PAIN® 144 (2009) 230–232

PAIN®

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Topical review

A neurocognitive model of attention to pain: Behavioral and neuroimaging evidence

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1. Introduction

The perception of pain is the result of a complex dynamic system that codes, transports and processes nociceptive signals. The relationship between nociceptive information and pain is profoundly affected by affective and cognitive factors [27]. A key role is played by attention, a mechanism by which sensory events are selected and enter awareness. Most literature on attention and pain has been informed by limited-capacity models of human cognition, proposing that sensory signals – including nociceptive ones – exceed processing capacity, and hence require attention to select the signals needed for goal-directed behaviors. Thus, directing attention away from nociceptive information would exclude it from further processing and in this way be analgesic. In this paper, we extend this general model with theories that distinguish between two modes of selection: top-down and bottom-up attention. We present data according to these two modes, integrate behavioral and neuroimaging evidence, and develop a neurocognitive model of attention to pain useful for further research and for the management of clinical pain.

2. Two modes of attentional selection

Multiple events arising from our environment compete for processing making selection a necessity. Some inputs must be prioritized over others to maintain behavioral coherence, to promote or sustain action, and ultimately to serve a super-ordinate goal of survival. Contemporary models incorporate two modes of attentional selection [4,29]. Top-down selection is an intentional and goal-directed process that prioritizes information relevant for current actions. This is achieved by modifying the sensitivity of stimulus-specific neural responses, i.e., by amplifying the activity of neurons that respond to relevant stimuli, and by inhibiting activity of those that respond to irrelevant stimuli [8]. Prefrontal and parietal areas are probably involved in these biasing mechanisms [4]. Bottom-up selection corresponds to an unintentional stimulus-driven capture of attention by events themselves [29]. Attentional capture is often imposed by the most salient stimuli in our environment, independent of intentional control. Salience is defined by the extent to which a stimulus contrasts in one or more perceptual features with surrounding competing stimuli [30]. Also salient are novel stimuli, consisting of events that were never presented before (new stimuli) or infrequently occurring events (deviant stimuli). Several pre-attentional systems are involved in salience and novelty detection. In auditory attention, for example, two separate systems have been identified that detect new and deviant stimuli, and that provide stronger neural activity for these events [13]. Because attention is transiently switched from current goals to these stimuli, it is often a source of distraction (i.e., poorer performance in goal-directed tasks). Although bottom-up attention is unintentional, it is not purely automatic and is influenced by top-down processes, amongst which are attentional load and attentional set. Attentional load refers to the amount of attention invested in a task. When attentional load for a task is high, there is less possibility of attentional capture by task-irrelevant stimuli [17]. The attentional set is the mental set of stimulus features that participants use to identify task-relevant stimuli. When a stimulus, even when it is task-irrelevant, matches one of these features, it will capture attention [29].

3. The bottom-up capture of attention by pain

The involuntary capture of attention by pain is a critical feature of its alarm function. It makes sense that pain should automatically demand attention, interrupt ongoing actions, and prioritize appropriate behaviors to escape from bodily threat. The attentional capture by pain has been demonstrated in behavioral studies using the primary task paradigm [11]. In this paradigm participants are instructed to perform a cognitive task while experiencing task-irrelevant pain. Attentional capture by pain is indexed by the degradation of task performance during pain. Studies showed that attention is unintentionally captured by pain when it is intense, novel and threatening [11].

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doi:10.1016/j.pain.2009.03.020

Neuroimaging studies are increasingly successful in visualizing the brain structures involved. EEG studies suggest that attentional capture by pain is mediated by the brain areas underlying the P2 responses of laser-evoked potentials [18]. P2 amplitude is indeed larger when nociceptive stimuli are novel and particularly salient, even when attention is primarily directed to another part of the body, or to stimuli from another perceptual modality. Noteworthy is the finding that stimuli that elicited the largest P2 amplitude also impaired performance on the primary task [21]. The midcingulate cortex (MCC) is one of the main generators of nociceptive-evoked P2 [14]. This brain structure plays a key role in novelty detection [9], orienting attention [1], and in situations needing adjustments in behavioral control [3]. The MCC might be seen as a crucial brain structure for the orienting of attention to salient and potentially painful stimuli. This role is further supported by PET/fMRI studies [2,10,23]. Because of its close relationship with premotor areas, one may think of the MCC as a structure necessary to prompt urgent motor reaction [14]. Additionally, earlier latency EEG nociceptive-evoked responses, mainly generated in operculo-insular areas, are also sensitive to salience and novelty [16,21]. Operculo-insular areas may also reflect systems involved in detecting salient and novel events by providing stronger neuronal responses to nociceptive stimuli.

