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The role of working memory in the attentional control of pain

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ABSTRACT

Attention is acknowledged as an important factor in the modulation of pain. A recent model proposed that an effective control of pain by attention should not only involve the disengagement of selective attention away from nociceptive stimuli, but should also guarantee that attention is maintained on the processing of pain-unrelated information without being recaptured by the nociceptive stimuli. This model predicts that executive functions are involved in the control of selective attention by preserving goal priorities throughout the achievement of cognitive activities. In the present study, we tested the role of working memory in the attentional control of nociceptive stimuli. In the control condition, participants had to discriminate the color of visually presented circles preceded by tactile distracters. In some trials (20%), tactile stimuli were replaced by novel nociceptive distracters in order to manipulate the attentional capture. In the working memory condition, participants had to respond to the visual stimulus presented one trial before, and were thus required to maintain the color of the visual stimulus in working memory during the entire inter-trial time interval. Results showed that, while novel nociceptive stimuli induced greater distraction than regular tactile stimuli in the control condition, the distractive effect was suppressed in the working memory condition. This suggests that actively rehearsing the feature of pain-unrelated and task-relevant targets successfully prevents attention from being captured by novel nociceptive distracters, independently of general task demands.

1. Introduction

The perception of pain depends on the attention that is allocated to a nociceptive stimulus. Directing attention away from a nociceptive stimulus has been shown to reduce pain effectively [54]. However, because pain signals the occurrence of potential tissue damage, nociceptive stimuli are able to capture attention despite voluntary control [24]. A recent model states that the effective attentional control of pain does not simply imply the disengagement of attention, but depends also on cognitive factors that guarantee that attention is maintained on the processing of pain-unrelated information without being recaptured by the nociceptive stimuli [39]. Indeed, experiments have shown that the ability of nociceptive stimuli to capture attention can be modulated by top-down factors [16,17,35,36,53].

In this frame, involvement of executive functions is outlined [39]. The present study aimed to investigate the role of working memory in the control of the attentional capture by nociceptive stimuli. Working memory is involved in the short-term maintaining and storing of information for its immediate manipulation [3–5]. It is suggested to regulate the top-down control of attention by maintaining current processing priorities during task performance [12,20]. Indeed, working memory has been shown to facilitate selective attention by maintaining the features of the relevant targets active and by preventing interference from irrelevant distracters [7,18,19,23,31–33,46].

Different paradigms have been proposed to explore the bottom-up capture of attention by nociceptive stimuli [13,38,53,54]. These studies have shown that the ability of a nociceptive stimulus to capture attention is based on mechanisms that are unspecific of nociception, such as mechanisms involved in the detection of novelty, which constitutes an important determinant of stimulus salience [21,39]. Therefore, in order to increase the ability of nociceptive stimuli to capture attention, we used a selective attention paradigm in which nociceptive stimuli were made novel and irrelevant for current cognitive goals [25–28,38,46,47,57,58]. Participants were confronted with a series of task-relevant visual targets shortly preceded by a task-irrelevant somatosensory tactile distracter. Occasionally, the tactile distracter was replaced by a nociceptive distracter. Contrasting the performance to visual targets following a novel nociceptive distracter and the performance to visual targets following a standard tactile distracter thus constituted an index of the capture of attention [26].

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The role of working memory in the control of attention towards nociceptive stimuli was investigated with 2 task conditions [46]. In the first condition, participants had to respond to the visual target directly after its presentation. Thereby, working memory was reset after each trial. In the second condition, participants were asked to delay their response until the presentation of the next target. Working memory was thus kept active during the entire time interval separating the 2 targets, and the representation of the correct response had to be rehearsed during the presentation of the somatosensory distracters [51]. We hypothesized that if working memory is involved in the control of attention, the active rehearsal of the visual target would prevent the intrusion of the distracter. Hence, distraction, that is, deterioration of performance induced by novel nociceptive distracters, would be reduced.

2. Methods

2.1. Participants

Participants were 10 healthy volunteers (mean age 30 ± 6 years; 4 women; 1 left-handed), with normal or corrected-to-normal vision, no prior history of neurological, psychiatric, or chronic pain disorders and no current psychotropic or analgesic drug use. Participants provided written informed consent. Experimental procedures were approved by the local Ethics Committee.

