**University of Bath**

# Cognitive load selectively influences the interruptive effect of pain on attention

David J Moore[1], Christopher Eccleston[1], Edmund Keogh[1,2]


[1] Bath Centre for Pain Research, The University of Bath, Bath, BA2 7AY, United

Kingdom

[2] Department of Psychology, The University of Bath, Bath, BA2 7AY, United

Kingdom


Corresponding author:

Edmund Keogh,

Department of Psychology,

University of Bath,

Claverton Down,

Bath, BA2 7AY,

United Kingdom.

Email address: e.m.keogh@bath.ac.uk

Running Head: Effect of pain on attention

Keywords: Attention, Pain, Executive function, Cognition, Load

1

**ABSTRACT**

Pain is known to interrupt attentional performance. Such interference effects seem to occur preferentially for tasks that are complex and/or difficult. However, few studies have directly manipulated memory load in the context of pain interference to test this view. Therefore, the present study examines the effect of experimental manipulations of both memory load and pain on three tasks previously found to be sensitive to pain interference. Three experiments were conducted. A different task was examined in each experiment, each comprising of a high and low cognitive load versions of the task. Experiment 1 comprised of an attention span (n-back) task, Experiment 2 an attention switching task, and Experiment 3 a divided attention task. Each task was conducted under painful and non-painful conditions. Within the pain condition, an experimental thermal pain induction protocol was administered at the same time participants completed the task. The load manipulations were successful in all experiments. Pain-related interference occurred under the high load condition, but only for the attention span task. No effect of pain was found on either the attentional switching or divided attention task. These results suggest that while cognitive load may influence the interruptive effect of pain on attention, this effect may be selective. Since pain affected the high load version of the n-back task, but did not interrupt performance on attentional switching or dual task paradigms, this means our findings did not completely support our hypotheses. Future research should explore further the parameters and conditions under which pain-related interference occurs.

**INTRODUCTION**

Pain functions to interrupt current concerns, warn of potential danger, and promote analgesic behaviour in oneself and from others [12]. This interruption can result in attentional focus to pain and away from other cognitive demand. Indeed pain-related cognitive deficits have been shown in both chronic pain [11], and using experimentally-induced pain with healthy participants [7; 21; 22; 40]. The magnitude of this effect may be altered by the nature of the task with findings using experimental pain models finding greater effects on complex dual-task performance compared to more simple tasks [29-31], and meta-analyses showing that the effects of chronic pain are greatest for complex memory, attention, and executive function tasks [3; 4; 33].

Task complexity has therefore been identified as a potential moderator, and could help explain the variation found in pain interference effects. Using a series of modified Stroop tasks which varied in complexity chronic pain patients with high intensity pain were found to be generally slower and less accurate on all tasks and these effects were most pronounced when the task was more cognitively demanding [14].

This effect of load is not limited to chronic pain population and such interference effects are also seen in pain-free adults who have been exposed to experimental noxious events. Bingel et al. [5] found that laser pain had a detrimental effect on participants' performance on a 2-back but not a 1-back task (measures of attention span), which was taken to suggest greater sensitivity to pain interference under high-load conditions. However, when Legrain et al. [21; 22] examined the effects of painful laser sensation on n-back performance, they found greater decrements in the lower load version of the task (0-back vs. 1-back task). This was taken by the authors to suggest that load may actually help protect against

interruption, possibly by increasing distraction from pain and therefore lower pain experiences. Indeed, distraction paradigms also suggest that *less* pain is reported when performing a high load distraction task [2; 42].

These contradictory findings demonstrate that the role of cognitive load in the interruptive effect of pain on attention is still unclear. There are few studies that have systematically examined the effects of load on pain-related interference on tasks which required differing aspects of attentional control. Our primary aim was, therefore, to examine the effect of cognitive load on pain-related attentional interference. As we have shown previously that the interruptive effect of pain on attention is greatest within the domains of attention span, attentional switching and divided attention [29; 30], we decided to focus on these three areas. Given that Bingel et al. [5] found that pain affected the 2-back task but not the 1-back, and our previous findings of pain interference using the 2-back task, we judged that increasing the load would increase attentional interruption further. Our specific hypotheses were that pain would interrupt participant speed and/or accuracy on the three cognitive domains, and that this effect would be moderated by cognitive load: the greater the load, the greater the disruptive effect of pain.

**GENERAL MATERIALS AND METHODS**

Three experiments were conducted using similar methods, recruitment procedures, and testing protocols. Common features of the experiments are first described followed by their unique elements.

4

**Participants**

Following institutional ethical committee approval (from the Department of Psychology, University of Bath) and provision of informed written consent, 63 healthy adult participants were recruited from the University of Bath staff and student population into one of the three experiments. Participants reported that they were not currently in pain, had no existing chronic pain condition, and were not taking analgesic medication. Participants were paid for participation (£5).