4. The top-down modulation of attentional capture by pain

The bottom-up capture of attention to pain can be modulated by top-down variables. Numerous behavioral studies have shown reduced pain when attention is directed away from nociceptive stimuli [28]. EEG studies showed that the amplitude of the P2 component of nociceptive evoked potentials is decreased when participants are performing a more demanding visual task (attentional load hypothesis) [19]. Neuroimaging studies have revealed that responses to nociceptive stimuli in the MCC, paracentral (SI/MI) and operculo-insular areas are decreased when attention is strongly invested in a primary visual task [2,25,26]. The observation that the responses in the primary and secondary somatosensory cortices are influenced by a manipulation of attentional load supports the hypothesis that top-down attention affects the processing of nociceptive stimuli at early levels by biasing somatosensory brain activity [20]. As a consequence, the neuronal responses to nociceptive stimuli are weaker and less effective in orienting attention. This explains why pain is reduced when attention is invested in the primary task [2].

In other situations top-down variables may facilitate attentional capture. For example, attention can be more easily captured by pain when irrelevant nociceptive stimuli share perceptual features with task-relevant targets (attentional set hypothesis). The nociceptive-evoked P2 response is larger when nociceptive stimuli are delivered to an attended part of the body (i.e., where task-relevant targets are expected to occur) [20]. Mutatis mutandis, individuals who expect somatosensory stimuli to be very painful, show more attentional interruption by non-painful somatosensory stimuli that are delivered at the same location [5]. This is especially the case for participants who report fear and catastrophic thoughts about pain [6]. Noteworthy are the findings that pain catastrophizing is associated with greater activity in operculo-insular and MCC areas [24].

It is well documented that the prefrontal and parietal areas are involved in the top-down modulation of attention towards nociceptive [27] and non-nociceptive stimuli [4]. Their precise role concerning pain remains unclear. Some insight may come from research on visual attention. Experiments in which the interaction between bottom-up and top-down attention was manipulated, suggest that the dorsolateral prefrontal cortex (DLPFC) is involved in maintaining goal-relevant priorities, principally by loading executive functions onto the processing of task-relevant information in order to avoid interference by goal-irrelevant information [17]. Concerning the parietal cortex, the intraparietal sulcus (IPS) was proposed to constitute a priority map of attention that attunes neural responses in sensory brain areas in favor of responses specific to the to-be-attended inputs [30]. We propose that the DLPFC and the IPS may help to maintain respectively attentional load and attentional set, to prevent attentional capture and interference by painful stimuli. More experimental research is needed to identify how exactly control over attentional capture by pain is achieved in the brain.

5. Implications

The above-reviewed data demonstrate that orienting attention to nociceptive events depends on both bottom-up and top-down influences (Fig. 1) [18]. The bottom-up factors act to signal the detection of salient events and to give these events a stronger neuronal representation. This salience detection can be held by operculo-insular areas, and by the MCC that triggers an attentional bias to nociceptive signals. This biasing influence may also be modulated by top-down factors. We conceptualize top-down modulators as acting through attentional load and attentional set. Attentional load corresponds to the effort made to invest available attention to primary goals. Attentional load can be supported by the DLPFC that maintains goal priorities by assigning executive functions to the primary task. An attentional set refers to a mental

