Attentional modulation of thermal pain during a working memory task

Vanessa Tabry

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Signed by the final examining committee:

Dr. Andrew Chapman Chair

Dr. Karen Li Examiner

Dr. Linda Booij Examiner

Dr. Louis Bherer Supervisor

Approved by Dr. Virginia Penhune
Chair of Department or Graduate Program Director

Dean of Faculty Dr. André Roy
Dean of Faculty

Date September 6, 2016

ABSTRACT

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Evidence suggests that pain processing and cognitive task engagement compete for resources under a shared resource model of attention, and that their interaction may be influenced by sensitivity to threat and executive functions factors. We examined the dynamics of pain-related task interruption and task-related pain inhibition in 41 adults with no current pain with the aim of examining whether task-induced analgesia and pain-related task interruption were individually moderated by threat-related psychological traits and executive functions. Participants completed a task while receiving thermal stimuli, and reported significantly lower pain during a challenging task than during a control task, while on average painful stimuli did not significantly impact task performance more than warm stimuli. However, trial-by-trial analyses revealed that reported pain fully explained a trend toward an interruptive effect of pain stimulus on task performance, and conversely, task performance partly counteracted the analgesic effect of task difficulty. Interestingly, weaker divided attention predicted more analgesia while performing the more challenging task, and the mutually inhibitory effects of pain perception and task performance on each other were enhanced in those with high threat sensitivity traits and with low divided attention. Our analyses indicate that individual dynamics of attention allocation between pain and a concurrent task can be partly explained by certain traits. Our results are in support of a limited resource model, and hint that laboratory measures of individual dynamics in attentional pain modulation, along with certain psychological traits and executive functions, could predict clinical pain impairment.

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Contributions of Authors

Vanessa Tabry: Experimental design, experimentation, data analysis, article manuscript writing.

Maxime Lussier and Philippe Brouillard: Executive functions tasks on electronic tablet.

Jason Buhle: Scripts for behavioral procedure of the pain-task paradigm.

Pierre Rainville: Equipment and technical support for thermal pain application, as well as pain theory support.

Mathieu Roy: Experimental design, data analysis support, article manuscript writing support.

Louis Bherer: Experimental design support, executive functions theory and practical support, analysis interpretation support, article manuscript writing support.

Table of Contents

List of Tables

List of Figures

Introduction

Pain is defined as an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or otherwise described in terms of such damage (Merskey & Bogduk, 1994). Pain serves as a warning message for bodily harm, and is therefore expected to interfere with ongoing activities in order to signal possible danger and mobilize the initiation of protective behaviors. As such, this alarm system often wreaks havoc on the daily life of the sufferer even in the absence of underlying pathology. Disability due to pain is a problem particularly in chronic cases, when pain persists long after the expected recovery time for an injury or even in the absence of injury (IASP Task Force, 2012); this is the case, for example, in rheumatoid arthritis and diabetic neuropathy, but also in fibromyalgia, an idiopathic pain condition. However, vulnerability to pain is not uniform - individuals vary in their capacity to resist pain's intrusive effects on other tasks, and long-term resilience to pain might hinge on this individual ability. Unfortunately, however, the psychology of pain and the impairments that accompany it are still not well understood, despite the fact that pain is the primary reason for medical visits in a third of patients (Caudill-Slosberg, Schwartz, & Woloshin, 2004; Mäntyselkä et al., 2001) and that when pain is chronic, it is often associated with marked cognitive impairment (Moriarty, McGuire, & Finn, 2011).

Here, we will begin by discussing pain-associated impairment broadly, and the issues involved with its variable nature across individuals. Literature on laboratory studies of pain-related cognitive impairment in healthy samples, and of the converse effect, distraction from pain by cognitive tasks, will be reviewed. Next, existing attempts to capture individual vulnerability to pain impairment in clinical and experimental studies will be examined. Finally, the limited-resource model of attention with regards to pain and concurrent task processing will be discussed. Based on this conceptual background, a laboratory study on the individual predictors of attentional modulation of pain when pitted against a cognitive task in a healthy, young adult sample will be presented. Then, the findings and their clinical pertinence will be discussed, and future research proposals will be presented.

Pain and associated disability

Chronic pain and associated disability have an enormous impact on society. This major health problem incurs costs associated with treatment and lost productivity estimated at $ 56-60 billion annually in Canada (Pizzo, Clark, & Carter Pokras, 2011). The disabilities that accompany pain range from physical limitations, to anxio-depressive symptomatology and sleep disturbances (Choinière et al., 2010). Pain can impact virtually any activity of daily living - from work, to relations with others, sleep, general mobility, and sexual intimacy. Despite its pervasive nature, it's often unknown how pain exerts its impacts. There is therefore a dire need to expand our knowledge on the multidimensional problem that is pain disability, and effective research and treatment should address both the primary pain and its role in everyday life. Indeed, many clinicians now recognize that functionality plays a pivotal role in recovery from pain conditions. Sullivan and Hyman (2015) defend that the ability to return to work, a behavioral indication of recovery and restoration of function, is as important as distress reduction as a pain treatment outcome. Accordingly, several multidisciplinary programs have been devised with disability reduction as a realistic primary outcome for sub-acute pain. In sum, disability is an important element accompanying pain experience, which still merits further examination in order to be better addressed.

The variable nature of pain disability

People vary in the degrees to which they are functionally impacted by pain, , making it a challenge to treat. It is now well known that tissue pathology does not effectively predict pain (Moseley, 2007), and that in turn, pain is a bad predictor of disability (Crombez, Vlaeyen, Heuts, & Lysens, 1999). It is therefore difficult to set standards in terms of the expected magnitude of disability resulting from given pain conditions. Indeed, while some are very crippled by their pain, remaining bedridden for weeks, others are resilient, quickly regaining normal function in the face of injury. In a striking display of resiliency, in June 2015, Foo Fighters frontrunner Dave Grohl suffered from a leg fracture during a concert in Sweden, yet continued to perform after briefly having his leg bandaged, announcing to the crowd, "You have my promise right now that the Foo Fighters, we're gonna (sic) come back and finish this show" (Coleman, 2015). Certainly, many in his shoes would not have had his glass-half-full perspective and would have instead terminated the performance without a second thought. What exactly about Grohl, or his particular context, made him capable of continuing the show despite the injury? What renders others completely incapacitated, and how can we predict this behavior?