**Materials**

The attentional tasks were designed and controlled using E-Prime II professional software [37]. Stimuli were presented on an Iiyama prolite B1902S TFT monitor, which was powered by a Viglen genie desktop computer with a 3GHz Pentium Intel Core 2 duo processor and 2Gb of RAM. Responses were made using a PST model 200a serial response box for the n-back and attentional switching tasks. For the divided attention task responses were made using a standard Viglen keyboard.

**Pain manipulation**

Participants completed each task twice: once in a no pain condition, and once in a pain condition. The order of pain testing as well as the order of the load condition was counterbalanced between participants in each experiment to create a factorial design.

Pain stimulation was achieved through the use of a Medoc PATHWAY - Advanced Thermal Stimulator (ATS). This equipment is designed for use in clinical and research settings, and induces pain through a plate placed on the skin. The plate

temperature increases or decreases, and is delivered and controlled through specialist hardware and software, designed for experimental purposes.

Participants' pain thresholds were individually generated using a search protocol. A 30mm x 30mm thermode was attached to the participant's right ankle. A baseline temperature of $32^0$C was used from which participants were instructed to increase the temperature (by pressing a mouse button, each time the participant pressed the button a small increase of approximately $.1^0$C occurred) until they felt that it was 'just painful'. After 15 seconds, participants were asked to confirm whether the sensation was still 'just painful'. If participants reported that the sensation was either no longer painful or was more than just painful then they were asked to adjust the temperature and the 15 second threshold check was performed again until a reliable threshold was reached.

Participants' individual thermal pain levels were used to design a protocol for use during the experimental tasks. In the pain condition temperature started at $32^0$C and increased at a rate of $8^0$C/second to $1^0$C above participants set pain threshold (up to a maximum of $48^0$C, with all thresholds higher than this tested at $48^0$C). The temperature then oscillated +/- $1^0$C around the participant's pain threshold at $8^0$C/second for 10 oscillations. After 10 oscillations the temperature returned to the baseline temperature ($32^0$C) at $8^0$C/second and immediately repeated the above procedure. Therefore pain was present throughout the cognitive tasks. This technique was used in our previous studies [19; 30; 32].

**Data Screening**

For all studies, participants' data were examined to ensure that they met parametric assumptions; all data were normally distributed, with skew values between

-2.56 and 2.56 [8]. Data were examined for outliers, based on mean scores greater than three standard deviations above/below the group mean [39]. Outlying data was detected for one participant in Experiment 1 (n-back) and one participant in Experiment 3 (divided attention). Exclusion of these data did not change the overall findings and therefore data are reported with all participants included.

## EXPERIMENT 1: Attention span

Attention Span is the amount of information that can be processed at any one time [24]. The n-back task measures attention span by asking participants to indicate if a current stimulus matches one presented previously.

## METHOD

### Participants

Twenty participants (11 female) were recruited for the test of attention span, with a mean age of 25.95 (SD=4.27).

### Materials and Procedure

Participants completed the task at two levels of difficulty; a 2-back (low load) and 3-back (high load) task. For the 2-back condition each participant's task was to report whether the current letter matched the letter presented two letters back (See Fig. 1). All 21 consonants were used in this task. Following 30 practice trials, participants were presented with a stream of 90 letters, each for 500ms, followed by a 1500ms blank screen. Participants pressed a key with their right hand if the letter was the same as two letters previously, and another with their left hand if the letter was different. For the 3-back task participants indicate whether the current letter was the

same as the one presented three letters back. For each task there were 30 target stimuli presented and 60 non-target stimuli randomly distributed through the task, and the task lasted approximately three minutes.

The outcome variables for the n-back task were the number of correctly identified targets (hits) and the number of times non-targets were identified as targets (false alarms).

**RESULTS**

Means and standard deviations are reported in Table 1. To investigate whether pain affected n-back task performance, the number of hits (i.e., number times participants correctly identified when the current letter matched the letter presented two/three back) and number of false alarms (i.e., times that participants incorrectly indicated that the current letter was the same as two letters previously) were entered into a 2 (load condition: high load vs. low load) x 2 (pain condition: pain condition vs. no-pain condition) within-groups ANOVA.

For hits there was a significant main effect of load, $F_{(1,19)}=25.25$, $p<.001$; participants identifying more hits in the low load condition compared to the high load condition. Although the main effect of pain condition was not significant, $F_{(1,19)}=2.59$, $p>.05$, a significant interaction was found between pain and load condition, $F_{(1,19)}=5.10$, $p<.05$. This interaction was examined using a simple main effects analysis, with a Sidak correction for multiple comparisons. When load was low (2-back), no significant differences were found between the pain and no-pain conditions ($p>0.05$). However, when the load was high (3-back), participants identified significantly fewer hits in the pain condition compared to the no-pain

condition (p<.05). This suggests that pain negatively impacts upon attention span when the task is more demanding i.e., high load condition.

