Review

The Unified Instinct of Top-Down and Bottom-Up Attention

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The Unified Instinct of Top-Down and Bottom-Up Attention

Running title: Top-Down vs. Bottom-Up Attention

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Abstract: The neural system has limited resources to interact with the environment, and this is where attention comes into play. Attention is a complex process that provides numerous benefits, but there has been a longstanding debate about the mechanisms involved in attentional orientation. Two widely proposed mechanisms are top-down and bottom-up, which relate to the organism's current behavioral goal and the salience of environmental stimuli, respectively. However, distinguishing between these mechanisms can be challenging in both behavioral and neural studies. This review introduces a new conceptualization in which both top-down and bottom-up mechanisms are viewed as aspects of the same process. This unified approach aims to prepare the organism to face stimuli and events based on its prior experiences, immediate (the current task that he/she is aware of), and innate (to be alive) demands.

Keywords: exogenous attention; endogenous attention; goal-directed; stimulus driven; selection; competition

1. Introduction

Driving on an empty stomach can potentially trigger a food craving, and a burger can serve as a convenient option for a fast meal (what's your idea?). Nevertheless, when on the lookout for a roadside burger joint, the blaring sound of a truck horn might cause the driver to momentarily lose focus, resulting in unintentionally missing the nearby burger shop. In such instances, being attentive plays a crucial role in enabling the driver to effectively engage with the surrounding environment, which abounds with diverse cues and stimuli.

The primary experiments have demonstrated that attention, as an emergent property of brain activity, is allocated in various ways. These ways include the subject's expectations, their behavioral goals, and the physical salience of the stimuli present in the environment (Groner & Groner, 1989). The allocation of attention can occur in two distinct ways, namely, top-down (goal-directed) and bottom-up (stimulus-driven), as initially conceptualized by William James over a century ago. James referred to these two forms of attention as active and passive attention, respectively (James, 1890).

During the 1970s, several years after Helmholtz postulated that attentional focus could be voluntarily shifted, the first experiments attempting to demonstrate the top-down deployment of attention were conducted (Eriksen & Hoffman, 1972, 1973; Posner, 1980). Then, theories about attention characterization emerged as the feature integration theory (Treisman & Gelade, 1980), the biased competition model (Desimone & Duncan, 1995), the normalization model (Reynolds & Heeger, 2009), etc.

Top-down and bottom-up attention represent two distinctive forms of attention regulation, and the key defining feature that distinguishes them is the extent to which the captured attention is related to the organism's behavior. Specifically, top-down attention, also known as goal-directed or endogenous attention, operates as a filtering mechanism that selectively captures information relevant to the current behavioral goal, thus reflecting voluntary control. In contrast, bottom-up

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attention, also referred to as stimulus-driven or exogenous attention, is triggered automatically in response to salient or unexpected stimuli in the environment, and as such, it is considered to be involuntary or reflexive. In essence, top-down attention reflects the organism's proactive orientation towards achieving a specific goal, while bottom-up attention reflects the organism's reactive response to the external world. (Carrasco, 2011; Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Kastner & Ungerleider, 2000).

The primary focus of this study revolves around the correlation between an organism's present behavioral objectives and the instinctual top-down and bottom-up models of attention control. Recently, this model has evolved into a trichotomy by including the subject's experiences (Awh et al., 2012). Therefore, the primary debate in this review centers on the relationship between these three components and how they interplay to influence an organism's behavior.

2. Where Both Mechanisms Meet

The "tabula rasa" concept, originating from the Latin term meaning "blank slate," posits that a newborn individual begins with no preexisting knowledge. According to this viewpoint, all mental characteristics and knowledge will be acquired through experiences. (Petryszak, 1981). On the contrary, certain characteristics of our mental makeup have been developed through evolution and operate much like a learned skill, such as driving. Initially, conscious effort is required to develop these functions into reflexive behaviors that require minimal effort to execute. (Hasher & Zacks, 1979). In this regard, while it is commonly believed that some actions are reflexive and therefore beyond conscious control, it is important to recognize that all behavior is ultimately directed by the nervous system. Whether or not an individual is consciously aware of their actions, they are still voluntary responses (of the whole system) to the stimuli they encounter. It should be noted, however, that the debate surrounding the inherent freedom of this voluntary behavior is outside the scope of this review.

