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Pain and Attention: Attentional Disruption or Distraction?

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Abstract: The effect of pain processing on attention capacity during visual search was examined in 2 experiments. In the first experiment, we investigated whether pain draws on the same limited resources as attentional task performance. It was hypothesized that pain would negatively affect task performance under different load manipulations. Low and high load conditions of a visual search task were presented in a mixed design combined with a painfully cold or neutral cold pressor test. Performance was not affected by pain. In experiment 2, low and high load conditions were separated in different blocks to study whether pain perception was affected when task load could be anticipated. Again, pain did not significantly affect task performance. In contrast, subjective pain intensity scores were significantly lower after performing the high load compared with the low load condition. Simultaneous recordings of event-related potentials indicated an increased negativity during the pain compared with the control condition. Also, in the early (350 to 450 msec) interval of event-related potentials, an increase in negativity was found for the high load compared with the low load condition. Topographic distributions suggested that pain and task load are mediated by qualitatively different resources.

***Perspective:** Our findings indicate that highly demanding attentional task performance and pain processing interfere as a result of difficulties in allocating attention. The clinical relevance of this finding is that performing a highly demanding task might distract attention from pain.*

***Key words:** Pain, cold pressor test, attention capacity, event-related potentials, distraction, visual search.*

It has long been recognized that there are limitations to the capacity to allocate attention.[21,38] The resource-based model of attention and pain processing suggests that pain and attentional tasks draw on the same limited attentional resources.[12] Results from studies investigating the role of attention in the processing of pain are, however, inconclusive. On the one hand, it has been shown that allocating attention to a cognitive task can modulate pain perception, ie, pain is perceived as less intense when distraction occurs,[12,45] although this has been challenged.[17,27] Performing an attention demanding cognitive task is hypothesized to displace attention available for the processing of pain. Moreover, a number of studies have shown that difficult tasks might be more successful in altering pain perception than easier tasks.[3,26,30,36] Hence, attention to a cognitive task might alter pain perception only when task load is sufficiently high.

On the other hand, it has been hypothesized that pain perception can modulate attention demanding task performance.[9] Pain is a high-priority signal for danger and threat and therefore draws on limited capacity, which might lead to capacity limits being exceeded and there-

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fore impaired performance.[12] Indeed, several studies have found cognitive impairments in chronic pain patients,[8-11,15] although some failed to find attentional deficits under pain.[2] Particularly when task difficulty was high, patients in high pain performed worse compared with patients in low pain or pain-free subjects. Note that task difficulty and capacity are closely related concepts, because task difficulty determines the intensity of resource demands.[23] Mixed results have been found with healthy volunteer studies using experimentally induced pain. Impaired task performance during experimentally induced pain has been found,[4,5,34,42] yet some studies only found impaired task performance during the anticipation of pain, but not during pain,[41] or even no impairment at all.[18]

Eccleston[9] proposed that attention and pain processing might have a bidirectional interaction that depends on the relative ability to capture limited attentional capacity resources. Accordingly, it is important to elucidate the factors that determine the relative extents to which pain interferes with task performance and to which attention to a task modulates pain perception. Despite many studies on attention and pain, there is no consensus about these factors. Furthermore, two other relevant issues remained untouched in previous studies. First, because impaired task performance of pain was more consistently found in experiments involving chronic pain patients, it cannot be ruled out that several common concomitant problems in chronic pain patients, such as depressive feelings, feelings of anxiety, pain catastrophizing, and somatic awareness, which have been demonstrated to extend the attentional demand of pain, influenced these performance deficits.[6,7,11,29,35] Second, studies up to now have mainly used tasks in which the difficulty levels were structured in separate blocks to assess the effects of increasing attentional demands, eg, interference tasks.[8-10] However, if such blocked tasks are used, subjects can strategically prepare themselves differently to the task at hand. Hence, when no effect of pain on task performance is found, this might not be due to different demands on resources but to different investments of attention to the task.[32]

In the present study, 2 experiments are reported that address the role of attention in pain processing in healthy volunteers. A visual search task was used, which has been demonstrated to invoke controlled search with high demands on attentional capacity[33,37,38] that exceed capacity limits as reflected in reduced processing of task-irrelevant information.[19,20,24,25]

The first experiment was designed to assess whether pain affects task performance, ie, the primary task paradigm, by presenting the visual search task in a mixed design, with unpredictably varying low and high load stimuli within blocks of stimuli, so subjects cannot strategically prepare themselves. By doing so, attention could not be allocated differently to low versus high load stimuli. Excess of limited capacity due to pain processing was expected to interfere more with high load than low load task performance, because pain competes for resources.