For false alarms there was a significant main effect of load condition, $F(1,19)=8.54$, $p<.01$; more false alarms were found in the high load (6.25) condition compared to the low load (2.80) condition. There was no main effect of pain condition, $F(1,19)=.93$, $p>.05$, and no significant interaction between these two variables, $F(1,19)=.06$, $p>.05$.

**EXPERIMENT 2: Attentional switching**

Task-switching paradigms are used to investigate executive control of cognition and the cost to performance of changing between tasks compared to repeating the same task [26]. Responses after task switches are typically slower and less accurate than task repetitions. These *switch costs* reflect an aspect of executive control processing, with some suggesting that task-switch costs in response time (RT) reflect the duration of an executive control process (e.g., [25; 27; 36].

**METHOD**

**Participants**

Twenty participants (15 female) were recruited, with a mean age of 30.95 (SD=8.27).

**Materials and procedure**

The current task was based on one described by Hester and Garavan [15]. Participants were first given one block of practice trials in which a memory list of 4

9

items was used. Following this in the main trials participants were initially presented with a list of either two (low load) or five (high load) letters for 6 seconds on the screen simultaneously, which they were asked to memorise. After an 8 second break for consolidation, participants were asked to complete one of two tasks. In both versions of the tasks, participants were presented with letters on the screen one at a time. If the letter was presented in black print they were asked to indicate if the letter had been in the memory list or not (by two forced choice responses i.e., yes or no). However, if the letter was presented in either green or red then participants were asked to indicate the colour (by a separate two forced choice response i.e., red or green) (see Fig. 2).

The critical factor relates to the type of instruction given in any one trial, and how it relates to the previous trial. For some trials participants were given the same instructions (repeat trials) whereas on others they were given different instructions (switch trials). It was the increase in the magnitude of the difference (both in reaction times and accuracy) between repeat and switch trials under the different levels of the experiment (load, pain) which was the primary interest.

Participants were presented with a total of 200 trials. Within each trial, the target item was presented until a response was made, or for a maximum of 2 seconds, whichever came sooner.

**RESULTS**

Means and standard deviations are available in Table 1. To investigate whether pain affected attentional switching, data were entered into two separate 2 (load condition; high load vs. low load) X 2 (switch condition: switch condition vs.

repeat condition) X 2 (pain condition: pain condition vs. no-pain condition) within-groups ANOVAs.

For reaction times, data analysis revealed a significant main effect of switch condition, $F_{(1,19)}=62.80$, $p<.001$; participants responded faster to repeat trials (806 msec) than to switch trials (987 msec). This also revealed a significant main effect of load condition, $F_{(1,19)}=5.01$, $p<.05$. Here faster responses were found in the low load (874 msec) condition compared to the high load condition (919 msec). There was, however, no significant main effect of pain, $F_{(1,19)}=.12$, $p>.05$, nor any significant interactions; all $F<1.5$, all $p>.05$.

A similar analysis was conducted on the accuracy data. Here a significant main effect of switch condition was found, $F_{(1,19)}=22.41$, $p<.001$. Participants were less accurate following a task switch (percentage correct =.84) compared to repeat (percentage correct =.88). There were no significant main effects of load condition, $F_{(1,19)}=.01$, $p>.05$, or pain condition, $F_{(1,19)}=2.46$, $p>.05$. There were no significant interactions between any of the variables; all $F<1.5$, all $p>.05$.

Increasing cognitive load, as predicted, reduces performance on the task. Pain, however, failed to affect performance.


**EXPERIMENT 3: Divided attention**

Divided attention can be considered to be the processing of more than one source of information simultaneously [43]. Divided attention is involved in most of the complex tasks performed in day to day life. When operationalised experimentally divided attention paradigms can comprise any combination of tasks which require the simultaneous performance of multiple tasks.

**METHOD**

**Participants**

Twenty-three participants (12 female) were recruited, with a mean age of 29.01 (SD=10.32).

**Materials and procedure**

The divided attention task used in the current experiment was based on that described by Della Sala et al. [9]. Participants were informed of a primary task to perform, and that they would do this under three different conditions. In one condition they performed this task alone i.e., no divided performance. In the two other conditions the primary task was accompanied with a secondary task i.e., divided performance conditions. In one version of the divided performance condition the secondary task was a low cognitive load, and in the other it was a high cognitive load.