The high variability in disability across pain patients is problematic for several reasons. First, the patients with no injury or revelatory scan to justify their disability are left out in the cold without adequate support and treatment. This is the case for those with fibromyalgia, for instance, a condition often accompanied by short-term memory difficulties and reduced concentration, often called "fibrofog", an affliction which might hinder their ability to work (Wolfe et al., 2010). Second, treatment raises important ethical considerations. How can one justify allocating more resources to a more impaired patient than to a resilient one, when objective evidence for pathology is identical? Conversely, how to prevent abuse of such a system, which could undermine the credibility of future pain patients with legitimate needs? In order to help resolve these issues, it is vital to better understand the factors that influence an individual's propensity to be impacted by pain.

Pain has long been associated with impaired cognition. In particular, clinical observations reveal self-reported memory and concentration difficulties in chronic pain sufferers, and indeed, chronic pain is consistently associated with difficulties reduced attentional abilities, worse executive functions, impaired learning and memory, and impaired perceptual-motor function (Moriarty et al., 2011). It has been argued that pain exacts costs on attentional processing by competing with other tasks for limited cognitive resources (Eccleston & Crombez, 1999; Verhoeven et al., 2011). In turn, however, cognitive integrity is vital for successful pain coping and self-management including remembering to take medications, maintaining social activities, and the maintenance of a number of health-related behaviors (Boggero, Eisenlohr-Moul, & Segerstrom, 2015; Solberg Nes, Roach, & Segerstrom, 2009). Cognitive capacity is also important for self-regulation in pain, that is, the ability to exert control over feelings, thoughts and behaviors in the face of pain (Solberg Nes et al., 2009), This allows one to effectively manipulate the expenditure of cognitive resources in the presence of pain.

As such, one way to obtain some relief from pain is by focusing on another task - obtaining 'task analgesia' (Legrain, Crombez, & Mouraux, 2011). Anecdotally, most can recall instances of becoming distracted from a nagging pain by absorption in engaging work. The ability to redirect attention away from pain and resist distraction by it is vital in the real world, and may be pivotal for resisting pain-related impairment long-term (Seminowicz & Davis, 2007a). It is therefore possible that those who are more disrupted by pain are less able to reallocate attentional resources to other targets in the first place. This raises a chicken-or-the-egg problem - does pain cause cognitive impairment, or do pre-existing cognitive difficulties lead to an inability to resist pain impairment? In order to better disentangle the relationship between cognition and pain, many have taken to the laboratory to study the interruptive effect of pain and the converse effect, distraction from pain by a cognitive task, and the contexts in which these effects arise. This work helps identify individual adaptive and maladaptive cognitive patterns in responding to pain when it first arises, potentially targeting the individual traits or qualities that predict such patterns.

Pain interference effects in the laboratory

Multiple studies have pitted an experimental pain stimulus against a cognitive task to test whether pain interrupts task performance, or 'pain interference'. A review of pain-related interference studies is included in Table 1. Review surveyed all primary research articles published between 1990 and 2015, involving healthy pain-free participants to whom noxious stimuli were administered during a competing cognitive task. In order to be included in the review, at minimum studies had to report pain ratings or task performance derived from the pain-task paradigm. The review returned 43 studies presenting a total of 56 separate experiments. The studies were performed on participants ranging (when reported) between the ages of 17 and 43.5, but were most typically carried out in undergraduate samples (age range 18-22). The experiments employ a variety of noxious stimuli, including heat, electrocutaneous stimuli, ice water (cold pressor test), laser, radiant heat, and esophageal pressure. Tasks used to measure interruption by pain are often working memory tasks, or otherwise challenging cognitive tasks. The most common measures taken were response time (RT) or accuracy on cognitive tasks, as well as pain (globally) or pain intensity (as separate from pain unpleasantness, see Rainville et al., (1992)) reported on numerical rating scales (NRS) or visual analogue scales (VAS). 15 experiments found evidence of interruption of task performance by experimentally delivered pain stimuli (Bingel, Rose, Gläscher, & Büchel, 2007; Buhle & Wager, 2010; Crombez, Eccleston, Baeyens, & Eelen, 1996, 1997; Crombez, Eccleston, Van Den Broeck, Van Houdenhove, & Goubert, 2002; Keogh, Moore, Duggan, Payne, & Eccleston, 2013; D. J. Moore, Keogh, & Eccleston, 2013; Van Damme, Crombez, & Eccleston, 2004; Van Ryckeghem, Crombez, Eccleston, Liefooghe, & Van Damme, 2012; Vancleef & Peters, 2006b). Twenty-one experiments failed to demonstrate a consistent impact of laboratory-induced pain on cognitive task (Coen et al., 2008; Crombez, Baeyens, & Eelen, 1994; Crombez, Eccleston, Baeyens, & Eelen, 1998b; Dick et al., 2006; Erpelding & Davis, 2013; Keogh et al., 2013; D. J. Moore, Keogh, & Eccleston, 2012; D. J. Moore et al., 2013; Petrovic, Petersson, Ghatan, Stone-Elander, & Ingvar, 2000; Pud & Sapir, 2006; Schrooten, Karsdorp, & Vlaeyen, 2013; Seminowicz & Davis, 2007b; Seminowicz, Mikulis, & Davis, 2004; Van Damme, Crombez, Van Nieuwenborgh-De Wever, & Goubert, 2008; Veldhuijzen, Kenemans, De Bruin, Olivier, & Volkerts, 2006; Wiech et al., 2005). Two studies found mixed results (Hood, Pulvers, & Spady, 2013; Houlihan et al., 2004), and the remaining studies did not report whether pain impacted performance on a concurrent task. Notably, the only tasks that were affected were those involving switching and divided attention (Keogh et al., 2013 task 1 ; Moore et al., 2013 task 3; Van Ryckeghem et al., 2012), as well as those requiring continuous updating of working memory, such as the *n*-back working memory task (Bingel et al., 2007; J Buhle & Wager, 2010; Moore et al., 2012 task 4, 2013 task1). However, in three instances, attentional shifting tasks and divided attention tasks were unaffected (Keogh et al., 2013; Moore et al., 2012, Moore et al., 2013). Among the tasks that were unaffected were inhibition tasks (Erpelding & Davis, 2013; Moore et al., 2012; David A.