In experiment 2, it was investigated whether task performance affects pain processing, ie, the distractor paradigm. For task load to affect subjective pain, the participant should be able to predict the occurrence of low versus high load conditions, so that the amount of selective attention devoted to the test can be strategically adjusted and therefore the amount of processing of distracting pain. Hence, high and low load conditions were separated in distinct blocks of trials, enabling such strategic adjustments. It was expected that in the high perceptual-load condition pain is processed to a lesser degree than in the low load condition. Furthermore, we included event-related potentials (ERPs) measures in the second experiment focusing on search negativity (SN), a negative shift with an onset latency of about 300 milliseconds, thought to be an electrocortical correlate of attentional resources being drawn on in high load conditions.[22,23,31,43,46] A similar effect has been reported for task stimuli under pain versus no pain.[18]

Materials and Methods

Participants

All participants were treated in accordance with the Declaration of Helsinki and its latest amendments and provided a written informed consent before participating in the study. Participants were recruited through advertisements on billboards at the University. They had normal or corrected to normal vision. Participants were free from a history of psychological, neurologic, or psychiatric disorders, as assessed by a medical questionnaire, and they did not use psychotropic medication. Compliance was tested by using a urine drug detection device (amphetamines, barbiturates, benzodiazepines, cocaine, morphine, and delta-9-tetrahydrocannabinol [THC]) and a breath alcohol analyzer. The amount of daily coffee intake, alcohol consumption, and smoking were recorded. Participants were screened on percentages of error rates because these might suggest that they operate closer to data-limited conditions than to resource-limited conditions.[24] To keep error rates low, participants could only enter the study when errors occurred in less than 20% of the trials for each display size in the practice condition. Participants were paid on completion of the experiment.

Twenty-two healthy volunteers participated in the first experiment (mean age, 22.9 years; range, 19 to 30 years). Four participants were excluded from the study because of pain complaints, other medical problems, or use of drugs. In addition, the data of 2 participants were excluded because of failure of experimental pain manipulation and high percentage of errors on a series of practice trials (>20%). Sixteen healthy volunteers (8 men and 8 women) completed the study.

Fourteen male students participated in the second experiment (mean age, 21.9 years; range, 19 to 25 years). Only men were included in this experiment, because no

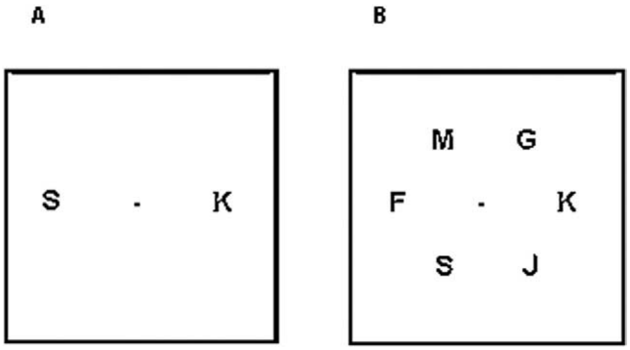

Figure 1. Examples of the displays used in experiments 1 and 2 for set sizes 2 and 6 (**A** and **B**). The participants' task was to identify which of the 2 target letters (*H* or *S*) was present in the display. Target location varied from trial to trial.

differences between men and women were found in the first experiment. Two participants were excluded from analysis, one because of pain complaints and one because of use of drugs. The remaining 12 participants completed the study.

Visual Search Task

The presentation of stimuli and measurement of responses were controlled by the Experimental Run Time System (ERTS). Stimuli were presented on a NEC Multisync monitor (NEC, München, Germany). Viewing distance was fixed at 60 cm. At this distance, the target and non-target letters each subtended a visual angle of 0.6 degrees vertically and 0.4 degrees horizontally and were positioned around the perimeter of an imaginary circle with a radius of 2.1 degrees from a central fixation point (adapted from Maylor and Lavie[25]).

A visual search procedure was chosen, in which healthy volunteers searched a circular display for a target letter. Two target letters, *H* and *S*, were used; each was assigned to one response key. Participants pressed a key according to which target occurred in the display. Assignment of targets to keys was counterbalanced across participants. A target was present in every trial.

The perceptual load was manipulated by varying the number of non-target letters on the display. A display of 6 letters was used as the high load condition, because it has consistently been demonstrated to involve demands that exceed capacity limits.[25] A display of 2 letters was used as the low load condition. In the low load condition a target and a non-target were presented laterally. The targets and non-targets were assigned randomly to the 2 positions. In the high load condition, 6 letters were presented, arranged around an imaginary circle, consisting of 1 target assigned randomly to 1 of the positions and 5 non-targets picked randomly from the non-target letter set to fill up the leftover spaces. Possible non-target letters were *B, D, G, J, Q, R, F, K, M, T, V* and *Z* (partially adapted from Madden and Langley[24]). All letters were presented in uppercase in white against a black background. Sample displays are shown in Fig 1. A dot was used as a fixation mark. Two blocks of 96 in total were presented, 48 trials at each display size. Assignment of blocks was balanced across participants. Participants were instructed to put their nondominant hand in a water basin. The visual search task was performed by using the index and middle fingers of the dominant hand.

In the first experiment, task conditions were randomly mixed within 2 blocks of trials, each with a duration of 1.5 minutes per block. A trial sequence consisted of a 100-millisecond display of a stimulus, followed by a fixed response window of 1700 milliseconds, after which a new stimulus was presented. In the second experiment, task conditions were blocked. Two blocks of trials were presented, 48 trials in total for each load condition. A trial sequence consisted of a 100-millisecond display of a stimulus, followed by a variable response window of 1600 to 1800 milliseconds (mean, 1700 milliseconds), after which a new stimulus was presented.