The primary task involved presenting participants with two single digit numbers at random locations on the screen for 500ms. Participants were asked to press the space bar whenever they saw either the number '0' or '5' appear. For the two divided attention conditions, participants were also asked to remember a series of letters before performing the primary task. When they finished the task, participants were asked to recall these letters. For the low load divided condition, participants were asked to remember three letters, whereas in the high load condition participants were asked to remember a seven item span (see Fig. 3). Each of the memory lists was presented for 4 seconds.

In an initial phase participants were given a block of practice trials in which a memory list of 2 items were used. In the main trials participants were presented with 18 blocks of 60 trials (six blocks of 60 trials for each of the three divided attention

conditions), and each block contained 12 targets. Each screen was presented for 500ms and each stimulus occupied .7° of visual angle. The load manipulation was made before each of the 18 number blocks and the order of the load tasks was presented in a random order. The task lasted approximately 12 minutes. The primary analysis of interest here is the reaction times and response accuracy to the number stimuli dependent on the number of items to be recalled.

**RESULTS**

Means and standard deviations are available in Table 2. To investigate whether pain or load affected divided attention performance a 2 (pain condition: pain vs. no-pain) x 3 (load condition: single task vs. low load divided vs. high load divided) within groups ANOVA was conducted.

For the reaction time data, no significant main effect of pain condition was found, $F(1, 22)=3.17$, $p>.05$. However, there was a significant main effect of load condition $F(2,44)=5.34$, $p<.01$. Simple main effects analysis, with a Sidak correction, revealed that participants took significantly longer to respond to stimuli in the high load condition (536 msec) when compared to the single task condition (524 msec) ($p<.01$). There were no significant differences between the high load and low load (528 msec) ($p>.05$) conditions, or between the low load and single task conditions ($p>.05$). Finally, no significant interaction was found between these two variables, $F(2,44)=.40$, $p>.05$.

For accuracy data a similar 2 x 3 ANOVA was performed. This revealed no significant main effects either of pain condition, $F(1,22)=2.31$, $p>.05$ or load condition, $F(2,44)=.25$, $p>.05$. No significant interaction was found between these variables, $F(2,44)=.98$, $p>.05$.

For recall of the original list data was missing from the first 9 participants due to a technical error in the program. Due to this the 'n' is likely to small and non-representative to make inferential analysis of these date of added value. Examination of the mean data however suggests that participants were able to engage well with the task.

**DISCUSSION**

Our investigation examined the role of cognitive load on pain-related attentional interruption. We modified three tasks shown to be sensitive to pain interruption [29] by manipulating cognitive load. Load manipulations were successful in all experiments: participants' performed worse in the high load versions of the attention span, switching and divided attention tasks when compared to the low load versions. Our primary interest was to examine whether this load manipulation affected pain-related interference. Pain interacted with load to affect cognitive performance. Unexpectedly this was found on only one of the three tasks. Specifically, for the attention span task high cognitive load resulted in pain-related interference. Furthermore, this pain interference effect was *only* found in the high load attention span task. This pattern of effects is surprising because we have previously found pain-related interference when using the low load (2-back) version [29; 30]. Furthermore, there is at least one additional study outside our own laboratory that found pain interference on the 2-back version of the attention span task [5].

The current findings suggest that whilst load seems to exacerbate pain interference it may be selective and limited to certain tasks. This was not due to the order or practice effects as entering task order as a within groups factor showed no interactions detected with this variable. One can speculate that the effects are due to

previous exposure to similar tasks [17] but there is no evidence to support this hypothesis and we were careful to use different samples. Further, despite the previous report of pain affecting switching, this did not emerge here [10; 12; 29; 30]. One possibility is that the effects of pain interference on these tasks are small and highly sensitive, and hence simply unreliable. Perfect replication is rarely predicted by significance testing so we should perhaps be unsurprised at the inconsistency [16; 38]. However, we would expect partial replication if the effects of interruption are large and robust.

Here we manipulated cognitive load based on working memory, it would therefore be interesting to explore the effect of alternative perceptual load paradigms (e.g. [35]). The load theory of selective attention and cognitive control proposed by Lavie et al. [20] suggests opposing effects of memory and perceptual load. In this account increasing memory load increases the interruptive effect of distractor stimuli due to the increased cognitive control required, whereas increasing perceptual load decreases distractor interference by reducing the individual's ability to perceive this. We might therefore expect that lower perceptual load results in greater task interference. An additional consideration, are the differences between studies in definition of 'low' or 'high' loads. For example, Legrain et al. [21; 22] utilised a 0-back and 1-back task to examine the effects of load, whereas we compared 2-back and 3-back versions. The current study therefore placed a higher load on participants, at many or all stages of the research. We selected a 2- and 3-back task because our previous studies found pain-related interference on a 2-back task, and we reasoned that by increasing the load, this would increase the interference effect found [18; 29-31].