Seminowicz & Davis, 2007b), a low-load 1-back task (Coen et al., 2008), visual search tasks (Veldhuijzen et al., 2006; Wiech et al., 2005), an interval repetition task thought to recruit the executive functions (Van Damme et al., 2008), a sustained attention task (Moore et al., 2013 task 1), a visuospatial task (Petrovic et al., 2000) and sensory discrimination tasks (Dick et al., 2006; Pud & Sapir, 2006). One sensory discrimination task, used throughout a series of studies, garnered mixed results. The task consisted of identifying whether an auditory tone was low or high pitched, where the tone was presented at three different latencies in the vicinity of a 1.5s presentation of either painful or non-painful electrical stimulation. Some reported significantly slower responses during shock (Crombez et al., 1996; Crombez, Eccleston, Baeyens, & Eelen, 1998a; Crombez et al., 2002) while others did not (Crombez et al., 1994, 1998b). Given these results, we can speculate that tasks involving multiple parallel subtasks and rapid focal attentional shifts (either in switching, divided attention or updating frameworks) may be more impacted by pain. During such focal attentional shifts, attention may become more vulnerable to bottom-up capture by stimuli like pain. Applied more directly to divided attention paradigms, if pain enters attention while the breadth of processing capacity limits is already nearly saturated by multiple tasks, pain monitoring may be automatically selected as a new subtask. This is supported by the interesting findings of Keogh et al. (2013), who found that a secondary task, but not the primary to-be-prioritized task, in a multitasking breakfast making paradigm was impacted by pain, which suggests that pain processing took the place of the secondary task in the attentional workspace. No modality of noxious stimulus in particular appears to provoke larger interference effects than others. In sum, there is mixed evidence for the interruptive effects of pain in healthy samples, with certain types of cognitive tasks being more affected than others. It seems that there is a difficulty consistently representing cognitive impairment due to pain in the laboratory.

A protective mechanism: distraction by cognitive task

As discussed above, engaging in a competing cognitive task may be analgesic. Returning to the example of the Foo Fighters lead, did absorption in the task of playing music temporarily pull Grohl's attention away from his injury? Did some pre-existing tendency to tenacity, the approval of a large audience and of course, the promise of a large financial reward, lead him to be completely distracted from his pain? The ability to temporarily withhold attending to pain to prioritize ulterior goals is a vital one, whether for escape, combat, or, in Grohl's case, music.

In particular, it has been proposed that working memory engagement can shield against distraction by pain (Legrain et al., 2011). Accordingly, complementary to the literature on pain-related task interference, a large body of studies has examined the converse effect, that of analgesia due to distraction by a cognitive task. A review of studies examining task-related analgesia is included in Table 1. The methodology is understandably similar to that in the pain interference literature, with the addition of the use of certain distraction tasks with no quantitative performance output (videogames, mental arithmetic, word generation). Most studies on task analgesia did not address whether pain interrupted task performance, even when performance measures were available. Twenty-eight experiments report statistically significant reductions of pain during cognitive distraction tasks (Bantick et al., 2002; Bingel et al., 2007; Buhle, Stevens, Friedman, & Wager, 2012; Buhle & Wager, 2010; Coen et al., 2008; Crombez et

Table 1

Review of pain interference and task analgesia literature in healthy adults from 1990 to 2015

			Stimulus		Task					
Author & date	Exp	N	Type	Calib	Type	Calib	PI	TA	Mod	Mod effects
Bantick et al. 2002		8 (2F)	heat	YES	Counting Stroop	NO	-	YES	-	
Bingel et al. 2007		16 M	laser	NO	n-back	NO	YES	YES	-	
Brooks et al. 2002		18 (6F)	heat	YES	Global motion discrimination	NO	-	-	-	
Buhle et al. 2010		24 (15F)	heat	YES	3-back	YES	YES	YES	-	
Buhle et al. 2012		33 (19F)	heat	YES	3-back	NO	-	YES		
Coen et al. 2008		12M	esophageal pressure	YES	1-back	NO	NO	YES	-	
Crombez et al. 1994		44 (33F)	radiant heat	NO	Tone discrimination	NO	NO	-	YES	Warnings about incoming stimuli reduced SCR and reported pain
Crombez et al. 1996		26 (16F)	ECS	YES	Tone discrimination	NO	YES	-	-	
Crombez et al. 1997		24 (15F)	ECS	YES	Tone discrimination	NO	YES	-	-	
Crombez et al. 1998a		38 (16F)	ECS	NO	Tone discrimination	NO	YES	-	YES	High-threat instructions increased interference
Crombez et al. 1998b	1	44 (32F)	ECS	NO	Tone discrimination	NO	NO	-	YES	Catastrophzing increased interference and increased effect of threat instructions on task
	2	36 (26F)	ECS	NO	Tone discrimination	NO	NO		YES	Catastrophzing increased interference
Crombez et al. 2002		67 (48F)	ECS	NO	Tone discrimination	NO	YES	-	YES	Catastrophizing but not negative affectivity increased interference