Cold Pressor Test

To induce pain during performance of the test, a cold pressor method was used. The cold pressor apparatus consisted of a 21 (height) by 25 (width) by 35 (length) cm basin with a built-in cooling and warming system and thermostat. The basin was filled with approximately 12 L of water. During the experimental trials, participants were instructed to place the nondominant hand in the water. The water level was 5 cm below the top of the basin, and the hand was immersed in the water up to the wrist. The 2 experimental conditions consisted of a painfully cold condition, in which the water was kept at an average temperature of 2°C, and a control condition, in which the water was kept at an average neutral temperature of 27°C in the first experiment. In the second experiment, an average temperature of a cold (but not painful) 20°C was used in the control condition in contrast to the 27°C in experiment 1 to avoid the possibility that differences between the pain versus the control condition were confounded by the sensation of coldness rather than pain. Conditions were balanced across participants. While performing the visual search task, between blocks of trials at least 5 minutes of rest were obligatory to regain warmth in the hand that was exposed to the cold pressor test. A towel was provided for this purpose.

Electrophysiologic Recordings

In the second experiment, continuous electroencephalogram was recorded by using a 32-channel tin electrode Electrocap (Electro-Cap International Inc, Eaton, Ohio) with the left mastoid as reference and one additional channel for recording the right mastoid. Vertical and horizontal electro-oculograms were recorded from electrodes placed above and below the left eye and on the outer canthi. Inter-electrode impedances were kept below 5 kilohms. All signals were amplified by Ampligraph amplifiers (EEG Technology BV, Leveroy, The Netherlands) with online high-pass filters at 0.05 Hz and low-pass filters at 100 Hz. Signals were digitized at 1024 Hz. Offline, electrophysiologic data were rereferenced against linked mastoids and down-sampled to 256 Hz with a bandpass of 0.05 to 30 Hz.

Subjective Assessments

Before the start of the experiment, an anxiety rating scale (STAI[39]), a depression scale (CES-D[1]), and a mood scale (POMS[28]) were completed by each participant. All participants scored beneath the cutoff score of 16 on the CES-D, and all scored within the normal range on the Dutch version of the STAI and POMS. Moreover, STAI state anxiety scores did not differ between the pain and control conditions in both experiments. The amount of experienced pain was assessed directly after removal of the hand from the water by using a visual analog scale (VAS). The left end of the 100-mm scale was labeled "no pain" and the right "unbearable pain."

Procedure

Participants were informed that a study was conducted on the effect of arousal on attention and that arousal would be induced by very cold water, which possibly could be painful. This mild deception was adapted from De Wied and Verbaten[45] and prevented the participants from focusing on pain and perhaps even fearing the pain stimulus. Each participant was allowed to consider participation in the study for at least 5 days before they were included. Furthermore, participants were given the opportunity to withdraw from the experiment at any time, but none of them did. Participants performed the task in 2 different sessions with an interval of approximately a week because of limits of the cold pressor apparatus. Each session lasted for about half an hour.

Participants were seated in front of a monitor in a dimly lit room. The cold pressor device was placed at the side of the nondominant hand. Participants were told that 1 of the 2 target letters would appear on every trial in 1 of 2 or 6 possible positions of a circular display and that a corresponding key should be pressed. Task instructions differed between experiments 1 and 2. In the first experiment, the participants were told that low and high load trials alternated within blocks of trials; in the second experiment, they were told that a block of only low or only high load stimuli was presented. They were told to keep their eyes focused in the center of the circle. Participants were encouraged to perform the task quickly while maintaining high accuracy. They first performed a practice block. Instructions concerning the cold pressor test followed the practice block. Participants were requested to place their hand in the water basin up to their wrist and hold the palm of their hand on the bottom plate. They were instructed to hold their hand in the water as long as possible, but that they could remove it if the water temperature would become unbearable. The short duration (1.5 minutes) of this manipulation was emphasized. Reaction time was measured from the onset of the display. Directly after removal of the hand from the water, participants were required to fill out the pain intensity VAS.

Data Analysis

Performance

For each participant, mean correct reaction times and error rates were calculated for each display load. Reaction times faster than 150 or slower than 1700 milliseconds in the first experiment and 1600 milliseconds in the second experiment were discarded. In line with Eccleston,[9] participants were assigned to the high or low pain intensity group according to their median VAS pain ratings in the painfully cold condition. All participants who scored above the median were assigned to the high pain intensity group, and all participants who scored below the median were assigned to the low pain intensity group.

ERPs

Filtered and down-sampled data were epoched 100 milliseconds before stimulus until 900 milliseconds after stimulus. Only trials with a correct response were selected for further ERP analyses. Trials with amplifier blocking, artifact, or flat lines were detected offline and omitted from further analysis. Ocular artifacts were controlled by time-domain regression analysis.[14] Average waveforms were computed separately for each experimental pain condition (pain and control) and load condition (low and high) at the 4 midline electrodes (Fz, Cz, Pz, and Oz). Fz data were lost in one participant in the pain condition during data collection. For statistical analysis, these data were replaced by the average data of the 5 nearest neighbors (AFz, F3, F4, FC1, and FC2). The number of trials constituting an individual ERP was at least 47 for the low load in the control condition, 37 for the high load in the control condition, 47 for the low load in the pain condition, and 37 for the high load in the pain condition. After inspection of grand average files and topographic distribution maps, average activity amplitudes were calculated for two 100-millisecond time periods, an early window (350 to 450 milliseconds) and a late window (500 to 600 milliseconds), because differences in conditions turned out to be largest in these windows.