2.2. Stimuli

Non-nociceptive somatosensory stimuli were constant-current square-wave electrical pulses (DS7 Stimulator, Digitimer Ltd, Hertfordshire, UK) of 0.5-ms duration delivered with a pair of skin electrodes (0.7-cm diameter, 2.5-cm interelectrode distance) placed on the left forearm, close to the wrist, over the superficial branch of the radial nerve (with the anode at the proximal location). For each participant, stimulus intensity was adjusted to elicit a tactile sensation or a nonpainful paresthesia in the corresponding sensory territory. The intensity was set at 1.5 times above the absolute detection threshold (mean: 0.89 ± 0.15 mA, ranging from 0.60 to 1.10 mA). This range of intensity was assumed to be above the threshold of Aβ fibers, but well below the threshold of nociceptive Aδ and C fibers [40].

Nociceptive somatosensory stimuli were pulses of radiant heat (50-ms duration) generated by an infrared CO_2 laser (10.6-μm wavelength; Université catholique de Louvain) (see [44]). Stimulus target, visualized by a coaxial He–Ne laser beam, was the sensory territory of the superficial branch of the radial nerve on the left hand. Beam surface area at target site was ~80 mm^2. For each participant, stimulus energy was adjusted to elicit a clear pinprick sensation, perceived as slightly painful, and related to the activation of Aδ fiber skin nociceptors (M = 790 ± 120 mJ; ranging from 620 to 930 mJ). To prevent nociceptor fatigue, sensitization, and skin overheating, the laser beam was displaced after each pulse.

Visual stimuli were presented on a 17″ cathode-ray tube monitor placed in front of the participant. Stimuli were colored circles presented at the fixation point at the center of the screen on a black background. Stimuli subtended 5.3° vertical and horizontal angles (6.5-cm diameter at a 70-cm distance). Inner-circle color was either blue (RGB 0∗0∗255) or yellow (RGB 255∗255∗0).

2.3. Procedure

The experimental paradigm is illustrated in Fig. 1. Participants were presented with 8 blocks of 60 trials on 2 different sessions (4 blocks per session). Time between sessions was between 2 and 10 days. During the entire block, a fixation cross was present at the center of the monitor. Each trial consisted of a pair of stimuli, starting with a somatosensory stimulus (tactile or nociceptive) followed shortly by a visual stimulus. The inter-trial time interval was 3000 ms, measured from onset to onset between 2 consecutive visual stimuli. The visual stimulus duration was 500 ms. Interstimulus time intervals (ISI) between the somatosensory and the visual stimuli varied according to the type of somatosensory stimulus, to account for the difference between the conduction velocities of Aβ and Aδ fibers [41]. Indeed, to reach their respective cortical receivers, Aδ fiber nociceptive input may be expected to require ~80 ms more than Aβ fiber nonnociceptive input [41,52]. For this