			Stimulus		Task					
Author & date	Exp	N	Type	Calib	Type	Calib	PI	TA	Mod	Mod effects
Dick et al. 2006		16 (11F)	ischemic pain	NO	Auditory mismatch negativity	NO	NO	-	-	-
Dowman et al. 2004		28 (5F)	TENS sural nerve	YES	Subtraction	NO	-	YES	-	-
Erpelding et al. 2013		80 (40F)	Tonic heat	YES	Numerical interference	NO	NO	NO	-	-
Frankenstein et al. 2001		12 (6F)	CPT	YES	Verbal attention	NO	-	YES	-	-
Hodes et al. 1990		45 (29F)	CPT	NO	Mental arithmetic	NO	-	YES	-	-
Hood et al. 2013		78 (39F)	CPT	NO	Letter-number sequencing	NO	MIXED	-	-	-
Houlihan et al. 2004		21(9F)	CPT	NO	Sternberg	NO	MIXED	NO	-	-
Keogh et al. 2013	1	62 (40F)	heat	YES	Breakfast-making (planning & multitasking)	NO	YES	-	-	-
	2	62 (40F)	heat	YES	word generation (planning & multitasking)	NO	NO	-	NO	Catastrophizing did not increase interference
Kóbor et al. 2009		15 (5F)	capsaicin + pinprick	NO	Facial discrimination	NO	-	YES	-	-
Lautenbacher et al. 2007		40 (20F)	heat + ECS	YES	Counting	NO	-	YES	-	-
Moore et al. 2012	1	20 (13F)	heat	YES	Sustained attention	NO	NO	-	-	-
	2	20 (10F)	heat	YES	Flanker	NO	NO	-	-	-
	3	20 (16F)	heat	YES	Posner	NO	NO	-	-	-
	4	20 (14F)	heat	YES	2-back	NO	YES	-	-	-

			Stimulus		Task					
Author & date	Exp	N	Type	Calib	Type	Calib	PI	TA	Mod	Mod effects
	5	20 (14F)	heat	YES	Go/no-go	NO	NO	-	-	-
	6	20 (7F)	heat	YES	Switch (prime)	NO	YES	-	-	-
	7	20 (12F)	heat	YES	Dual-task	NO	YES	-	-	-
Moore et al. 2013	1	50 (29F)	heat	YES	n-back	NO	YES	-	NO	high-threat instructions had no effect
	2	(w/in S)	heat	YES	Switching task	NO	YES	-	NO	high-threat instructions had no effect
	3	(w/in S)	heat	YES	Divided attention	NO	NO	-	NO	high-threat instructions had no effect
Petrovic et al. 2000		10M	CPT	NO	Computer maze	NO	NO	YES	-	-
Pud et al. 2006		60 (46F)	heat	NO	Tone discrimination	NO	NO	YES	-	-
Raudenbusch et al. 2009	1	30 (22F)	CPT	NO	Videogames	NO	-	YES	NO	aggressiveness and competitiveness did not play a role
	2	27 (13F)	CPT	NO	Videogames (sports and fighting types)	NO	-	YES	NO	aggressiveness and competitiveness did not play a role
Remy et al. 2003		12 (6F)	heat	Yes	Word generation	NO	-	YES	-	-
Roelofs et al. 2009		90F	CPT	NO	Tone discrimination	NO	-	NO	-	-
Schlereth et al. 2003		10 (6F)	laser	NO	Subraction	NO	-	YES	-	-
Schrooten et al. 2013		98 (76F)	ECS	NO	Impression formation (perseveration task)	NO	NO	-	YES	Catastrophizing reduced time allocated to task during pain
Seminovicz et al. 2004		18 (10F)	TENS median nerve	YES	Counting stroop	NO	NO	-	-	-

			Stimulus		Task					
Author & date	Exp	N	Type	Calib	Type	Calib	PI	TA	Mod	Mod effects
Seminovicz et al. 2007		23 (12F)	TENS median nerve	YES	Multisource interference	NO	NO	NO	-	-
Terkelsen et al. 2004		26M	TENS sural nerve	YES	Mental arithmetic	NO	-	YES	-	-
Valet et al. 2004		7 (1F)	heat	YES	Stroop	NO	-	YES	-	-
Van Damme 2004		37 (31F)	ECS	NO	Tone discrimination	NO	YES	-	-	-
Van Damme 2008		101(79F)	CPT	NO	Random interval repetition	NO	NO	YES	YES	High-threat instructions increased pain interference, did not affect task analgesia
Van Ryckeghem et al. 2012		60 (48F)	ECS	YES	Task-switching paradigm	NO	YES	-	-	-
Vancleef et al. 2006†		48 (36F)	ECS	NO	auditory tone discrimination	NO	YES	-	YES	Catastrophizing increased interference
Veldhuijzen et al. 2006	1	16 (8F)	CPT	NO	Visual search	NO	NO	-	-	-
	2	14M	CPT	NO	Visual search	NO	NO	YES	-	-
Verhoeven et al. 2011		91 (72F)	CPT	NO	Random interval repetition	NO	-	YES	YES	Inhibition predicted faster responses on task during CPT (no pain-free condition)
Wiech et al. 2005	1	11 (3F)	capsaicin & heat	YES	Rapid serial visual processing	NO	NO	-	-	-
	2	15 (5F)	capsaicin & heat	YES	Rapid serial visual processing	NO	-	YES	-	-
Yamasaki et al. 2000		11 (3F)	ECS	YES	Mental calculation or memorization	NO	-	YES	-	-

Note. Calib = calibration; Exp = experiment; Mod = moderation; PI = pain interference; TA = task analgesia.