A related issue to consider is our choice to focus on the structural features of the tasks (i.e. the cognitive task parameters). It is possible that this had the effect of relegating any functional concerns with the meaning of pain, natural prioritization of task, or individual differences. Indeed, it is possible that our structural approach makes interruption effects highly sensitive to minor alterations in characteristics of experimental design, meaning that without exact replication (using exact materials, tasks, etc.) differences will emerge. We acknowledge a limitations with our study is that we did not examine individual differences, and that with a larger sample the effects of sex, age, IQ, and/or affective state could potentially appear. It is also possible that variation in pain threshold might be related to the magnitude of attentional interruption. Further work that allows for tests of individuals differences is warranted.

Perhaps more intriguing is the possibility that load operates on interruption by pain in a non-linear fashion: load may influence pain with a U-shaped function. That is, the interruptive effect of pain is most pronounced when executive control is either not engaged or is fully engaged and so fails. In-between interruption is shielded, as suggested by Legrain et al. [22]. Here our proposal would be that low load tasks recruit limited attentional motivation and can be relatively easy to complete, and so pain is able to have a larger effect on the participant. However, at moderate load engagement increases and distracts people from pain. At the highest load we predict that the task would become 'impossible' and participants engagement would reduce leading to greater pain processing [34]. If this U-shaped pattern of pain-attention relationship is to be substantially supported then a more fine-grained examination of the effect of cognitive load with a greater number of levels is needed.

One additional consideration is that different participants were used across the three reported experiments. This does not allow us to examine the pattern of interference across experiments by participant. Although a within participants design may have been desirable, this would have brought other problems, such as extending the time required to complete the high and low load conditions of each task, and thus introducing fatigue into performance. It is also necessary to consider whether different outcomes would have been observed with larger sample sizes. In the current study, we sought to identify relatively large effect sizes based on previous research using similar tasks to designed to investigate the interruptive effect of pain on attention [29; 30]. It is however possible that larger samples may produce data with a greater signal to noise ratio.

For future directions it will be useful to consider further the parameters and conditions under which pain-related interference occurs. Factors that might enhance people's engagement with the attentional task and reduce the interruptive effect of pain on attention have been proposed. Verhoeven et al. [41] suggested giving participants additional motivation to perform well on attentional tasks, for example a financial reward. They found that the experience of pain can be reduced and performance increased, indicating that both top-down control of pain factors (e.g., avoidance of harm and threat value) as well as bottom-up saliency factors (e.g., intensity and novelty) are important [23]. Further research is required to consider which factors and in what combination pain interference is more or less likely to be observed. It should, however, be noted that findings about the effect of threat manipulations are mixed. Some studies find that manipulating the threat value of pain affects increases interruption [6], whereas others, using similar task to those here, have failed to find greater pain interference under high threat [30].

A second consideration for future research relates to our practice of using experimental pain in relatively static and controlled motivational environments. Naturally occurring everyday pain has fundamentally different qualities to those found in the laboratory [13], and we have argued that, although challenging, it is valuable (and may be necessary) to develop protocols for including people with naturally occurring pain in studies of attentional interference [28]. Of particular interest given the frequency of the pain experience are those of headache or menstrual pain. Indeed we have provisionally shown the impact of headache and menstrual pain on task performance [1; 18; 31]. Important differences exist between experimentally induced and real world pain, in that the former is somewhat artificial and controllable. It would be intriguing to see, therefore, whether similar, or perhaps even stronger, pain-interference effects would be found in those presenting with a wide range of real world pains.

Although these data are based on an experimental pain model there are potential clinical implications if these results are replicated in applied settings. Patients are frequently given large amounts of information to recall (i.e. medication schedules) upon discharge from services, as well as procedural information to process (i.e. physiotherapy). Competing information needs to be processed, updated and switched between, for treatment adherence. High levels of cognitive load when presenting this information may lead to sub-optimal processing and poorer outcomes. We therefore propose that clinicians might consider how information is presented and if they can reduce the need to hold information in memory. Patients may benefit from electronic reminders, or an indexed file that may help them to perform tasks better for their treatment.

In conclusion, the present findings suggest that cognitive load may be selective in the influence it has on the interruptive effect of pain on attention. So far, the exact form of the influence of cognitive load is unclear and the effects are intriguingly inconsistent. This may provide indirect support for Legrain's 'shielding' hypothesis that the interruptive effect of pain is most pronounced when executive control is idle or is fully engaged [22]. The affective-motivational features of pain may be more important in predicting the interruption of pain rather than the structural features of the stimulus and competing task.