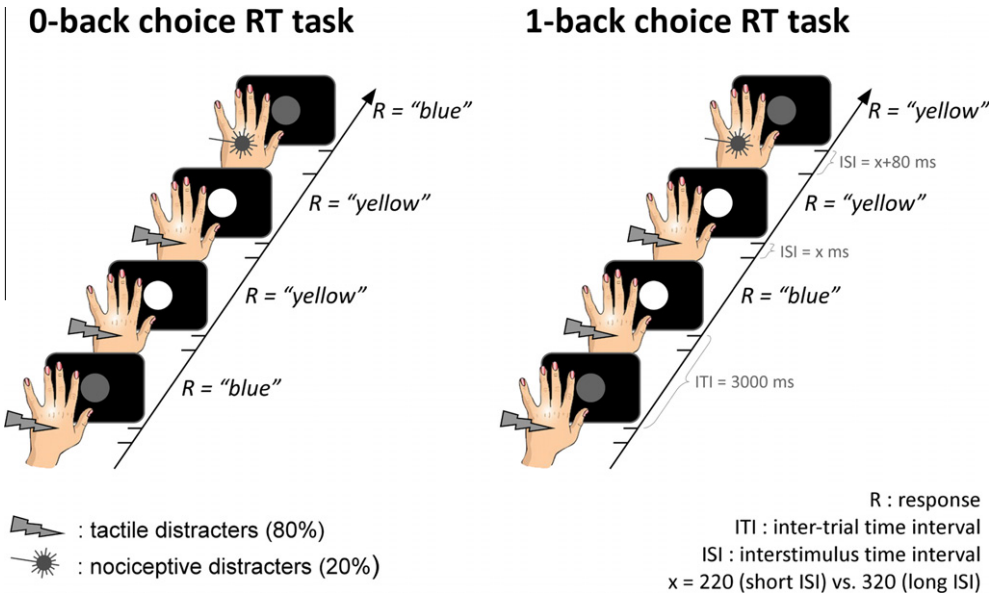

Fig. 1. Experimental paradigm. In the 0-back choice reaction-time (RT) task participants were asked to discriminate the color of each circle presented on the screen as fast and as correctly as possible (blue circles are represented in gray, yellow circles in white). In the 1-back RT task, they were asked to respond to the color of the circle presented one trial before and to rehearse the target color during the inter-trial interval (ITI). Each visual stimulus was shortly preceded by a somatosensory stimulus on the left hand that could be an electrocutaneous tactile stimulus in 80% of the trials or a laser nociceptive stimulus in 20% of the trials. ITI was 3000 ms. Inter-stimulus time interval (ISI) between the somatosensory stimulus and the visual stimulus was 220 ms (short ISI) or 320 ms (long ISI) when the somatosensory stimulus was tactile, and 300 ms (short ISI) or 400 ms (long ISI) when it was nociceptive.

reason, ISI was 320 ms for tactile-visual trials and 400 ms for nociceptive-visual trials during one experimental session (long ISI), and 220 and 300 ms, respectively, during the other experimental session (short ISI). Long and short ISIs were used to test the critical time delay between the somatosensory distracter and the visual target during which interference effects from the distracter on the target can be observed. This kind of experimental paradigm was initially designed for event-related potential studies (see [26] for review). Therefore, the time interval between the distracter and the target was set in order to avoid, as much as possible, overlap between the brain potentials evoked by the distracters and the potentials evoked by the targets. However, we know from pilot experiments conducted in the frame of present and previous studies [38] that the time interval between the distracter and the target is critical to observe significant difference between regular distracters and novel distracters. Within each block, the trials were pseudo-randomly delivered with the following restrictions: (i) the probability of occurrence was 0.8 for tactile-visual trials (48 per block) and 0.2 for nociceptive-visual trials (12 per block); (ii) 2 consecutive nociceptive-visual trials were separated by at least 3 tactile-visual trials; (iii) the 4 first trials never contained a nociceptive stimulus; (iv) the probabilities of responses "*yellow*" or "*blue*" were equivalent; (v) the proportion of responses "*yellow*" vs "*blue*" associated with the nociceptive and the tactile stimuli were the same (i.e., one block contained 6 nociceptive trials associated with a response "*yellow*" and 6 nociceptive trials associated with a response "*blue*"); (vi) the proportion of *repetition/no-conflict responses* vs *alternation/conflict responses* (see below) was nearly equivalent (less than 5% difference); (vii) this equivalence was maintained across the 2 types of somatosensory distracters.

Participants were instructed to pay attention to the visual stimuli and to respond to the color of each circle by pressing the corresponding key with their right middle and index fingers on the numerical pad of a computer keyboard (2-choices reaction-time task). They were asked to respond as accurately and as fast as possible. They were encouraged to focus on the visual task and to ignore the somatosensory stimuli that were presented to them as "*distracters used to increase task difficulty*." They were not informed about differences in probability of occurrence between nociceptive-visual and tactile-visual trials. For each session, during 2 blocks, participants were asked to report the color of the visual stimulus that was currently presented (0-back condition). During the 2 other blocks, they were asked to respond to the stimulus that was presented on the preceding trial (1-back condition). Sessions were balanced and the order of the blocks was randomized for each participant. Prior to the experimental session, participants were familiarized to visual stimuli and practiced the 1-back task with a block of ~20 visual stimuli without any associated somatosensory stimulus. During the 1-back condition, participants were encouraged to mentally and phonologically rehearse the target color during the interval between visual stimuli. They were told that rehearsal was "*the only way to perform the memory task correctly*." Participants were also instructed to keep both fingers on the response keys. This instruction prevented them from cueing the correct response simply by positioning the correct finger on the key and, subsequently, from using this proprioceptive and/or tactile information to respond.

