressed intention to pay attention to it. However, in general, the brain of primates, and particularly the human brain, has evolved dissociated mechanisms for exogenous and endogenous control of behavior (Stout, 2010). Endogenous attention requires a connection between selection mechanisms and the representation of goals and expectations, as when I intend to select the voice of a colleague to understand what s/he is saying in a noisy context, or when I search for a friend with a blue cap among a crowd of people wearing caps of many colors. These examples refer to the selection of perceptual information, but something similar occurs in the domain of action control. Well-learned actions are automatically triggered by the stimulation and involve very little, if any, attention. Nevertheless, when intentions conflict with automatic tendencies or require planning a new sequence of actions to adapt to a changing context, developing appropriate responses consumes a good deal of attention resources (Kahneman, 1973; Norman & Shallice, 1986). Posner and colleagues coined the term *executive attention* to refer to attention-related mechanisms that underlie our awareness of the world and the voluntary regulation of thoughts, feelings, and actions. These are mechanisms of conscious detection, conflict resolution (mostly exerting inhibitory control over dominant but undesired actions), switching responses in changing contexts (cognitive flexibility), and error correction (Posner & DiGirolamo, 1998; Posner & Rothbart, 1998; Rueda et al., 2011). The evolution of this attention-based cognitive control system in the human brain is concomitant to the expansion of cortical regions of the frontal and parietal cortices, including the anterior cingulate (Fjell et al., 2015), which is considered a main node of executive attention (Petersen & Posner, 2012; Posner, Rothbart, Sheese, & Tang, 2007b).

Living in a complex changing environment requires being able to develop and exploit behaviors that lead to positive outcomes (e.g., obtaining desired food, receiving social appreciation, etc.), as well as adapting to changes or improving outcomes by exploring new behaviors. A property of our cognitive system is its proneness toward generating courses of actions that are low-demanding in terms of executive control resources. This economizes the use of cognitive resources and maximizes its distribution toward more attention-demanding actions or trains of thoughts. Learning processes governed by this principle of economization of resources (automatization) are very much entrenched in our cognitive system and can be observed even after just one trial. For example, it is well known that if I just perform a difficult task, for example, a task involving some degree of conflict, resolving a similar situation is facilitated, as compared to when a difficult task follows an easy one. These are known as sequential effects (G. Gratton et al., 1992). In addition, there is evidence that executive control processes, like switching between task sets, can be influenced by contextual conditions, such as increased frequency or larger incentives for switching trials, which are associated with reduced switching costs (Braem & Egner, 2018). In our view, this is another example of how the cognitive system adjusts to the characteristics of the environment under favorable or propitious conditions, likely applying basic learning principles (see Abrahamse et al., 2016), in order to minimize the use of attentional resources. However, as much as automatization facilitates fast responses and economizes resources, an excess of it may lead to inflexible behavior. Therefore, flexible adaptation to rules and goals requires the regulation of automatic response tendencies. Hence, optimal performance demands a fine balance between the activation of learned and/or automatic pathways and control processes that regulate them. Conscious and deliberated decisions, particularly in contexts that are rich in interference between what is dominant and what is desired, cannot be made by applying a set of learned rules, and thus cannot be reached without attention (Kane & Engle, 2002). This is why consciousness and volition have been largely linked to attention (Posner & Rothbart, 1998).

The interplay of brainstem regions involved in arousal, such as the norepinephrine (NE)-rich locus coeruleus (LC-NE system), and cortical regions that represent goals and regulate responses (i.e., the executive networks, Figure 2) is thought to provide a brain mechanism for this attention-dependent efficacy-adaptability balance (Aston-Jones & Cohen, 2005). The LC presents two modes of function: phasic and tonic. The tonic mode represents the LC baseline activity. In the phasic mode, bursts of activity are observed in association with task-related decision processes and are coupled with accurate actions. The relative phasic-tonic LC response is necessary for optimizing the balance between responding to the current task and adapting to complex, changing environments, including the (either implicit or explicit) search for regularities that could eventually be learned. When the tonic mode is elevated, phasic bursts are absent and behavior is more distractible (i.e., less attention-focused). The modulatory effects of the LC-NE system over cortical circuits involved in goal-directed actions permits to adaptively adjust the performance to exploiting old actions or exploring new ones. The optimal balance is observed under moderate levels of tonic LC activity, which allow a good relative tonic-phasic signaling (Aston-Jones & Cohen, 2005). The relationship between this brain mechanism, alertness and performance is represented in Figure 3.

4 | DEVELOPING ATTENTION NETWORKS

The developmental framework offers a deeper understanding of attention, as an integral theory of what attention is and what are its links to perception, learning, and memory must include an understanding of what is the origin and what are the building blocks of this cognitive function. Viewing attention as an organ system associated with brain circuits involved in alerting, selection, and executive control provides a way to analyze both the genetic origins as well as the experiences that modulate both the expression of genes and the ontogenetic building process of those circuits (Posner & Fan, 2008; Rueda et al., 2015).