† No noxious stimuli used provoked sensations reaching or surpassing the pain threshold.

al., 1998a, 1998b, 2002; Dowman, 2004; Frankenstein, Richter, McIntyre, & Rémy, 2001; Hodes, Rowland, Lightfoot, & Cleeland, 1990; Kóbor, Gál, & Vidnyánszky, 2009; Lautenbacher, Prager, & Rollman, 2007; Petrovic et al., 2000; Pud & Sapir, 2006; Raudenbush, Koon, Cessna, & McCombs, 2009; Rémy, Frankenstein, Mincic, Tomanek, & Stroman, 2003; Schlereth, Baumgärtner, Magerl, Stoeter, & Treede, 2003; Terkelsen, Andersen, Mølgaard, Hansen, & Jensen, 2004; Valet et al., 2004; Van Damme et al., 2008; Vancleef & Peters, 2006b; Verhoeven et al., 2011; Yamasaki, Kakigi, Watanabe, & Hoshiyama, 2000). Only two experiments demonstrated no analgesic effect of a task (Houlihan et al., 2004; Roelofs, Peters, Van Der Zijden, & Vlaeyen, 2004). One group performed a series of studies where they split the study sample according to whether pain increased or decreased during the competing task (Erpelding & Davis, 2013; Seminowicz & Davis, 2007b; Seminowicz et al., 2004), a strategy that is discussed below. Harder tasks are proposed to be more analgesic (Seminowicz & Davis, 2007b), and electroencephalography (EEG) studies show that the amplitude of P2 component of nociceptive evoked potentials is reduced under more difficult task conditions (Legrain, Bruyer, Guérit, & Plaghki, 2005), suggesting reduced attentional capture by pain. The general finding is that engaging in a cognitive task can inhibit experimentally induced pain, and there is more experimental evidence for the use of cognitive distraction than of the interruptive effects of pain on cognitive tasks. In experimental literature, task performance tends to prevail.

Predictors of clinical pain and related disability

A recent clinical approach has been to seek individual traits that prospectively predict the course of pain and related impairment, over and above that predicted by known tissue damage. Indeed, several studies support the contention that certain affective tendencies or cognitive traits may favor more severe pain and impairment. In particular, the predictive values of depression, anxiety, fear of pain, catastrophizing, and mood have been examined. These have given way to the development of a pivotal model to explain the perpetuation of pain, the fear-avoidance model of chronic pain (Crombez, Eccleston, Van Damme, Vlaeyen, & Karoly, 2012), in which disability and suffering associated with pain arise and are maintained in a cycle that includes maladaptive beliefs about pain, fear of pain, activity avoidance, and negative affect. A related concept, pain catastrophizing, is a relatively stable trait that has been initially defined as 'an exaggerated negative "mental set" brought to bear during actual or anticipated pain experience' (Sullivan, Bishop, & Pivik, 1995). It has also been described as 'the tendency to magnify the threat value of pain stimulus and to feel helpless in the context of pain, and by a relative inability to inhibit pain-related thoughts in anticipation of, during or following a painful encounter' (Quartana, Campbell, & Edwards, 2009). Pain catastrophizing is consistently found to play an important role in pain in some indices of experimental pain sensitivity as well as in clinical pain outcomes, including clinical pain severity, pain-related disability, depression, and changes in social support networks (Quartana et al., 2009). In addition, a study found that a depressive disorder was a long-term risk factor for incidence of back pain (Larson, Clark, & Eaton, 2004). The effects of negative affect on pain appear to be bidirectional: a literature review (Dersh, Polatin, & Gatchel, 2002) demonstrating a high prevalence of depression in chronic pain sufferers suggests that depression and frequently comorbid anxiety worsen pain states through a diathesis-stress model, in which pre-existing semi-dormant traits become exacerbated by the stress of pain, which in turn worsen the pain condition. Finally, mood seems to play a role in pain even on a day-to-day basis. Connelly et al. (2007) examined daily diary samplings of pain and affect in rheumatoid arthritis patients, and found that patients who effectively regulated negative affect or maintained elevated positive affect over two consecutive days experienced decreased arthritis pain on the following day. Fear of pain, anxiety and catastrophizing may increase pain impairment by magnifying attentional engagement to pain and pain-related threat (Eccleston, Crombez, Aldrich, & Stannard, 1997; Keogh, Ellery, Hunt, & Hannent, 2001; Liossi, 2012). There is therefore ample evidence that certain individuals are predisposed to feel more pain, or to be more impaired by pain, both short-term and over longer periods of time, by virtue of their anxio-depressive symptomatology and their tendency to experience pain-related threat.

Broadly, trait mindfulness is the ability to attend to the present moment without being preoccupied (Brown, Ryan, & Creswell, 2007; Sauer et al., 2013). Mindfulness as a trait and as cultivated through meditation or mindfulness-based interventions has received a large amount of attention of late, for its benefits in mental health outcomes (Keng, Smoski, & Robins, 2011), the promotion of mental well-being (Hanley, Warner, & Garland, 2015), and for its proposed role in improving cognitive ability (Chiesa, Calati, & Serretti, 2011). Mindfulness-based interventions have been used for chronic pain; however, a systematic review of randomized control trials of mindfulness-based therapies for chronic pain did not find that the interventions reduced pain intensity, but found instead that they improved mental health in pain sufferers (Song, Lu, Chen, Geng, & Wang, 2014). Indeed, mindfulness has been defined as the ability to foster a non-judgmental acceptance of emotions, thoughts and sensations on a moment-to-moment basis (Lutz, Slagter, Dunne, & Davidson, 2008). The two key components of mindfulness, awareness and non-judgment, may serve first to render a pain sufferer aware of their own negative thought patterns, and then to reduce their occurrence. Mindfulness is thought to act on mood disorders by bringing the suffer to recognize maladaptive automatic thoughts that fuel or maintain negative affective states, and eventually to reduce the automaticity of such thoughts (Kang, Gruber, &