2.4. Analyses

Eight conditions resulted from the combination of the 3 different independent variables: *somatosensory distracter* (tactile vs nociceptive), *working memory* (0-back vs 1-back), and *inter-stimulus interval* (long vs short). Performance of the visual task was measured by the mean reaction times (RTs) for speed, and the percentage of errors for accuracy. For each condition, RTs were averaged using only trials with correct responses. The first responses of each block, as well as the responses with RTs <150 ms or >1000 ms were rejected. Errors were expressed as the percentage of incorrect responses (i.e., wrong key pressed), and anticipations as the percentage of responses with RTs <150 ms, relative to the total number of trials per condition (96 tactile stimuli, 24 nociceptive stimuli). Reaction times, error and anticipation ratios were analyzed using a 2∗2∗2-factors analysis of variance (ANOVA) for repeated measures. An index of the effect of novelty was also computed by subtracting RTs to the visual targets following a novel nociceptive distracter from RTs to the visual targets following a regular tactile distracter. A one-sample Student's *t*-test was used to test whether this index was significantly different from zero.

Typically, working memory paradigms do not only involve storing and rehearsal but also involve executive control such as updating and conflict monitoring [4,50,56]. In the present 1-back condition, interference between the memory template of the preceding stimulus and the current stimulus could occur (e.g., the preceding target is yellow, the correct response is "*yellow*," but the current stimulus is blue) and this conflict requires inhibition of the incorrect response (e.g., "*blue*"). Therefore, 1-back trials with conflict (i.e., trials in which the correct response and the current stimulus differed) were separated from 1-back trials without conflict (i.e., trials in which the correct response and the current stimulus were identical), such as to conduct an ANOVA with ISI, conflict, and somatosensory stimulus type as factors. Similarly, in a simple reaction-time task, a cost due to alternating the response (e.g., a "*yellow*" trial occurring after one or more "*blue*" trials) can be observed (e.g., see [42,49]). Therefore, in the 0-back condition, trials with alternation (i.e., trials in which the correct response differed from the preceding response) were separated from trials without alternation (i.e., trials in which the correct response was identical to the preceding response), such as to conduct an ANOVA with ISI, alternation, and somatosensory stimulus type as factors.

When appropriate, contrast analyses were used. Effect sizes were expressed with partial Eta-squared for ANOVA and with Cohen's d for *t*-tests. Significance level was set at $P \leqslant 0.050$.

3. Results

The global mean error ratio was 1.85%. Analyses only revealed a significant working memory ∗ ISI interaction ($F_{1,9} = 17.33$, $P = 0.002$, $\eta^2 = 0.658$). With short ISIs, participants made less errors in the 1-back than in the 0-back condition (1.04% vs 1.82%: $F_{1,9} = 5.55$, $P = 0.043$, $\eta^2 = 0.381$). With long ISIs, the reverse – but not significant – trend was observed (2.97% vs 1.56%: $F_{1,9} = 3.64$, $P = 0.089$, $\eta^2 = 0.288$). Importantly, there was no interaction with the type of somatosensory distracter ($F_{1,9} = 0.26$, $P = 0.876$, $\eta^2 = 0.003$).

Participants did not anticipate responses in the 0-back condition, whereas 4.30% of the responses were anticipated in the 1-back condition ($F_{1,9} = 18.78$, $P = 0.002$, $\eta^2 = 0.676$). Again, there was no interaction with stimulus type ($F_{1,9} = 1.04$, $P = 0.334$, $\eta^2 = 0.104$).

Mean RTs of correct responses are shown in Fig. 2A. The main result from the ANOVA was the significant interaction of the type of somatosensory distracter and working memory ($F_{1,9} = 12.93$, $P = 0.006$, $\eta^2 = 0.590$), with no significant main effect of the type of somatosensory stimulus ($F_{1,9} = 4.34$, $P = 0.067$, $\eta^2 = 0.325$). In the 0-back condition, RTs to visual targets were increased when targets were preceded by a novel nociceptive stimulus as compared to a regular tactile stimulus ($F_{1,9} = 7.59$, $P = 0.022$, $\eta^2 = 0.458$). In contrast, in the 1-back condition, there was no significant difference between tactile-visual and nociceptive-visual trials ($F_{1,9} = 0.01$, $P = 0.928$, $\eta^2 = 0.001$). This was confirmed by the analysis of difference indexes (RTs to nociceptive-visual trials *minus* RTs to tactile-visual trials). Fig. 2B shows that the difference was ~35 ms in the 0-back condition, whereas it was ~0 ms in the 1-back condition. The difference observed in the 0-back condition was significantly different from