Statistical Analysis

Analysis of variance (ANOVA) for repeated measures was conducted on mean correct reaction times with within-subjects factors Pain (pain versus control) and Load (high versus low) and between-subjects factors subjective Pain Intensity (high versus low) and Order of Pain Manipulation (control-pain versus pain-control). Between-subjects factor of Gender (male versus female) was also included in the analyses of the first experiment, and between-subjects factor Order of Task Presentation (high-low load versus low-high load) was also included in the second experiment. Between-subjects factors were included in the analyses to investigate the possibility of increased variance of within-subjects effects as a result of the difference in between-subjects factors. If this appeared to be not the case, then they were subsequently excluded from the model. Error rates were analyzed by using the Wilcoxon nonparametric test for 2 related samples.

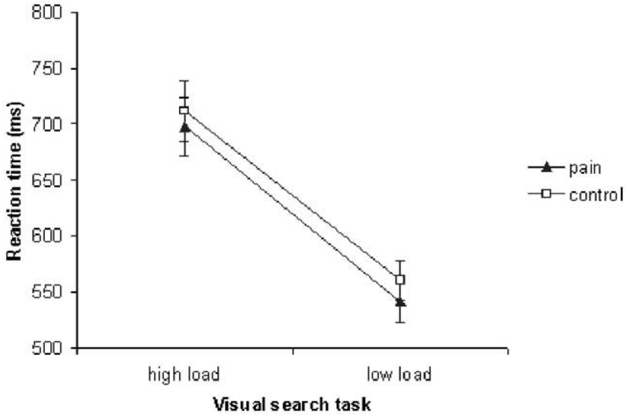

Figure 2. Mean reaction times on the high and low load tasks in the control and pain conditions of experiment 1.

VAS pain intensity scores of the first experiment were analyzed with within-subjects factor Pain (pain versus control) and between subjects factors Order of Pain Manipulation (control-pain versus pain-control) and Gender (male versus female). In the second experiment, within-subjects factors were Pain (pain versus control) and Load (high versus low), and between-subjects factors were Order of Pain Manipulation (control-pain versus pain-control) and Order of Task Presentation (high-low load versus low-high load).

Regarding electrophysiologic data, statistical analysis involved repeated measures of within-subjects factors Pain, Load, Locus (Fz, Cz, Pz, Oz), and Interval (early versus late window) and between-subjects factors Pain Intensity, Order of Task Presentation, and Order of Pain Manipulation. Greenhouse-Geisser epsilon and corrected *P* values are reported where applicable. For all tests a critical α-level of 0.05 was used. Statistical analyses were performed with SPSS 11.0.1 for Windows (SPSS Inc, Chicago, Ill).

Results

Experiment 1

Pain Intensity

Mean pain intensity VAS ratings in the pain and control conditions were 5.5 cm (standard deviation [SD], 2.0) and 0.1 cm (SD, 0.1), respectively. Median pain intensity rating was 5.9 cm in the pain condition. These values are comparable to values obtained in other cold pressor–induced pain experiments.[13,45] The cold water was rated as significantly more painful than the control water ($F_{1,15} = 129.74$, $P < .0001$), confirming that pain was effectively manipulated. No gender effects were found on pain intensity scores.

Reaction Time

Fig 2 shows the overall mean reaction time data for the low and high load conditions of the task on both the control and pain conditions. There was a significant main effect of Load ($F_{1,15} = 169.00$, $P < .0001$). As expected, participants were slower in the high load condition than in the low load condition, confirming that perceptual load was effectively manipulated. There was not an effect of Pain, Gender, Order of Pain Manipulation, or Pain Intensity, and there was not an interaction between Pain and Load or between any other factors. Mean reaction times and error rates (±SD) from experiment 1 are shown in Table 1.

Error Rate

The assumption of normality was not met for the error rate data, and transformation of data to obtain normalization was not possible. Therefore, these data were analyzed by using the Wilcoxon nonparametric test for 2 related samples. As was expected, an overall significant effect of load ($Z = -3.5$, $P < .0001$) was found. More errors were made in the high load condition compared with the low load condition. However, this effect was not larger in the pain condition in comparison with the pain-free condition, because no significant interaction was found with pain. Also, no main effect of pain was observed.

In addition, a tradeoff analysis was performed. A significant correlation between reaction times and error rates was found (Pearson $r = 0.50$, $P < .0001$). Participants with faster responses made significantly more errors.

Experiment 2

Pain Intensity

Mean VAS pain intensity ratings in the pain and control conditions were 5.9 cm and 0.6 cm, respectively. The me-

Table 1. Mean Reaction Times (RT), Error Rates (%), and Standard Deviations (SD) for Experiments 1 and 2

	CONTROL CONDITION		PAIN CONDITION	
	HIGH LOAD	LOW LOAD	HIGH LOAD	LOW LOAD
Experiment 1: N = 16				
RT (SD)	711.7 (112.6)	560.5 (79.7)	697.6 (108.6)	541.4 (82.9)
Error rate (SD)	12.2 (6.2)	2.4 (2.5)	10.9 (7.9)	3.4 (5.1)
Experiment 2: N = 12				
RT (SD)	733.4 (64.2)	566.9 (53.6)	702.5 (74.4)	537.2 (47.1)
Error rate (SD)	9.0 (6.5)	0.7 (1.4)	11.8 (7.3)	0.5 (0.9)