References

[1] Attridge N, Noonan D, Eccleston C, Keogh E. The disruptive effects of pain on n-back task performance in a large general population sample. PAIN In press;Publish Ahead of Print.

[2] Bantick SJ, Wise RG, Ploghaus A, Clare S, Smith SM, Tracey I. Imaging how attention modulates pain in humans using functional MRI. Brain 2002;125(2):310-319.

[3] Berryman C, Stanton TR, Bowering KJ, Tabor A, McFarlane A, Moseley GL. Evidence for working memory deficits in chronic pain: A systematic review and meta-analysis. Pain 2013;154(8):1181-1196.

[4] Berryman C, Stanton TR, Bowering KJ, Tabor A, McFarlane A, Moseley GL. Do people with chronic pain have impaired executive function? A meta-analytical review. Clinical psychology review 2014;34(7):563-579.

[5] Bingel U, Rose M, Gläscher J, Büchel C. fMRI reveals how pain modulates visual object processing in the ventral visual stream. Neuron 2007;55(1):157-167.

[6] Boston A, Sharpe L. The role of threat-expectancy in acute pain: effects on attentional bias, coping strategy effectiveness and response to pain. Pain 2005;119(1-3):168-175.

[7] Buhle J, Wager TD. Performance-dependent inhibition of pain by an executive working memory task. Pain 2010;149(1):19-26.

[8] Clark-Carter D. Quantitative Psychological Research: A Student's Handbook. Hove, UK: Psychology Press, 2004.

[9] Della Sala S, Baddeley AD, Papagno C, Spinnler H. Dual task paradigm: A means to examine the central executive. In: GK J., F Boller, editors. Structure and functions of the human prefrontal cortex. New York: Annals of the New York Academy of Sciences, 1995. pp. 161–172.

[10] Eccleston C. The attentional control of pain: Methodological and theoretical concerns. Pain 1995;63(1):3-10.

[11] Eccleston C. Chronic pain and distraction: An experimental investigation into the role of sustained and shifting attention in the processing of chronic persistent pain. Behaviour Research and Therapy 1995;33(4):391-405.

[12] Eccleston C, Crombez G. Pain demands attention: A cognitive–affective model of the interruptive function of pain. Psychological Bulletin 1999;125(3):356-366.

[13] Edens JL, Gil KM. Experimental induction of pain: Utility in the study of clinical pain. Behavior Therapy 1995;26(2):197-216.

[14] Grisart JM, Plaghki LH. Impaired selective attention in chronic pain patients. European Journal of Pain 1999;3(4):325-333.

[15] Hester R, Garavan H. Working memory and executive function: The influence of content and load on the control of attention. Mem Cogn 2005;33(2):221-233.

[16] Hubbard R, Lindsay RM. Why P Values Are Not a Useful Measure of Evidence in Statistical Significance Testing. Theory & Psychology 2008;18(1):69-88.

[17] Jaeggi SM, Buschkuehl M, Perrig WJ, Meier B. The concurrent validity of the N-back task as a working memory measure. Memory 2010;18(4):394-412.

[18] Keogh E, Cavill R, Moore DJ, Eccleston C. The effects of menstrual-related pain on attentional interference. Pain 2014;155(4):821-827.

[19] Keogh E, Moore DJ, Duggan GB, Payne SJ, Eccleston C. The Disruptive Effects of Pain on Complex Cognitive Performance and Executive Control. PLoS ONE 2013;8(12):e83272.

[20] Lavie N, Hirst A, De Fockert JW, Viding E. Load theory of selective attention and cognitive control. Journal of Experimental Psychology: General 2004;133(3):339.

[21] Legrain V, Crombez G, Mauraux A. Controlling attention to nociceptive stimuli with working memory. PLoS One 2011;6(6):e20926.

[22] Legrain V, Crombez G, Plaghki L, Mouraux A. Shielding cognition from nociception with working memory. Cortex 2013;49(7):1922-1934.

[23] Legrain V, Van Damme S, Eccleston C, Davis KD, Seminowicz DA, Crombez G. A neurocognitive model of attention to pain: Behavioral and neuroimaging evidence. Pain 2009;144(3):230-232.

[24] Lezak MD, Howieson DB, Loring DW. Neuropsychological assessment (4th ed) New York: Oxford University Press, 2004.

[25] Meiran N. Reconfiguration of processing mode prior to task performance. Journal of Experimental Psychology: Learning, Memory, and Cognition 1996;22(6):1423-1442.

[26] Monsell S. Task switching. Trends in Cognitive Sciences 2003;7(3):134-140.

[27] Monsell S, Mizon GA. Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? Journal of Experimental Psychology: Human Perception and Performance 2006;32(3):493-516.