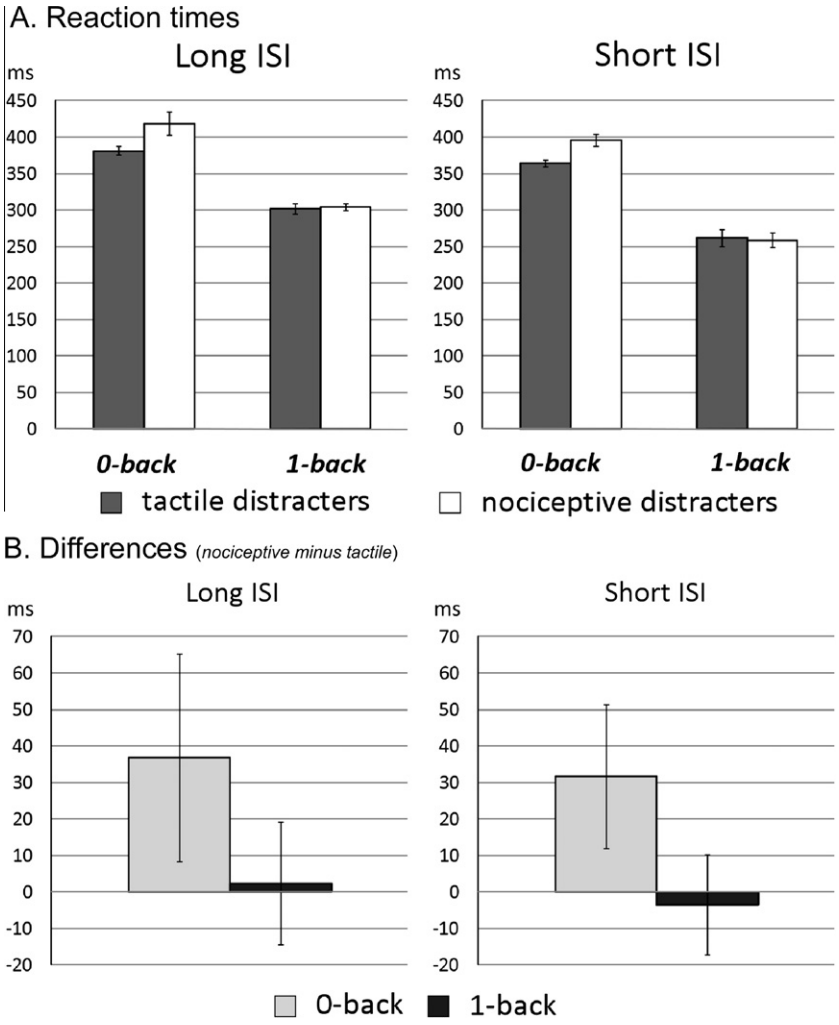

Fig. 2. (A) Mean reaction times (RTs) to visual stimuli (in milliseconds) according to ISI, working memory, and the type of somatosensory distracter. The left graphic illustrates the RTs during the session with long inter-stimulus time interval (ISI) between the somatosensory distracter and the visual target, the right graphic during the session with short ISI. Dark gray boxes represent RTs to visual stimuli that followed regular tactile stimuli, white boxes RTs to visual stimuli that followed novel nociceptive stimuli. Because mean RTs were analyzed in a within-subject design, error bars illustrate confidence intervals [11]. (B) Differences between the 2 conditions (*nociceptive-visual RTs minus tactile-visual RTs*), according to ISI and working memory. Light gray boxes represent RTs in 0-back condition, black boxes in 1-back condition. Because differences were analyzed with single-sample *t*-tests, error bars illustrate standard deviations.

zero with short ISIs ($t_9 = 3.41$, $P = 0.008$, $d = 1.077$), but failed to reach significance with long ISIs (long ISI: $t_9 = 2.14$, $P = 0.061$, $d = 0.676$). The difference observed in the 1-back condition was not significantly different from zero, either with long ($t_9 = 0.38$, $P = 0.710$, $d = 0.121$) or with short ISIs ($t_9 = -0.69$, $P = 0.506$, $d = 0.219$).