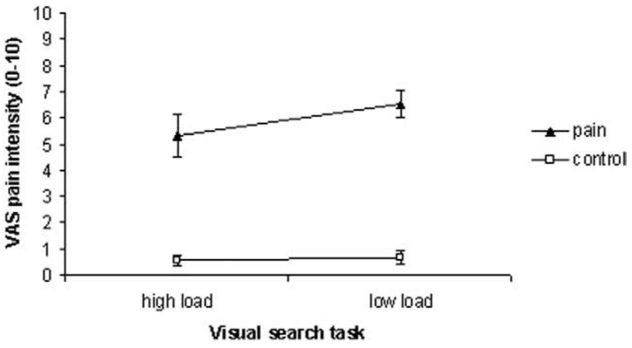

Figure 3. Mean VAS scores after the high and low load tasks separately for the control and pain conditions of experiment 2.

dian pain intensity score, averaged over load conditions, was 5.53 in the pain condition. These values are comparable to those of experiment 1. Statistical analysis revealed a significant effect of Pain ($F_{1,11}$ = 108.01, $P < .0001$), confirming that the pain manipulation was effective.

Mean VAS pain intensity scores after performing the low load condition was 6.5 cm (SD, 1.8) and after the high load condition 5.3 cm (SD, 2.9). Statistical analysis revealed a significant Load effect ($F_{1,11} = 8.59$, $P < .014$). More importantly, analysis revealed a significant interaction between Pain and Load for VAS scores ($F_{1,10} = 6.95$, $P < .025$). Post hoc analyses revealed that, in the pain condition, participants reported significantly lower pain intensity scores in the high load compared with the low load condition ($F_{1,10}$ = 12.49, $P < .005$). In the control condition, no significant differences between task load conditions were found for pain intensity scores (Fig 3).

Reaction Time

Fig 4 shows the overall mean reaction time data per condition for the low and high load task levels separately. There was a significant effect of Load ($F_{1,11}$ = 150.33, $P < .0001$). As expected, participants were slower in the high load condition than in the low load condition, confirming that perceptual load was effectively manipulated. In line with the findings of experiment 1, the analysis revealed neither an effect of Pain nor a significant interaction between Pain and Load. Reaction times and error rates from experiment 2 are shown in Table 1.

Error Rate

The assumption of normality was again not met for the error rate data. Data were analyzed by using the Wilcoxon nonparametric test for 2 related samples. Analysis only revealed a significant effect of Load ($Z = -3.1$, $P < .002$), indicating that more errors were made in the high load condition when compared with the low load condition.

Furthermore, a tradeoff analysis was performed. Comparable to experiment 1, a significant correlation between reaction times and error rates was found (Pearson $r = 0.48$, $P < .0001$). Participants with faster responses made significantly more errors.

ERPs

Grand average waveforms for the Load and Pain conditions are shown in Fig 5. Fig 6 displays the difference wave for Load, obtained by subtracting grand average ERPs for the high load minus the low load level, and the difference wave for Pain, obtained by subtracting grand average ERPs for the pain minus the control condition. Statistical analysis revealed a significant effect of Pain ($F_{1,11}$ = 13.85, $P < .003$), indicating that amplitudes in both intervals were significantly more negative in the pain condition compared with the control condition. No effect of Load or an interaction between Pain and Load was found.

A significant interaction of Locus and Load ($F_{3,9} = 4.91$, $P < .042$, $\epsilon = .379$) and a significant interaction between Load and Interval were found ($F_{1,11} = 102.14$, $P < .0001$). To examine these effects, post hoc analyses were carried out. Load (averaged across intervals and pain conditions) was only significant for Pz ($F_{1,11} = 5.75$, $P < .035$) and Oz ($F_{1,11}$ = 6.36, $P < .028$). Furthermore, Load (averaged across loci and pain conditions) was only significant in the early window of 350 to 450 milliseconds ($F_{1,11}$ = 16.37, $P < .002$) and not in the late window of 500 to 600 milliseconds. In this early window, significantly more negativity was found in the hard task compared with the easy task.

Maps were computed from grand average difference waves for the Load and Pain effects separately, as shown in Fig 7. For Load, a pronounced negativity can be seen between 350 and 450 milliseconds over parietal and occipital regions. The topographic map for Pain shows a negativity, which appears to be more centrally and more diffusely distributed than the effect of Load. Also, the duration of the pain effect appears to be more protracted than the effect of Load. These topographic voltage distributions suggest that the demands on resources by pain and load might not rely on the same brain regions.

The difference potentials for Load and Pain were statistically compared for the early and late intervals on the 4 midline electrodes to investigate possible significant differences in topographic distributions. Data were transformed by using an amplitude normalization procedure (transformation vector scaling across subjects[40])

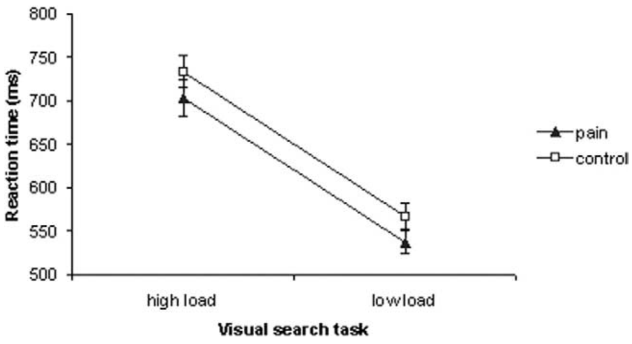

Figure 4. Mean reaction times on the high and low load tasks in the control and pain conditions of experiment 2.