[28] Moore DJ, Keogh E, Crombez G, Eccleston C. Methods for studying naturally occurring human pain and their analogues. Pain 2013;154(2):190-199.

[29] Moore DJ, Keogh E, Eccleston C. The interuptive effect of pain on attention. Quarterly Journal of Experimental Psychology 2012;65(3):565-586.

[30] Moore DJ, Keogh E, Eccleston C. The effect of threat on attentional interruption by pain. Pain 2013;154(1):82-88.

[31] Moore DJ, Keogh E, Eccleston C. Headache impairs attentional performance. Pain 2013;154(9):1840-1845.

[32] Moore DJ, Law A. The disruptive effects of pain on multitasking in a virtual errands task. Scandinavian Journal of Pain In Press.

[33] Moriarty O, McGuire BE, Finn DP. The effect of pain on cognitive function: A review of clinical and preclinical research. Progress in Neurobiology 2011;93(3):385-404.

[34] Richter M. A closer look into the multi-layer structure of motivational intensity theory. Social and Personality Psychology Compass 2013;7(1):1-12.

[35] Romero YR, Straube T, Nitsch A, Miltner WH, Weiss T. Interaction between stimulus intensity and perceptual load in the attentional control of pain. Pain 2013;154(1):135-140.

[36] Rubinstein JS, Meyer DE, Evans JE. Executive control of cognitive processes in task switching. Journal of Experimental Psychology: Human Perception and Performance 2001;27(4):763-797.

[37] Schneider W, Eschman A, Zuccolotto A. E-Prime user's guide. Pittsburgh: Psychology Software Tools, Inc, 2001.

[38] Sohn D. Statistical Significance and Replicability: Why the Former Does not Presage the Latter. Theory & Psychology 1998;8(3):291-311.

[39] Stevens J. Applied multivariate statistics in the social sciences: 3rd edition. New Jersey: LEA, 1996.

[40] Veldhuijzen DS, Kenemans J, de Bruin C, Olivier B, Volkerts ER. Pain and attention: Attentional disruption or distraction? The Journal of Pain 2006;7(1):11-20.

[41] Verhoeven K, Crombez G, Eccleston C, Van Ryckeghem DML, Morley S, Van Damme S. The role of motivation in distracting attention away from pain: An experimental study. Pain 2010;149(2):229-234.

[42] Wiech K, Seymour B, Kalisch R, Enno Stephan K, Koltzenburg M, Driver J, Dolan RJ. Modulation of pain processing in hyperalgesia by cognitive demand. NeuroImage 2005;27(1):59-69.

[43] Williamson DJG, Scott JG, Adams RI. Traumatic brain injury. In: R. L. Adams, O. A. Parsons, J. L. Culbertson, SJ Nixon, editors. Neuropsychology for clinical practice Etiology, assessment and treatment of common neurological disorders. Washington, DC: American Psychological Association, 1996. pp. 9–64.

Table and figure captions

Table 1 Means and standard deviations for the n-back and switching tasks under different levels of load and pain (Note: RT = reaction time)

Table 2: Means and standard deviations for the divided attention task under different levels of load and pain (Note: RT = reaction time)