Additionally, the ANOVA revealed that short ISI duration decreased global RTs to visual targets ($F_{1,9} = 11.28$, $P = 0.008$, $\eta^2 = 0.556$) and that RTs were also decreased by the involvement of working memory in the 1-back condition ($F_{1,9} = 88.05$, $P < 0.001$, $\eta^2 = 0.907$). Despite a significant interaction between the 2 factors ($F_{1,9} = 9.01$, $P = 0.015$, $\eta^2 = 0.500$), the effect of working memory was not significantly influenced by ISI duration (short ISI: $F_{1,9} = 71.76$, $P < 0.001$, $\eta^2 = 0.889$; long ISI: $F_{1,9} = 98.53$, $P < 0.001$, $\eta^2 = 0.916$). All other ANOVA effects were not significant (all $P > 0.067$, all $\eta^2 < 0.325$).

Analyses of the effects of response conflict in the 1-back task (Fig. 3) revealed a significant effect of conflict ($F_{1,9} = 6.50$, $P = 0.031$, $\eta^2 = 0.419$), suggesting a processing cost during conflict between the correct response and the current stimulus. This effect did not interact with the type of somatosensory distracter ($F_{1,9} < 0.01$, $P = 0.971$, $\eta^2 < 0.001$), and there was no significant main effect of the somatosensory distracter ($F_{1,9} = 0.02$, $P = 0.895$, $\eta^2 = 0.002$). Because conflict can increase task demands and affect performance [50], and because it is known that task demands can modify nociceptive processing independently of which executive function is involved in the pain-unrelated primary task [9,39], results were reanalyzed after excluding the conflict 1-back trials from the data set. The results obtained after exclusion are identical to those obtained when including all 1-back trials. Indeed, the analysis of variance still revealed a significant interaction between the type of somatosensory distracter and the working memory task ($F_{1,9} = 7.91$, $P = 0.020$, $\eta^2 = 0.468$), with no significant main effect of distracter type ($F_{1,9} = 4.86$, $P = 0.055$, $\eta^2 = 0.351$). This indicates that the results cannot be attributed to the conflict more specifically involved in the 1-back condition. Conversely, the analyses of the effect of response alternation in the 0-back task did not reveal a main effect of response alternation ($F_{1,9} = 0.02$, $P = 0.880$, $\eta^2 = 0.003$), although there was a slight but significant interaction between response alternation and the type of somatosensory stimulus ($F_{1,9} = 5.17$, $P = 0.049$, $\eta^2 = 0.365$): the effect of distraction was greater when the response was repeated ($F_{1,9} = 8.08$, $P = 0.019$, $\eta^2 = 0.473$) as compared to when the response had to be alternated ($F_{1,9} = 3.99$, $P = 0.077$, $\eta^2 = 0.307$). Again, RTs were shorter with short than with long ISIs

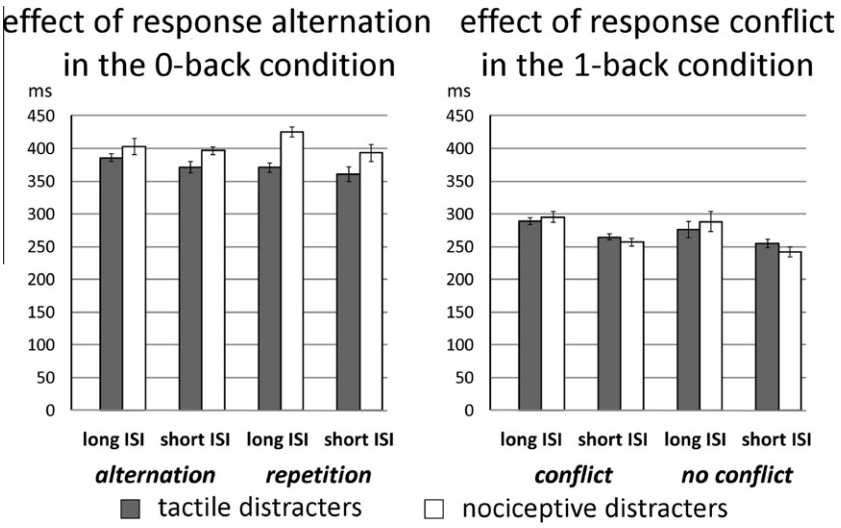

Fig. 3. Mean reaction times (RTs) to visual stimuli (in milliseconds) according to the response alternation/conflict variable. The left graphic illustrates the RTs during the 0-back choice RT task condition, the right graphic during the 1-back condition. Dark gray boxes represent RTs to visual stimuli that followed a regular tactile distracter, white boxes represent RTs to visual stimuli that followed a novel nociceptive distracter. Error bars represent confidence intervals [11].