In the first paragraph, it is not explicitly clear what the driver's primary objective is. Is he solely focused on driving and navigating the road? Or is he more interested in finding a burger shop? Alternatively, is his number one priority to ensure his safety and avoid accidents? In actuality, the driver has various goals that he is attempting to accomplish all at once, with finding the burger shop appearing to be at the forefront of his mind. However, it is important to remember that he is also driving and navigating the road and attempting to avoid any potential hazards that may come his way. In terms of attentional deployment, it is useful to think of it as an analogy. As we engage in performing a task, our attention shifts based on the most relevant information to our current task's demands. In fact, our attentional priorities are updated dynamically depending on the situation we encounter with (Todd & Manaligod, 2018). At the same time, we are constantly engaged in the long-lasting task of staying alive - a task that every living organism has evolved to prepare for and learn from. This task cannot be considered involuntary; it is a struggle that we undertake consciously or unconsciously every moment of our lives. In this sense, the bottom-up and top-down shift of attention can be seen as two sides of the same coin, both riding on the same highway.

3. Master maps of integration

The proposed computational model of attention states that the process of selecting the next target for attention and gaze relies on a master map, known as the saliency map, which represents the relative strength of the scene's stimuli based on their features. At any given moment, the most active area in the saliency map determines the most salient location in the space and directs the locus of attention in a winner-takes-all (WTA) manner (Itti et al., 1998; Itti & Koch, 2000, 2001; Koch & Ullman, 1984, 1985). Although the concept of a saliency map was initially associated with bottom-up influences, researchers have since adopted a new term that encompasses both bottom-up and top-down effects: the priority map (Bisley & Goldberg, 2010; Bisley & Mirpour, 2019; Fecteau & Munoz, 2006).

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Recent studies conducted on monkeys have shed light on the crucial role played by certain brain areas in the formation of the saliency/priority map within the neural system. These areas include the primary visual cortex, the posterior parietal cortex, the frontal eye field, the superior colliculus, and the substantia nigra (Basso & Wurtz, 2002; Bisley & Goldberg, 2010; Bisley & Mirpour, 2019; Li, 2002; McPeek & Keller, 2002; Schall & Hanes, 1993; Thompson & Bichot, 2005; Veale et al., 2017; White et al., 2017). The selection process ultimately combines the available information regarding the current task (referred to as top-down information) with the physical salience of the surrounding stimuli (known as bottom-up information) in order to determine the most pertinent location/object (to review see Narhi-Martinez et al., 2023) with the current goals (the goals which are the subject is consciously aware of them or not) of our life as an evolutionary gift, not an unfortunate. Therefore, according to the biased competition theory, the won object representation becomes dominant in all feature dimensions (Desimone & Duncan, 1995; Duncan et al., 1997; Shipp, 2004).

The features of a stimulus that are deemed salient are those that have gained significance over time due to the subject's life experiences and inherited traits through evolution. Such features are essential for the organism's survival or hold a rewarding nature, which adds value to the stimuli (Anderson, 2013; Theeuwes, 2019). Studies have demonstrated that learning induces changes in the sensory processing of the cortex in response to learned features through training. These changes occur by altering the signal-to-noise ratio, encoding of neural populations, and response threshold, resulting in increased engagement of the organism in the task at hand (Caras & Sanes, 2017; Choi et al., 2018; Makino & Komiyama, 2015; Poort et al., 2015).

4. What Do the Brain and Behavior Define?

Many experiments conducted so far have focused on distinguishing between top-down and bottom-up mechanisms and have studied them independently. As a result, there have been opposing findings, with some studies suggesting that the physical characteristics of the stimulus have a greater impact on where an individual directs their attention (Theeuwes, 1994, 2004), whereas others indicate that the individual's intentions and goals play a more prominent role (Folk et al., 1992) depending on the context. Furthermore, it is worth noting that emotional stimuli, particularly those of a threatening nature, possess a potent ability to regulate attention. Such stimuli hold a stronger sway over individuals prone to anxiety as they exert a bias towards threatening stimuli during the process of attentional competition (Bishop, 2008; Mathews & Mackintosh, 1998; Mulckhuyse, 2018). Hence, the debate regarding the significance of each mechanism in regulating the focus of attention continues. (Anderson et al., 2021; Theeuwes, 2010). In addition, it has been established that bottom-up factors play a crucial role in shaping the initial stages of processing. Conversely, the latter stages appear to be more heavily influenced by top-down factors (Theeuwes, 1994, 2004; Van Der Stigchel et al., 2009). Although behavioral studies have suggested a specific timing window influenced by attentional mechanisms in the brain, fMRI and ERP studies have not entirely agreed with this conclusion. Some researchers have argued that top-down signals play a significant role in visual search, and they attribute bottom-up priming effects to attentional guidance (see Van Der Stigchel et al., 2009).

