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Review

Attention to pain! A neurocognitive perspective on attentional modulation of pain in neuroimaging studies

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ABSTRACT

Several studies have used neuroimaging techniques to investigate brain correlates of the attentional modulation of pain. Although these studies have advanced the knowledge in the field, important confounding factors such as imprecise theoretical definitions of attention, incomplete operationalization of the construct under exam, and limitations of techniques relying on measuring regional changes in cerebral blood flow have hampered the potential relevance of the conclusions. Here, we first provide an overview of the major theories of attention and of attention in the study of pain to bridge theory and experimental results. We conclude that *load* and *motivational/affective* theories are particularly relevant to study the attentional modulation of pain and should be carefully integrated in functional neuroimaging studies. Then, we summarize previous findings and discuss the possible neural correlates of the attentional modulation of pain. We discuss whether classical functional neuroimaging techniques are suitable to measure the effect of a fluctuating process like attention, and in which circumstances functional neuroimaging can be reliably used to measure the attentional modulation of pain. Finally, we argue that the analysis of brain networks and spontaneous oscillations may be a crucial future development in the study of attentional modulation of pain, and why the interplay between attention and pain, as examined so far, may rely on neural mechanisms shared with other sensory modalities.

1. Introduction

Pain and nociception are not the same phenomena. Nociception refers to the peripheral and central nervous system processes triggered by the activation of nociceptors (Sherrington, 1906). Pain is a subjective experience, one of the possible outcomes of nociceptors activation. Several behavioral studies have shown that pain can induce attentional biases (but see Crombez, Van Ryckeghem, Eccleston, & Van

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Damme, 2013 for an important meta-analysis on the topic), and may interrupt behavior (Eccleston & Crombez, 1999; Moore, Keogh, & Eccleston, 2012). However, attentional manipulations can also modulate the perception of pain and reaction times to nociceptive stimuli, especially when the concurrent pain-unrelated task requires effort and demands cognitive resources (Buhle & Wager, 2010; Legrain, Crombez, & Mouraux, 2011; Romero, Straube, Nitsch, Miltner, & Weiss, 2013; Verhoeven et al., 2011).

In a recent review we offered a critical perspective on the influence of cognition/attention on the electrophysiological responses to nociceptive and painful stimuli, particularly on the functional relationship between attention and the magnitude of event related potentials (ERPs) (Legrain et al., 2012). The aim of the present review is to discuss the contribution of neuroimaging research to the study of attentional modulation of pain and nociceptive inputs with a special emphasis on theoretical and methodological perspectives.[1,2]

The first functional neuroimaging studies on the attentional modulation of pain often referred to 'attention' as a monolithic construct. This was likely motivated by practical operational reasons and by the fact that the concept of attention is difficult to disentangle from the concept of consciousness or executive control. However, attention is not a unitary process. Therefore, it should be considered that different attentional processes can modulate pain and cortical responses to nociceptive stimuli via different mechanisms mediated by different neural substrates (Raz & Buhle, 2006). Here, we will attempt to highlight how interpreting attention as a unitary construct might have led to partially contradictive findings and, occasionally, over-generalized conclusions. We will first outline some key concepts of attention, in particular those relevant for a critical review of neuroimaging studies on the attentional modulation of pain.

1.1. *Attentional processes*

1.1.1. *Selective attention*

Selective attention is one of the most used notions when referring to attention. The concept of selectivity was introduced more than a century ago by James (1890), who defined attention as a restricted focus of consciousness on one out of several objects physically present in the environment. In this view, selective attention would constitute a means to filter the flow of incoming information in order to prioritize the processing of information according to its relevance. Why should it be important to select relevant information? According to the limited-capacity bottleneck theory (Broadbent, 1958), we are unable to process all the available information simultaneously; therefore, a selection is required. Importantly, this limited capacity could be related more to the limited number of actions that an individual can perform rather than the limited amount of sensory information that is processed. In this vein, selective attention would serve to prioritize the processing of information that enables us to select the most relevant among several possible actions (Allport, 1987; Hommel, 2010). This interpretation implies that selective attention to painful stimuli would prioritize escape or defensive actions to maintain the integrity of the body.

1.1.2. *Executive attention*

Executive attention is a concept strictly linked to that of executive functions, proposed as part of attentional processes in the influential theory of attention by Petersen and Posner (2012), Posner and Petersen (1990). Executive attention would refer to the ability to keep the effective processing of a target stimulus regardless of concomitant distraction by irrelevant elements. The concept of executive attention clearly overlaps with that of selective attention (or according to the authors' terminology *focal attention*). However, the definition of 'executive attention' by Petersen and Posner (2012) does not place much emphasis on spatial or motor aspects. Rather, it conceives executive attention as the process that enables us to maintain cognitive control and, for instance, to stay on task while filtering irrelevant distractive information. Moreover, in the Petersen and Posner model, each component of attention is wired in specific brain regions and networks. Executive attention is associated with the activity of the anterior cingulate cortex and networks comprising it (Dosenbach et al., 2007, 2006).

The concept of executive attention is relevant for the study of pain in that it explains why the concomitant execution of pain-unrelated cognitive tasks can prevent the attentional capture by nociceptive/painful inputs (Buhle & Wager, 2010; Legrain et al., 2011; Seminowicz & Davis, 2007a; Van Damme, Gallace, Spence, Crombez, & Moseley, 2009; Van Damme, Legrain, Vogt, & Crombez, 2009; Verhoeven et al., 2011).

Posner and Petersen's theory also describes other types of attention such as *alerting attention*, i.e., the ability to increase and maintain response readiness to an impending stimulus, and *orienting attention*, i.e., the ability to select specific stimuli among multiple sensory stimuli. For this latter concept, the authors refer to the influential work by Corbetta and Shulman (2002) on the dorsal attentional network, which we will explain in the next paragraph.

1.1.3. *Bottom-up versus top-down processes*

Some stimuli are particularly difficult to ignore and capture attention automatically even when they are far away from the focus of attention (Theeuwes, 1991). This involuntary capture of attention is defined as "bottom-up" or "stimulus driven". Bottom-up attention is an exogenous attention, meaning that it is triggered by external cues or events and is opposed to the top-down, endogenous, and often voluntary deployment of attention (Egeth & Yantis, 1997; Knudsen, 2007). While top-down attention allows an individual to focus on what is relevant in terms of goals and motivations, bottom-up capture

[1] Throughout the review, we will refer sometimes to 'nociceptive' and sometimes to 'pain' modulation. The rationale of using either term was based on the terminology used in the reviewed literature. We used the term 'pain' if the original article reported the term 'pain', nociception if it was unclear whether the stimuli could be qualified as painful. Furthermore, the use of the concept 'pain' can be misleading in imaging studies. Indeed, the activation of brain regions in response to nociceptive inputs is not sufficient to be referred to as 'pain' when no subjective report on the perceived quality of the stimulus is available.

[2] In this review, we will elaborate on why attention cannot be considered as a unitary concept. However, we will also use the notion of '*attentional modulation of pain*' as a general term to refer to all possible effects of attention on pain and nociception.