(1-back: $F_{1,9} = 13.60$, $P = 0.005$, $\eta^2 = 0.602$; 0-back: $F_{1,9} = 9.86$, $P = 0.012$, $\eta^2 = 0.523$), but that factor did not interact with other variables (all $P > 0.065$, all $\eta^2 < 0.329$).

4. Discussion

In the present study, we demonstrated that when participants are engaged in a visual task, the involvement of working memory in task performance can prevent the participants from being distracted by the occurrence of a novel nociceptive stimulus.

We employed a paradigm designed to explore the involuntary capture of attention by exogenous sensory events [1,25,27,28,38,46,47,57,58]. Using a similar paradigm, it was previously shown that the occurrence of nociceptive task-irrelevant stimuli can interfere with the processing of visual targets, especially when the nociceptive stimuli are contextually novel [38]. Indeed, as compared to standard nociceptive stimuli, unexpected novel nociceptive stimuli elicited brain responses of larger magnitude, and, in turn, the brain responses elicited by the subsequent visual target were reduced at a latency compatible with late perceptual analysis occurring before response selection [55]. As a consequence, because the processing of the visual target was altered, a cost in the behavioral response to the target was observed (delayed reaction times). It indicates that nociceptive task-irrelevant distracters, due to their novelty, induce distraction by affecting the processing of the relevant visual targets. As demonstrated by experiments having manipulated attention in a cross-modal fashion [54], it also shows that mechanisms underlying nociceptive processing largely share resources with the processing underlying the perception of stimuli belonging to other sensory modalities [38,40]. In the present study, the novelty of the somatosensory distracters was characterized by a difference in their perceptual quality. In other words, we created a context that rendered nociceptive stimuli highly likely to capture attention. Indeed, novelty, which is increased by reducing the probability of occurrence of the stimulus, is acknowledged to constitute a crucial factor determining the ability of any sensory event to involuntarily capture attention [22,30,34–38,40]. Frequent tactile stimuli were included in order to avoid any confounding effect between selective attention and alerting attention [29]. The present study confirms the results reported by previous experiments having shown impairments of performance in choice RT tasks produced by the interference of nociceptive stimuli [13–16,38,53]. The moderate effect observed with long ISIs points to the role of the sensory context in the capture of attention (e.g., overlap in time increases competition [14]). This could explain why several previous studies have failed to find significant competitive effects between the processing of nociceptive and non-nociceptive stimuli (see [9]). Selective attention is requested when competition between different interfering stimuli exceeds the limits of processing capacity, while their respective processing can be achieved with low interference when the competition is below those processing limits [2,21,43].

The primary objective of the present study was to examine the role of working memory in controlling the capture of attention by nociceptive stimuli. To achieve this aim, we used a simple discrimination task in 2 conditions. In the 2 conditions, the task was highly similar: participants were asked to discriminate the color of visual targets and to respond to the correct color by pressing the corresponding button. Both conditions engaged the same perceptual and action processes, but in the 1-back condition, the response to the current target had to be delayed until the next trial. Therefore, during the time interval between 2 visual targets, during which the somatosensory distracter was presented, working memory was occupied with the representation of the correct target. In the 0-back condition, working memory could be reset after each trial. Results showed that when participants were asked to rehearse their response in working memory in order to perform the task correctly, a marked reduction of distraction induced by novel nociceptive distracters was observed. Indeed, in the 1-back condition, there was no difference between the RTs to visual targets following a regular tactile stimulus and the RTs to visual targets following a novel nociceptive stimulus. The role of working memory in selective attention has also been evidenced in studies exploring other sensory modalities, in particular the visual modality [31–33]. These studies have shown that participants are less efficient to control intrusion of distracters in visual tasks when working memory resources are used in a second unrelated task [18,19,31,33]. Furthermore, functional magnetic resonance imaging and event-related potential studies have shown that the control of distraction by working memory may be achieved through an inhibition of the central sensory processing of the distracters [19], as well as an inhibition of the brain processes controlling the orientation of attention [7,46]. Therefore, it can be suggested that the reduction of the attentional capture by nociceptive stimuli induced by

engaging working memory is likely to decrease their further processing and, consequently, to reduce pain [9].