Gray, 2012). This process may also underlie alterations in pain appraisal, through the de-automatization of highly engrained maladaptive cognitive responses to expected or experienced pain - a clear nudge to catastrophizing. Accordingly, many mindfulness-based cognitive therapies for pain seem to target pain catastrophizing, and higher mindfulness is known to predict lower pain catastrophizing (Mun, Okun, & Karoly, 2014a; Schütze, Schütze, & Preece, 2009). Upon testing the notion that mindfulness is the antithesis of catastrophizing, however, a study in healthy participants found the two constructs to be correlated but conceptually distinct once having controlled for the confounding factor of worry (Day, Smitherman, Ward, & Thorn, 2014). Similarly, a study carried out in chronic pain patients undergoing mindfulness-based cognitive therapy did not find a relationship between mindfulness and catastrophizing scores (de Boer, Steinhagen, Versteegen, Struys, & Sanderman, 2014). There is therefore reason to believe that, while mindfulness and catastrophizing may share common variance, there is still a portion of mindfulness that is not captured by catastrophizing, and therefore it merits examination as a trait in its own right. Notably, in pain-task concurrent contexts, mindfulness may act by increasing the spread of attention between pain and task, promoting nonreacting and nonjudgment of incoming pain threat. In addition, mindfulness has been proposed to be associated with increased cognitive flexibility, or the ability to adapt cognitive processing strategies in the face of new and unexpected situations (A. Moore & Malinowski, 2009). In sum, mindfulness is likely to influence one's ability to handle complex competing task paradigms involving pain, partly by counteracting the effects of catastrophizing but also in part by exerting non-catastrophizing mediated effects on attentional control.

Having stronger executive functions may help resist the tendency to orient automatically towards pain and threat, an ability that may be protective long-term. Accordingly, a few recent studies suggest that weaker executive functions prospectively predict worse pain. Executive functions can be conceptualized as domain-general cognitive abilities that are responsible for planning and attention allocation, especially in complex task contexts. They include the capacities to inhibit prepotent responses, to switch between multiple task sets, to update the contents of working memory, and to divide attention between co-occurring tasks (Miyake et al., 2000). The cognitive flexibility afforded by executive functions is proposed to allow the selection and maintenance of positive coping strategies, such as distraction, and the suppression of automatic maladaptive strategies, such as excessive rumination (Solberg Nes et al., 2009). In a prospective study in breast cancer patients, executive functions as measured on the Trail Making Test B one month prior to surgery predicted the presence of chronic pain six and 12 months post-operatively (Attal et al., 2014). In a longitudinal study conducted in a community-dwelling elderly sample, pain, general health, and task-switching ability were sampled every six months for five years. When participants reported higher-than-usual pain, lower task-switching ability predicted poorer health at follow-up visits (Boggero et al., 2015), suggesting that task-switching ability was involved with successful coping with pain. In sum, there is accumulating evidence that the integrity of executive functions predicts one's susceptibility to be impaired by pain.

Experimental studies of vulnerability to pain disruption

Being sensitive to threat and having weaker executive functions may constitute vulnerability factors for pain-related impairment. If such factors increased pain impairment even pre-clinically, then they may be detectable in experimental paradigms. Therefore, in an attempt to capture the variable nature of pain-related impairment, some have taken an experimental approach that attempts to highlight individual differences in behavior in laboratory paradigms.

Seminovicz, Mikulis & Davis (2004), Seminowicz & Davis (2007b), and Erpelding & Davis (2013) gave young adults a cognitive task and concurrent pain stimuli, and split their sample according to participants' performance on the task while in pain. Those who performed faster during painful stimulation than with no stimulation were characterized as A-type ('attention dominates'), those who slowed down as a result of the pain stimuli were categorized as P-type ('pain dominates'). Based on this characterization, the authors argued for the existence of distinguishable individual tendencies to favor pain or a task when presented concurrently, reflecting potential vulnerabilities to pain interference. However, contrary to the authors' conclusions, evidence of A-type and of P-type as a sustained trait over repeated testing has not yet been found; a detailed critique of the study and some follow-up work is presented in the General Discussion. Nevertheless, the studies represent new attempts to capture interindividual differences in the attentional management of pain, and urge the conducting of better-controlled and more meticulous studies on individual differences.

Other studies have examined the factors that modulate laboratory pain-related interference. Table 1 includes a review of the literature on moderation of pain and performance in concurrent paradigms. Some studies found that instructions designed to increase the threatening nature of the pain tended to boost its interference effect on task performance (Crombez et al., 1998a; Van Damme et al., 2008), while one found that they had no effect (Moore et al., 2013). Other studies found a moderating role of pain catastrophizing, in that those with higher self-reported pain catastrophizing displayed larger interruptive effects of pain on task performance (Crombez et al., 1998b, 2002; Schrooten et al., 2013; Vancleef & Peters, 2006a). However, Keogh et al. (2013) and Moore et al. (2013) found no influence of threat instructions nor pain catastrophizing on the task-interruptive effect of pain. In particular, it seems that catastrophizers may have more difficulty disengaging from pain cues than non-catastrophizers (Van Damme et al., 2004). Executive functions in turn are likely to play a protective role in experimental pain-task paradigms - even without a high threat value, pain typically intrudes as an exogenous, automatic attentional capture in the context of other ongoing tasks. As such, management of pain and a controlled task should employ attentional resources, the allocation of which is controlled by domain-general executive functions. For instance, worse inhibition abilities may predict larger interruptive effects on task performance, by virtue of a difficulty suppressing attention to pain. Similarly, the ability to switch rapidly between attentional targets may permit rapid reinstatement of attentional focus on a task when being distracted by pain. Conversely, better divided attention ability could favor simultaneous processing of both pain and task. In the only known study to date on the effects of executive functions on pain-task paradigms (Verhoeven et al., 2011), better cognitive inhibition as measured by an anti-saccade task predicted faster responding on a challenging task during a cold pressor test. However, it is important to note that task performance during pain was not compared with a pain-free control condition. As such, there was no examination of pain interference per se, only a measure of individual executive function ability that may or may not have been affected by the concurrent pain stimulus; a better-controlled study is warranted to this effect. In sum, there is moderate evidence that catastrophizing and pain threat increase pain's interruptive effect, and very limited evidence that executive functions moderate attentional modulation of pain.