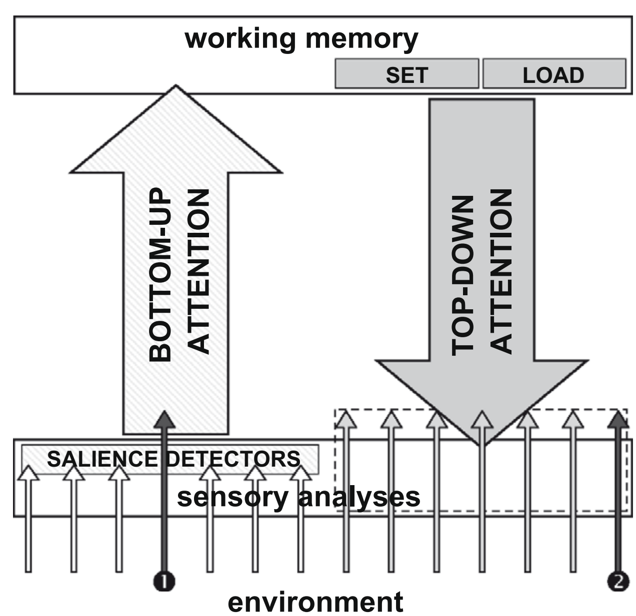

Fig. 1. Constantly confronted with multiple sensory signals (bottom arrows), the brain has to select signals that are most relevant for behaviors and gives them priority access to working memory for conscious processing. Two forms of selection can be achieved. Bottom-up selection consists of the capture of attention triggered by sensory stimuli themselves, and is initiated by pre-attentional detectors that identify salient stimuli (black arrow #1) and give them stronger neural responses to prioritize their processing. Top-down selection is directed by cognitive goals activated in working memory. Goals define the stimulus features that are task relevant (attentional set) and the amount of attention deployed to achieve the task (attentional load). Top-down selection increases the neural responses to goal-relevant signals (grey arrows) and inhibits the responses to goal-irrelevant signals (white arrows). The model predicts that when we try to discard attention from pain, a nociceptive stimulus can still capture attention in two ways (1) when it is salient enough (black arrow #1) and (2) when it shares one of the perceptual features defined by the attentional set (black arrow #2). (Adapted from [18].)

array of stimulus features that the individual is attending to for identifying goal-relevant information. All stimuli (including distracters) that meet one or more of these features will capture attention. The attentional set may depend on local goals (i.e., task instruction) but also on general homeostatic goals (i.e., response to body-threatening stimuli). This ability can be related to the activity of the IPS which represents relevant features of the stimuli, facilitates neural responses to attended features, and inhibits responses to unattended features. These ideas are based on a dynamic model in which the attentional modulation of pain depends on a balance between bottom-up and top-down influences, but need to be systematically investigated.

This model allows us to generate hypotheses for clinical research. Much of the relevant research to date has been with experimentally induced pain. Typically, experimental pain is expected and delivered under controlled conditions. Although there are clinical situations in which pain is both expected and its delivery is controlled (e.g., procedural pain), naturally occurring pain often arises in more complex environments (e.g., pain from injury occurring with little or no warning). Modeling acute pain remains a significant scientific and ethical challenge. Also relevant is the case of persistent or recurrent pain. Chronic pain patients often display cognitive deficits, and can be impaired in the performance of cognitively demanding tasks [15]. These deficits are often explained in terms of anxiety, or in terms of the specific construct of a "hypervigilance" to pain, i.e., a tendency to increase attentional allocation to pain-related information [7]. The neurocognitive model helps to refine the aspects of attention affected in clinically relevant pain. Salience detectors can be highly sensitive to somatosensory inputs (bottom-up hypothesis). Equally possible is that patients are unable to exercise executive control over nociceptive interference (top-down/attentional load hypothesis). Largely unexplored is the role of executive functions in patients suffering from pain. Another possibility is that patients maintain features of excessive somatosensory expectations within their attentional set (top-down/attentional set hypothesis). This might be related to habits to attend to bodily sensations in general, but may also be related to the persistent search for pain relief in patients [12]. Finally, the model provides guidance on the cognitive deficits that chronic pain patients may display. Neuropsychological assessment should be targeted at specific rather than global deficits in cognitive functioning, particularly attentional inhibition, attentional switching, and prospective memory. Similarly, attention management may be a more important component of cognitive behavioral rehabilitation than traditionally considered [22].

Acknowledgements

The paper results from the Special Interest Meeting "Symptom Perception and Illness Behaviour" in Belgium and was supported by a FWO (Flanders) Grant (WO.001.07N). V.L. is supported by the EFIC-Grünenthal Grant. S.V.D. is a postdoctoral researcher of the Fund for Scientific Research Flanders, Belgium (FWO). G.C. is partially funded by a Ghent University Research Grant (GOA 01G00106). We thank Miss Gaëlle Meert (Université catholique de Louvain, Belgium) for her insightful comments and her help with the figure. The authors have no conflict of interest related to the editorial.

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