Alternative interpretations of our results should be considered. We observed that response latencies obtained in the 1-back condition were globally shorter than those obtained in the 0-back condition, probably because, for each new 1-back trial prompting a response, the preceding target is already processed and the response probably selected [50,51] (however, participants had to rehearse the representation of the response before its execution). Therefore, it could be argued that distraction was modified due to differences in general task demands [33,39]. Indeed, in order to "*distract*" attention from pain, previous studies have used tasks involving executive functions (eg, [6,8,35,45,48]). However, because these studies have compared tasks with different levels of difficulty, modulation of nociception and pain can be attributed to differences in the allocation of general attentional resources independently of the processes specifically involved in the task [9]. In the present study, it is unlikely that the results could be attributed to differences in task difficulty and demands. First, the 2 conditions differed mainly by the fact that the 1-back condition required to rehearse the representation of the target during the time interval separating its occurrence and the execution of the response. Second, our measures of behavioral performance did not reveal specifically more demand in the 1-back condition. Indeed, working memory did not significantly increase the error ratios and facilitated response latency, suggesting an overall benefit, instead of a cost, of working memory on performance. Third, a reduction of the disruptive effect of novel nociceptive distracters was similarly observed both in the more demanding trials (ie, trials with conflict between the correct response and the current target) and in the less demanding trials (ie, trials without conflict).

A second alternative explanation could be that our results reflect a difference in terms of the level at which the processing of the target is disrupted by the distracter. Indeed, the intrusion of the somatosensory distracter occurred during the evaluation of the visual target during the 0-back condition, while it occurred just before the execution of the response during the 1-back condition. One could argue that response execution is less sensitive to distraction. However, this alternative interpretation is contradicted by previous studies having shown that action *is* sensitive to distraction [10].

According to the model of Baddeley and Hitch, working memory is composed of a central executive component and slave rehearsal/store components [3–5]. The central executive is a supervisory system binding information from different sources (ie, from perception and long-term memory), regulating the processing of this information and coordinating the slave systems. The slave systems are involved in the temporary store and rehearsal of verbal, visuospatial, and biographic information. Despite the fact that modulation of the store/rehearsal systems constituted the primary aim of the present study, the involvement of the central executive cannot be ruled out. N-back tasks involve memory updating in order to refresh the memory template with the new targets [56]. However, a role for updating in the present study is unlikely because updating occurred only after response delivery and, therefore, after the processing of the new target. In addition, the role of conflict monitoring seems to have been minimized in the 1-back condition because no difference between tactile and nociceptive distracters was observed in the visual task, even in the trials with no conflict. In turn, in the 0-back condition, while rehearsal was not required, conflict monitoring could have been involved when the response to the current target competed with the response to the previous target (alternation trials) [42,49]. However, no main effect of response alternation was identified, although response alternation did slightly reduce the disrupting effect of the nociceptive distracter. Further research is needed to explore which components of working memory might be effective in controlling attention to nociceptive stimuli, and how pain can be affected by such a modulation.

Our results suggest that working memory is likely to be actively involved in inhibiting the ability of nociceptive stimuli to capture attention and thereby, in preserving the performance of pain-unrelated cognitive activities. The knowledge of such a control could be useful to adapt and test the effectiveness of psychotherapeutic strategies for pain management. Indeed, there is growing evidence that some chronic pain patients are characterized by an excessive attentional profile, making them over-attentive to pain-related signals [54]. Based on present results, we can suggest that this over-attentiveness may result from an inability to inhibit the intrusion of nociceptive input in working memory. Therefore, strategies to cope with pain could involve high executive control exercised on information processing in order to exclude, as much as possible, pain-related information from cognitive priorities and task setting.

Conflict of interest statement

The authors have no conflict of interest related to the present article.

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