Models of attention to pain and task - single-capacity and bottleneck theories

While several studies examine task-analgesic and pain-interruptive processes separately, very few have examined them together. However, in theory, these processes should interact, since pain typically emerges in the context of ongoing competing activities. In cases of total absorption in a task, concentration may shield from nociception. If, however, pain is felt as very intense, it should pull attention away from other task targets. In other words, task performance and pain processing should be mutually inhibitory. This would apply in a single-capacity model (Kahneman, 1973), where attention is drawn from a common, limited pool and therefore its allocation to one target decreases availability for other potential targets. Additionally, this tradeoff may be also well described by some bottleneck theories (Broadbent, 1966) in which two targets of attention cannot be processed simultaneously if they share a common underlying mechanism. According to such theories, if no consistent for support of a shared resource is found, then it may be that both are carried out by separate mechanisms. Bottleneck theories also propose that filters at different stages of perceptual processing control contents of attention, and may help account for top-down inhibition of pain at the early sensory or spinal level (Roy, Lebuis, Peretz, & Rainville, 2010). As such, both attentional theories combined may help paint a useful portrait of attention to pain and a simultaneous task. In any case, within attentional theories, task analgesia and pain-related interruption should be anticorrelated, thereby reflecting the tradeoff in processing of either pain or task in the context where they compete.

Executive functions and threat-related psychological traits should play roles in a shared-resource model of pain and competing task performance. If pain and concurrent task processing are managed by attention, then individual state and trait differences in attention should affect behavior in pain-task contexts. More specifically, the requirement to inhibit pain in order to favor task performance, and to alternate attentional targets in such contexts, suggests that better cognitive inhibition and switching abilities should facilitate attentional control. Performing a task while processing pain has also been conceptualized as a divided attention task (Seminowicz & Davis, 2007b), and as such, individual divided attention capacity should affect performance in such paradigms. As well, given that catastrophizing and anxiety are known to act partly through an attentional bias to threat (Cisler, Bacon, & Williams, 2009), they should also predict attentional dynamics in pain-task paradigms. The finding of moderating factors might also help explain the inconsistent findings with regards to experimental models of pain-related task interference. Indeed, it may be that key contextual differences between experiments brought to bear the manifestation of various individual traits, and that these factors capture substantial variability in results.

Attentional models of pain-task interactions in experimental application

Most studies seem to assume that pain perception is high in conditions where pain interrupts tasks, without actually linking task interruptions with the sensation of pain. It is possible, for instance, that pain-related interruption is actually accompanied by attenuated pain perception, or that task-related analgesia can occur even for low levels of task performance. Without verifying that pain interruption is associated with high reported pain levels, and that task analgesia is linked with high performance on a task, we cannot demonstrate the limited quality of attention in pain-task contexts.. In order to do so, it would be necessary to show that task-related analgesia is actually linked to higher task engagement, and that pain-related task interruption is linked to more pain processing. To our knowledge, one study (Buhle & Wager, 2010) found tradeoffs between cognitive task performance and pain perception using multilevel statistical methods. In their experiment, healthy young adults received three different levels of heat pain while completing a challenging 3-back working memory task, and were to rate their pain after every 20s task trial. First, they found a dose-dependent impact of applied pain level on task performance, and a complementary analgesic effect of the task on pain, compared to a passive watch condition. Using multilevel mediation models, where individual experimental trials are nested within participants, the authors show that trial-by-trial increases in task performance inhibited pain, and that conversely, higher reported pain impacted task performance. In essence, they demonstrated that moment-to-moment fluctuations in attention allocation were liable to affect performance and pain across individual trials, even within the same task condition. To our knowledge, their work is the first and only study to show direct support of the attentional tradeoff between task performance and pain perception. However, the authors defend an attentional model that is purely one of shared common-pool resources, without discussing the contributions of a bottleneck model or its features to their own model. Additionally, the study did not test the effects of individual psychological and cognitive factors on the attentional dynamics between task performance and pain perception. Finally, some important methodological improvements to their study can be made, and are described below.

Motivations for current work

The motivations to carry out the current research are multiple. First, given that the work by Buhle and Wager (2010) on trial-by-trial fluctuations in pain and concurrent task processing is the first of its kind, there is a clear need to replicate evidence for or against a resource model hypothesis of attentional modulation of pain. Then, in the event of characterizing a concurrent pain-task processing model, whether or not it adheres to the shared-resource model, it would be important to examine the contribution of psychological and cognitive factors, notably threat-related psychological factors and of executive functions, to the model. Finally, the addition of features of bottleneck theories to the current shared-resource model for pain and task performance may provide useful supplemental explanations to previous findings and to those in our study.

Methodological considerations

We approached the conception of a new experimental project with multiple methodological considerations in mind. We chose the n-back task because it has been shown to be vulnerable to disruption by pain in some studies (Bingel et al., 2007; J Buhle & Wager, 2010; Moore et al., 2012 task 4, 2013 task 1). We set the n load to 2, after having found that n = 3 was considered too difficult by pilot participants. Thermal stimuli were used because it is possible to rapidly deliver continuous pain for a duration that could cover a portion of a cognitive task trial. These task and pain modalities were also selected with the aim of replicating of the work of Buhle and Wager (2010).

In the literature in Table 1, most studies apply noxious stimuli that are individually calibrated for individual sensitivity differences. This helps ensure that those experiencing higher pain-related interference do not do so because they feel more pain. In order to avoid this possibility, in our currently proposed study, we control for differences in pain sensitivity. While noxious stimulus intensity is typically adjusted for individual differences, calibration of the competing task to participants' abilities is infrequent - the only known case to date being that of Buhle and Wager (2010). This may lead to vastly different degrees of task-related analgesia and individual vulnerability to task disruption. For instance, those with slower processing speed might engage in more effortful performance, which in turn may be more analgesic. In order to avoid such confounding effects, we control for baseline task performance in our current study. Also, although many studies compare pain to non-painful sensory conditions, Buhle and Wager (2010) compare three different levels of pain sensation, but use no non-painful heat condition. To ensure that task interruption effects are due to pain, over and above sensory distraction alone, our experiment compares a Pain condition to a non-painful Warm condition. In addition, Buhle and

Wager (2010) compare a 3-back task to no a no-task condition. This, however, may allow the use of coping methods to reduce pain (relaxed or accelerated breathing, meditation, displacement of pain by pinching another body part, pain faces, vocalizations). Indeed, pilot participants in a no-task condition of the current study often outwardly displayed such coping mechanisms and later corroborated them with verbal reports. We wanted to avoid the use of coping mechanisms, as they are themselves subject to variation (Heyneman, Fremouw, Gano, Kirkland, & Heiden, 1990; Hirsh, George, Riley, & Robinson, 2007); as such, we chose a simple attentional task as an 'easy' control for the 2-back task. We therefore propose a study that combines several carefully selected methodological strategies in one experiment.