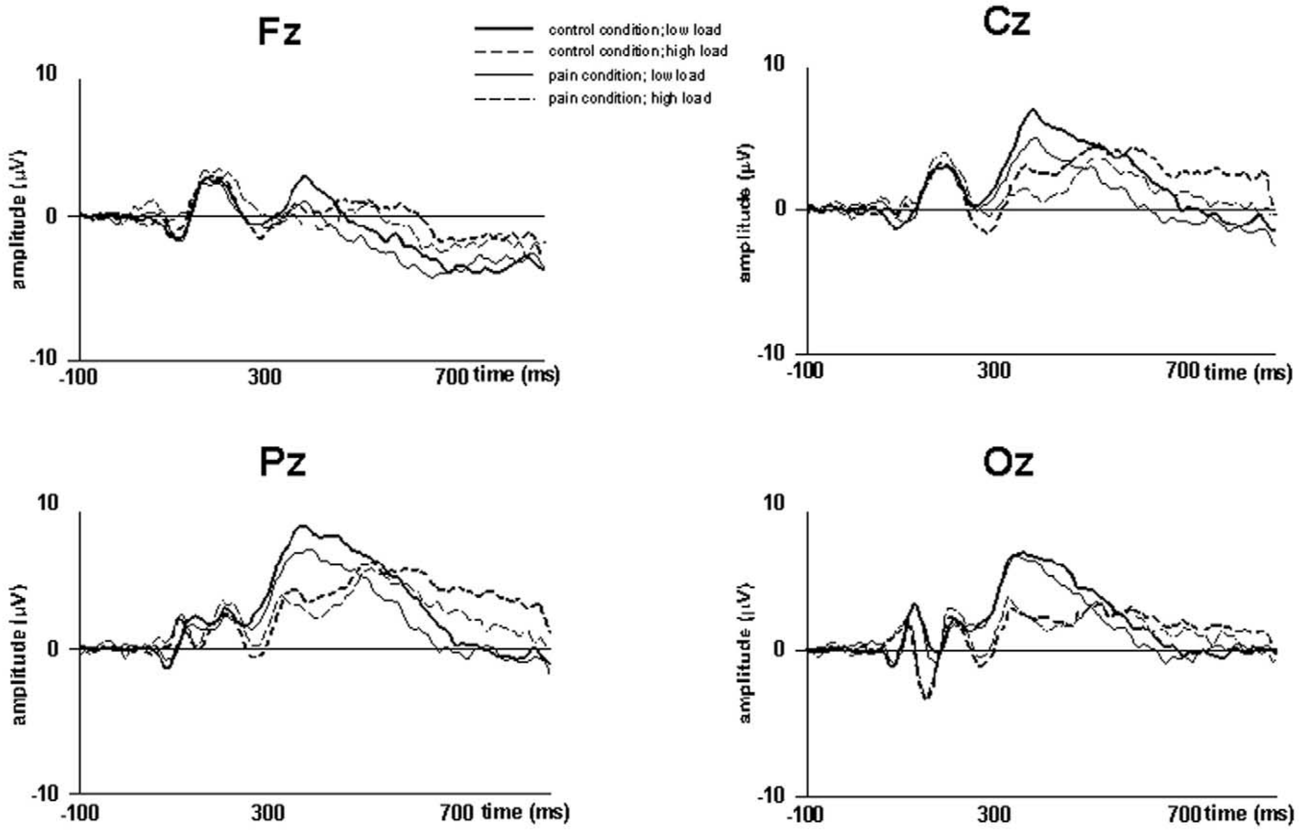

Figure 5. Grand average ERP waveforms for high and low loads in the control and pain conditions at the 4 midline electrodes.

to protect against significant interactions resulting from mere differences in strength between generators, instead of location differences. Both non-normalized raw data and normalized amplitude data were analyzed. Analysis of raw data revealed a significant interaction between Condition (Load vs Pain) and Electrode (Fz, Cz, Pz, and Oz) for the early interval ($F_{3,21} = 18.43$, $P < .0001$, $\epsilon = .453$) and late interval ($F_{3,21} = 4.09$, $P < .045$, $\epsilon = .409$), indicating that the effects of Load versus Pain differ between electrodes in both intervals. Results of analysis with normalized data were comparable to the raw data. Again, significant interactions were found in the early ($F_{3,21} = 8.55$, $P < .002$, $\epsilon = .490$) and late intervals ($F_{3,21} = 4.09$, $P < .044$, $\epsilon = .417$).

Discussion

Several authors have proposed that pain and attention rely on the same resources, and therefore, demands on capacity are conflicting. The objective of this study was to elucidate whether pain interfered with cognitive task performance (primary task paradigm), or whether high attentional demands altered pain perception (distractor paradigm). The experiments reported here were novel with respect to the applied attentional demanding task and the experimental pain paradigm that was induced in healthy volunteers. Furthermore, in the second experiment, ERP measures were included to clarify brain processes underlying behavioral measures. Topographic analyses were used to investigate whether resource allocation related to pain processing was generated in the same cortical areas as resource allocation related to task load is. We focused on SN, which is a negative shift with an onset latency of about 300 milliseconds lasting for several hundred milliseconds. The SN is generally thought to be an electrocortical correlate of controlled search, reflecting more attentional resources being drawn on in high load conditions.[22,23,31,43,46] A similar effect has been reported for task stimuli under pain versus no pain.[18] Because specific task instructions did not explicitly state that pain was induced, differences in threat awareness could not have confounded our results.