Behavioral studies examining the endogenous and exogenous orienting of attention yield conflicting results. Certain studies support a unified mechanism for attentional control (Jonides. J, 1981; Warner et al., 1990), while others propose two distinct mechanisms (Müller & Rabbitt, 1989). Nevertheless, the ultimate outcome is cohesive - directing attention to the most pertinent location for an organism's objectives. Additionally, psychologically, the attentional system's selection process is governed by the dynamic interplay between top-down and bottom-up signals (Connor et al., 2004).

The current review discusses the terminology of bottom-up and top-down attention, conflicting results in behavioral experiments, and the suggestion of partial segregation in the brain's network controlling these processes proposed by some researchers (Corbetta & Shulman, 2002) but, some electrophysiological studies have failed to distinguish between related neural activities in the frontoparietal network (Katsuki & Constantinidis, 2012, 2014) which is responsible for target selection and distractor suppression in prefrontal (Cosman et al., 2018) or extrastriate cortex (Klink et al., 2023). Additionally, certain studies using functional magnetic resonance imaging (fMRI) have

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demonstrated that in the extrastriate cortex, both top-down and bottom-up elements play significant roles in perceptual grouping competition (Beck & Kastner, 2007; Kastner et al., 1998). Likewise, the suggested core set of mechanisms in the visual selective attention based on recent discoveries in spatial and feature-based attention (Chapman & Störmer, 2024). It has been suggested that these two attentional oreinting mechanisms are components of the same neural networks, rather than being separate from one another, due to the similarities in the way they influence stimulus representation (Sarter et al., 2001; Treue, 2001). Although there is a growing body of evidence supporting the notion of top-down biasing competition in various cortical regions, resulting from the separate consideration of the top-down/bottom-up mechanisms for deploying attention, it would be worthwhile to explore other biasing mechanisms (bottom-up factors) and determine if they have comparable effects on multiple brain regions (Beck & Kastner, 2009). Stated differently, attention may be regarded as an emerging feature of the comprehensive system, wherein the constituent mechanisms are indivisible (Deco et al., 2002). In this regard, the pulvinar serves as a central hub responsible for integrating bottom-up and top-down factors, which collectively form a single pathway that facilitates selection (Shipp, 2004).

5. Gain Working Memory Is the Ultimate Goal of the Process

According to the framework introduced by Eric I. Knudsen, four processes are fundamental to attentional control: working memory, top-down control, competitive selection, and bottom-up filtering (Knudsen, 2007). Based on this framework, the last three components determine which input information can access working memory by taking into account current biases. The output of the working memory then affects subsequent biases based on the most recently evaluated information. Various studies have shown that working memory influences attention in both voluntary and involuntary ways, depending on the specific task at hand (see Soto et al., 2008). The attentional system plays a significant role in resolving competition in favor of accessing goals information in the working memory. This process ultimately helps the organism to interact with its environment in an effective and appropriate manner.

6. Conclusion

To sum up, the dichotomy of top-down/bottom-up attention has driven researchers to design and conceptualize experiments and explore findings at both the behavioral and neural network levels. Nevertheless, despite mounting evidence, concerns have been raised about the similarities between these two attention mechanisms and their impact on behavior and related neural networks. These issues must be addressed in future research.

In this perspective, all behaviors are intricately linked to the demands of the nervous system in every single moment. As a result, there is no singular objective that can be used to categorize behaviors as either relevant or irrelevant. In essence, it can be inferred that in every moment, there exists an additional goal, which may not be immediately apparent, that is, TO BE ALIVE. The prerequisites of this inherent longing are acquired either through evolutionary processes or the past encounters of the organism.

It is crucial to understand that this perspective yields two significant advantages in the field. Firstly, it provides a framework to carefully contemplate the organism itself and its behavior before delving into the description and analysis of any observed behavior and associated neural activities. This approach encompasses a comprehensive examination from the cellular level to the circuit level. Secondly, it emphasizes the importance of conceptualizing experiments in both design phase and when discussing the results. For instance, if we were to examine the results of a trained subject solely based on a top-down task without taking into account its training history (spanning multiple days), our conclusions regarding brain networks responsible for top-down attention control might be skewed. By disregarding other pertinent factors, we risk overlooking valuable insights that could be derived from a more holistic approach.

It is important to mention that this review does not aim to reject the top-down/bottom-up dichotomy. Instead, it seeks to provide insights into how these terms are intertwined with the current

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goals of an organism throughout its life. The review highlights that an organism's current goals are influenced by its history of learned experiences, immediate demands, and innate demands, even if the organism is not consciously aware of all of them at present.

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