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 (see Petersen & Posner, 2012). This information has greatly helped to understand the genetic origins of attention networks by studying the genes that influence the expression and function of those particular neuromodulators and their impact

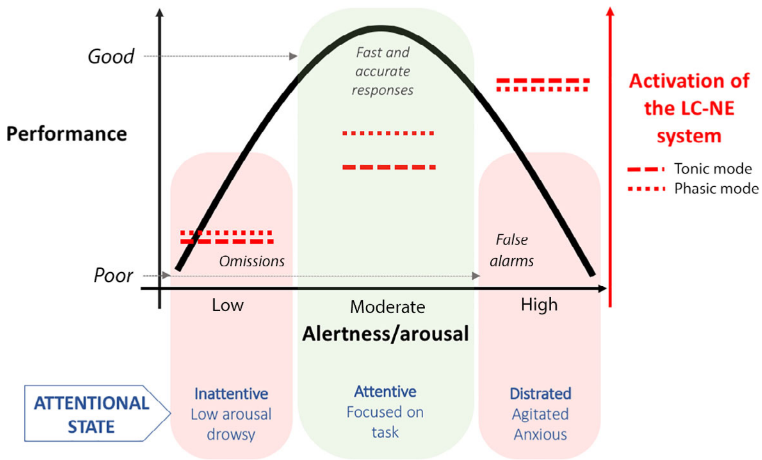

FIGURE 3 Relationship between alertness and performance, in relation to the function of the locus coeruleus-norepinephrine (LC-NE) system and the attentional state of the individual. Attention is related to the mode of activation of the LC-NE system in connection with cortical regions involved in executive attention (Aston-Jones & Cohen, 2005). This curve explains the classical Yerkes and Dodson (1908) law, which relates arousal and performance

on individual differences in efficacy at both the behavioral and brain function levels (Fan et al., 2003; Posner, Rueda, & Kanske, 2007c). Although the genetic influence appears to be somewhat stronger for alerting and executive control than for orienting, much investigation has shown that, for instance, dopamine-related genes interact with life experiences and educational factors to explain individual differences in executive attention along development (Rueda et al., 2005; Voelker et al., 2009).

On their part, behavioral studies have demonstrated a protracted and heterochronous process of development of the attention functions (Pozuelos et al., 2014). All three functions emerge along the first year of life and seem much more interdependent in the early stages of development (Rothbart et al., 2011). Attention in the time domain varies from transient bursts of alerting to incoming stimuli to sustained attention over prolonged periods. From very young, infants show changes in phasic alertness and orientation to external stimulation, while endogenous sustained attention shows a long trajectory of progress toward increased independency from external cues and temporal span (Berger et al., 2000; Rueda et al., 2004). Similarly, in the visuospatial domain, exogenous orientation is present from early on, whereas the capacity for endogenous control of attention progressively emerges from about 4–6 months of age (Johnson et al., 1991) and shows great maturation in the following years (Clohessy et al., 2001; Plude et al., 1994; Pozuelos et al., 2014). Executive attention functionally emerges at the end of the first year of life, when babies start to show a rough capacity to inhibit prepotent courses of actions and to flexibly shift attention according to changes in patterns of stimulation (Conejero & Rueda, 2018; Holmboe et al., 2018). Just at that time babies also show behavioral and brain signs of error-detection (Berger et al., 2006; Wynn, 1992). From there on, attention-related executive processes show dramatic changes in the preschool period and a protracted developmental course extending up to late adolescence (Davidson et al., 2006; Pozuelos et al., 2014).

This heterochronous and long-lasting developmental process parallels the developing trajectory of brain circuits supporting attention. A recent neuroimaging study shows that babies along the first year of age already show activation in frontal and parietal regions while performing an attentional cueing task in the MRI scanner (Ellis et al., 2021). Beyond the first year, structural and functional imagining has shown a protracted maturation of the hierarchical organization of subcortical as well as posterior and anterior cortical regions supporting attentional functions (see Amso & Scerif, 2015 for a review). Biasing competition processes that underlie attentional selection operate through an intricate system of feedforward (bottom-up) and feedback (top-down) organization of connections mostly in the caudal–rostral axis (Itti & Koch, 2001; Summerfield & de Lange, 2014). This functional architecture serves the selection of both sensory input as well as task-goals and responses. The development of this circuitry progress from functional specialization and segregation at the local level to increased functional integration between long-distant regions, particularly between parietal and frontal areas (Fair et al., 2007), which parallels the related increased efficiency of attention control skills that are observed with age (Hwang et al., 2010).

Much developmental research has also shown the relevance of attention processes for other cognitive domains, such as learning and memory. Maintaining information in an active, highly accessible state, is particularly important when other potentially interfering stimulation is present. When there is not contextual regularities susceptible to be learned, attention resources are necessary to establish what information is to be maintained and what to be blocked according to the task set. Thus, executive attention and working memory are highly interdependent processes. There is evidence showing that attention control largely contributes to WM and short-term memory development (Shimi et al., 2014, 2015). Also, tasks used to measure WM span, inhibitory control, as well as general intelligence skills appear to relate to a common factor of executive attention (Kane et al., 2007; Tiego et al., 2020). Likewise, the deliberated and conscious mode of processing characteristic of the attentive state enables superior executive processes such as fluid reasoning. We have demonstrated that children with higher fluid intelligence use proactive control for context monitoring to a greater extent and display greater activation of sustained and executive attention networks (Rico-Picó et al., 2021). Attention is the platform for executive processes enabling deliberated goal-directed actions, and the core function of intelligent behavior (Rueda, 2018). The development of these abilities predicts many aspects of life, including academic achievement and socio-emotional adjustment (Rueda et al., 2010; Simonds et al., 2007) as well as individual differences in health, wealth and socialization in adulthood (Moffitt et al., 2011).

5 | CONCLUSION

Living in a complex environment requires balancing cognitive resources in order to maximize efficacy and adaptability. Better fitted organisms are those that develop fast and efficacious responses to repeating events (exploit learning) but are able to switch courses of actions (adjustment and/or innovation) when learned responses are not appropriate giving changes in contextual contingencies or variation of goals and motivations. Executive attention is the cognitive mechanisms that enables the flexible regulation of perception and action that is characteristic of strategic behavior. The development of attention mechanisms of activation, selection and control both in phylogeny and ontogeny support the extraordinary capacity for self-regulation of cognition and action that human beings are capable of.

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This is an opinion paper in which already published data are referenced.

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