With respect to the effects of the load manipulation, the results from experiments 1 and 2 showed that the high load condition was a harder and more demanding task than the low load condition. Participants made significantly more errors in the high load than in the low load condition, and reaction times were significantly longer in the high load than in the low load condition. Consistently, ERP results showed that more resources were required in the high load than in the low load task condition, because more negativity was present in the high load versus the low load condition.

Regarding the pain manipulation, in both experiments, participants rated the cold water as significantly more painful compared with the control water. On measures of task performance, however, no significant effect

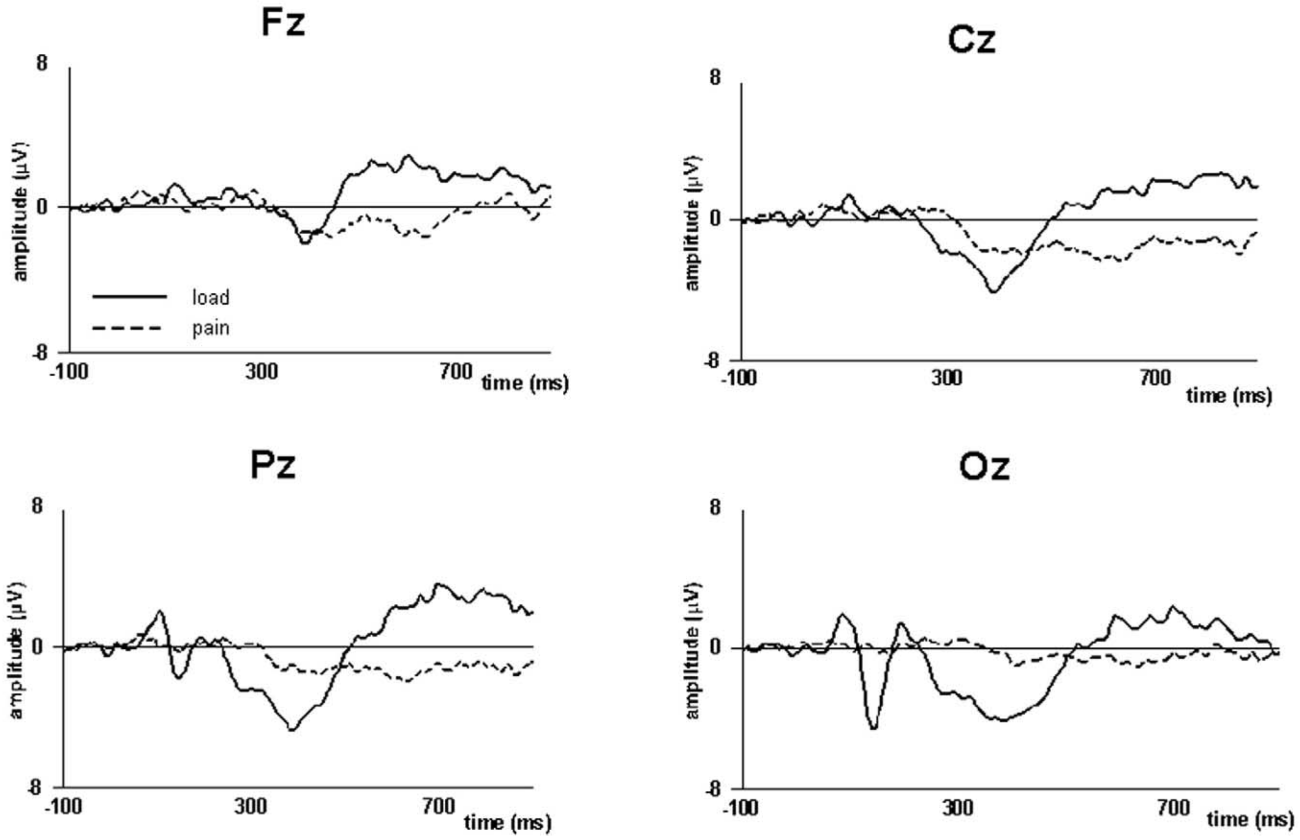

Figure 6. Difference waves for the effect of Load (high load minus low load) and Pain (pain minus control) at the 4 midline leads. Difference waves represent mathematical differences between ERPs obtained in different conditions. With the subtraction of one condition minus the other, the difference between conditions can be clarified.

of this pain manipulation was found. In contrast, ERP recordings appeared to be more sensitive and did show an effect of pain manipulation. Replicating the results of Houlihan et al,[18] more negativity in response to task stimuli was found in the pain condition compared with the control condition.