Figure 1: Example of two-back task

Figure 2: Example of the switching task
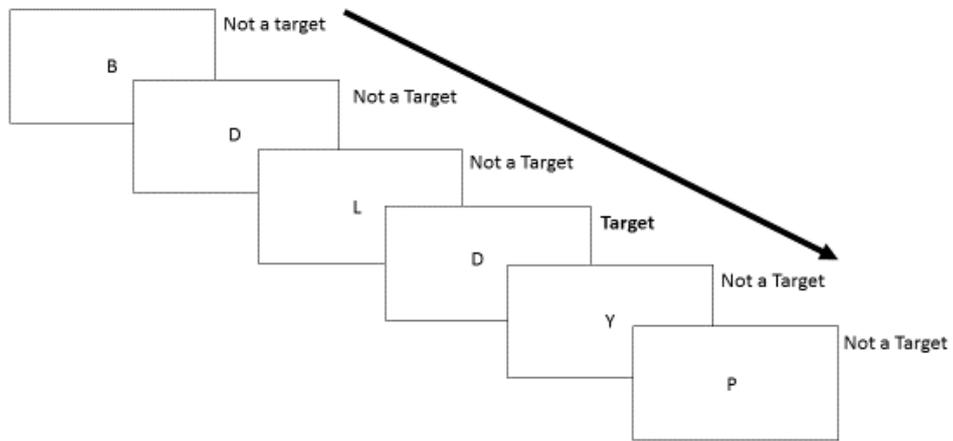
Figure 3: Example of the divided attention task
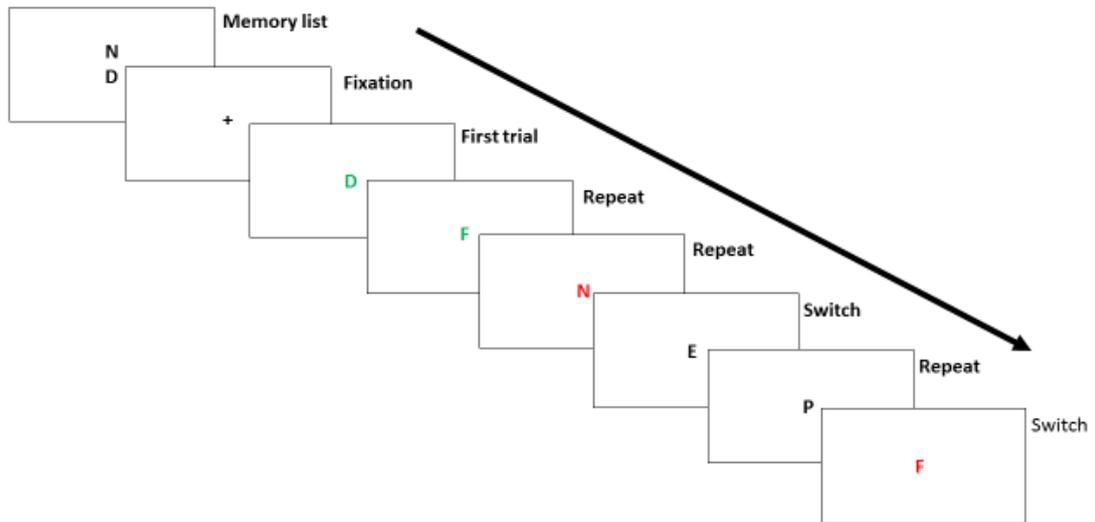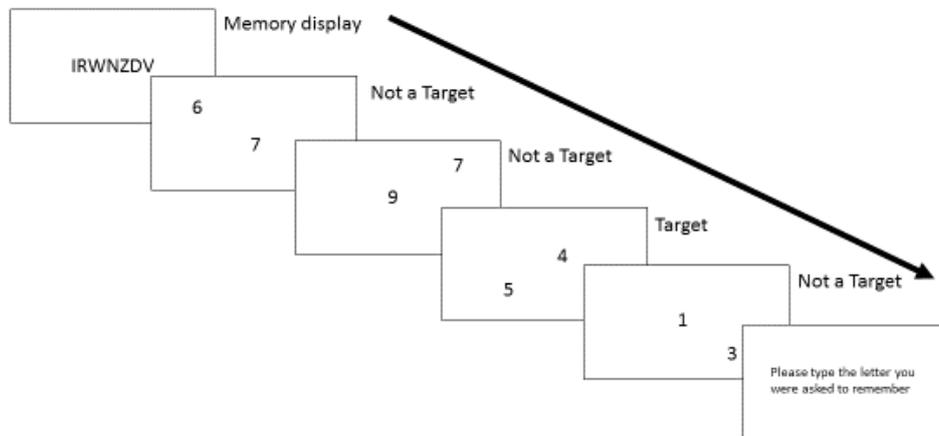
Figure 1

Figure 2

Figure 3

| Task | | Low load | | High load | |
|---|---|---|---|---|---|
| | | *No pain* | *Pain* | *No pain* | *Pain* |
| n-back | Hits | 23.35 (4.70) | 23.25 (4.96) | 21.00 (5.15) | 18.85 (6.40) |
| | False Alarms | 3.20 (3.16) | 2.40 (1.76) | 6.85 (8.93) | 5.65 (4.76) |
| | | | | | |
| Switch | Repeat (RT) | 787 (126) | 783 (126) | 834 (164) | 819 (127) |
| | Switch (RT) | 975 (194) | 953 (167) | 1007 (198) | 1014 (201) |
| | Repeat (accuracy) | .85 (.20) | .91 (.13) | .85 (.23) | .92 (.14) |
| | Switch (accuracy) | .82 (.19) | .87 (.14) | .81 (.21) | .87 (.16) |

Means and standard deviations for the divided attention task under different levels of load and pain

| Task | Single task | | Low Load | | High Load | |
|---|---|---|---|---|---|---|
| | No-Pain | Pain | No-Pain | Pain | No-Pain | Pain |
| RT | 526 (46) | 523 (45) | 532 (53) | 524 (48) | 540 (47) | 533 (43) |
| Accuracy | .69 (.08) | .71 (.08) | .69 (.08) | .70 (.08) | .70 (.08) | .69 (.07) |
| Recall accuracy | N/A | N/A | .95 (.13) | .86 (.17) | .69 (.22) | .68 (.26) |

Note: RT = reaction time