No significant interactions between pain and task load were found for performance data, not even in the high pain intensity group. Our results are in line with a few studies that also did not find that attentional task performance was affected by pain.[2,18,34] Whichever resources were demanded in the high load condition, they were apparently not shared by pain processing. Consistently, analysis of topographic maps of the ERP data revealed that the distributions of scalp potentials differed significantly between the effects of load and pain. The task load effect was most pronounced between 350 and 450 milliseconds and was distributed predominantly in parietal regions. In contrast, the pain effect had a more widespread distribution and was prolonged in duration (350 to 600 milliseconds). Thus, pain did affect the processing of task stimuli but in a topographically different manner than the effect of task load and, moreover, independent from load manipulation. Thus, no support was found for the hypothesis that pain is processed at the expense of task performance.[9]

However, as predicted from the distractor hypothesis, a significant effect of task load on subjective VAS pain intensity ratings was found. Pain intensity was significantly reduced while performing the more demanding high load condition, relative to the low load condition. This suggests that performing a more demanding task distracts attention from pain perception. Within the context of the limited capacity model, it can be argued that task performance is selected above pain processing when capacity limits are exceeded. Thus, our data support the distractor hypothesis that pain sensitivity is affected by attentional demands.

Given the results of the present studies, the effectiveness of the different manipulations needs to be considered. It has been suggested that to find an effect of pain on task performance, the task should be difficult, and the level of pain should be high.[12] Moreover, both should involve controlled processing to capture resources. With respect to task difficulty, as discussed earlier, Shiffrin and Schneider[38] clearly argued that the visual search task used in the experiments presented here is a controlled task and demands attentional resources. Moreover, Maylor and Lavie[25] demonstrated that with display load 6, demands on resources are high enough to exceed resource capacity, because distractor information is not processed anymore. Concerning pain intensity, VAS scores showed that pain was intense. Because pain processing is a controlled task by nature,[10] it always requires resources, even if induced shortly. Further-

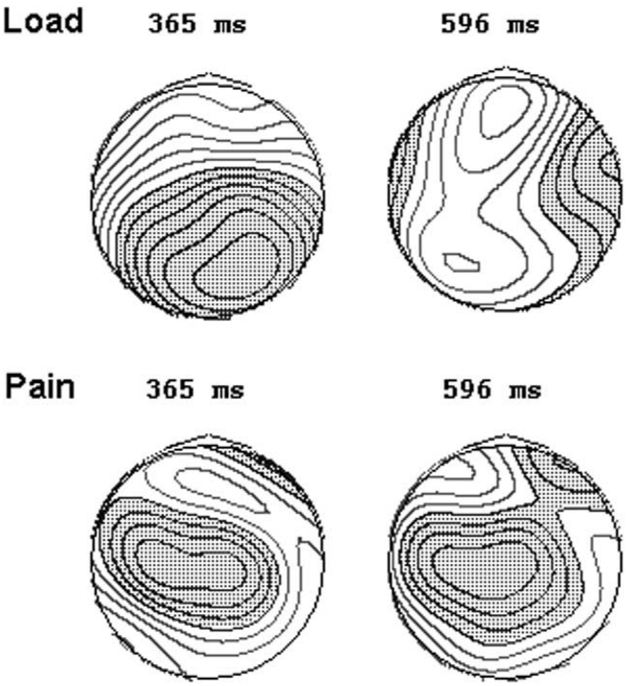

Figure 7. Topographic voltage distribution of the difference waves for the Load and Pain effects, separately. Maps of the maximal effects of the difference waves in the early and late intervals are shown. Top row: effect of load; bottom row: effect of pain. Shaded areas represent negativity; non-shaded areas represent positivity.

more, the cold pressor paradigm is a widely accepted pain induction method that has been applied in many studies to investigate pain perception.[16] It can be argued that, because pain was continuously present with the application of the cold pressor test, participants were able to suppress it after a while, which could have improved focusing on the visual search task. In contrast, the administration of a pain stimulus in each new trial would urge the attentional system to select information each time again, and such a condition might possibly reveal attentional disruption by pain. Although it is worthwhile to examine this possibility, generalizability of these short-lasting phasic pain stimuli to clinical chronic pain can be questioned.

The question remains, however, as to the exact nature of the bidirectional interaction between attention and pain processing. First, from a multiple resource perspective,[44] the performance results of both experiments indicate that the resources on which visual search depends were not claimed by pain processing. Other authors have reported on chronic pain patients, showing larger impairing effects of pain during more difficult task conditions.[10,11] In these studies, difficulty was manipulated in terms of incompatible stimulus-response relations, which might tax more central resources, relative to the perhaps more perceptual resources involved in visual search. It could be that these central resources are shared with pain processing to a larger extent.

Second, the ERP data from the second experiment suggest that, during pain, an additional mechanism operates with respect to processing of task stimuli. This mechanism could well be related to a "switching"[10] of resources from pain processing to task-related processing, resulting in unimpaired task performance during pain (relative to no pain). Such a switching mechanism continuously reallocates attention from pain to task to maintain the level of performance and minimize the disruptive effects of pain; however, this switching mechanism itself is demanding of attention.[4,10,33] In the present conditions, the switching mechanism recruited more resources for task performance in the high than in the low load condition, which in turn resulted in reduced subjective pain in the high load condition.

The results of the present study should be interpreted in light of the limitation of the small sample size of both experiments. Future studies with larger sample sizes are required.

In conclusion, the interaction between task load and pain processing appeared to be asymmetric. The hypothesis that pain competes with resource capacity and negatively interrupts task performance was not supported. Subjective pain intensity assessments (VAS) revealed supportive evidence for the limited capacity distractor hypothesis, because decreased pain intensity scores were found after task performance in the high load condition compared with the low load condition. Furthermore, the ERP results indicated that visual search task load and pain draw on resources implemented in at least partly different cortical areas.

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