Project aims and hypotheses

With our proposed study, we aimed to examine attentional modulation of pain and task in a context where they compete, as well as the contributions of psychological and executive functions factors of interest. Study hypotheses are depicted in Figure 1. Specifically, we wanted to test the hypotheses that a pain stimulus will impact performance on a challenging cognitive task (Hypothesis 1), and that a challenging task will reduce pain perception (Hypothesis 2), where both pain intensity and cognitive task difficulty were individually calibrated to each participant at baseline. We aimed to replicate and expand upon previous results (Buhle & Wager, 2010), and verify whether the pain-inhibitory effects of the difficult task are mediated by task performance (Hypothesis 3), and conversely, whether the task-interruptive effects of pain were mediated by higher pain perception on a trial-by-trial basis (Hypothesis 4). Finally, and most importantly, we wanted verify whether pain catastrophizing, trait anxiety, and mindfulness (Hypothesis 5a), and inhibition, switching, and dual-tasking costs (Hypothesis 5b) moderated the trial-by-trial individual dynamics between pain and performance. Specifically, we expected high catastrophizing, high anxiety, low mindfulness, and worse executive functions to predict higher pain interference, and less task analgesia effects. We had no specific hypotheses regarding the moderation of the mediated effects.

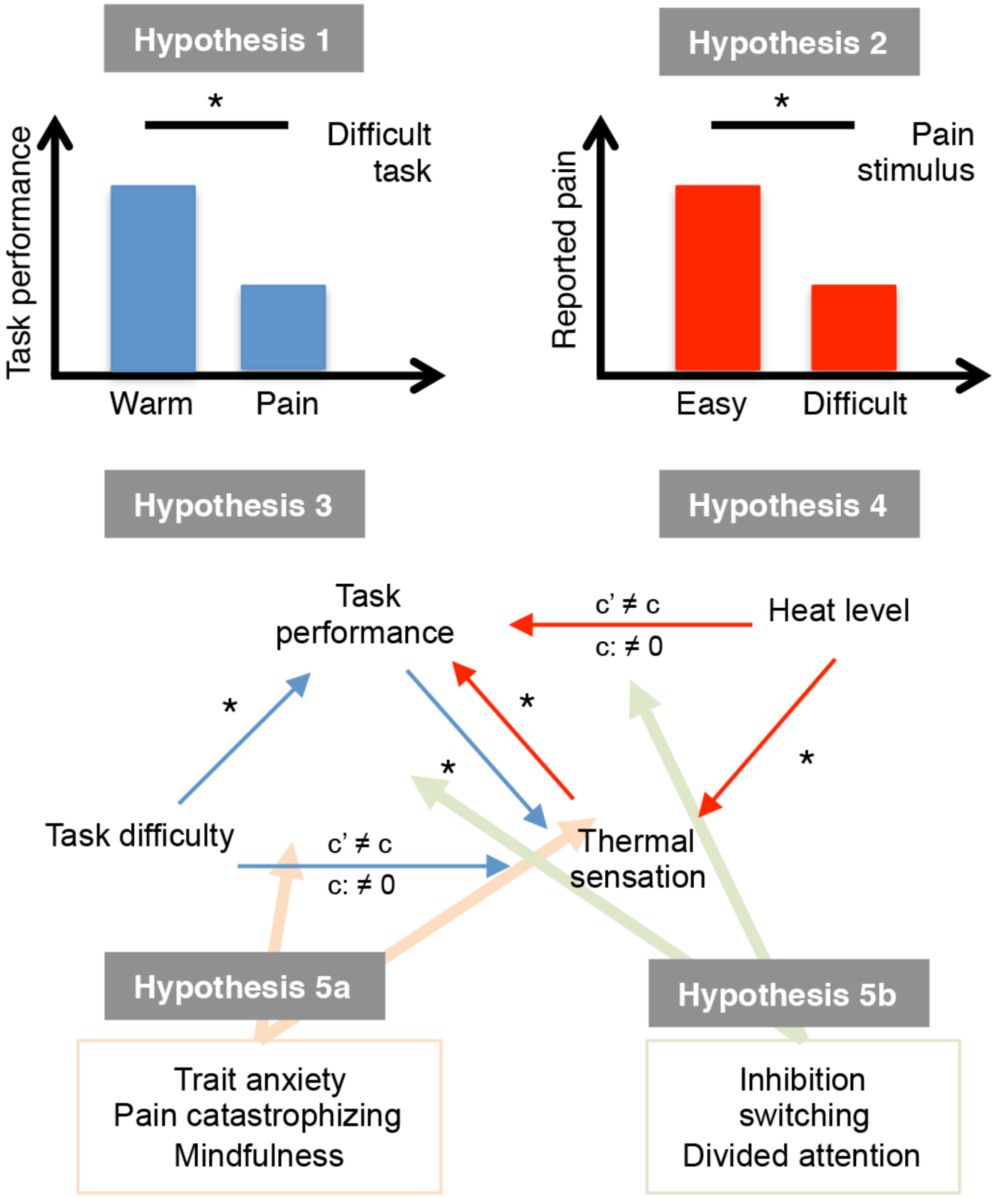

Figure 1. Illustration of the hypotheses for an experimental study on attentional modulation of pain and task performance in a context where they are pitted together.

Study

Moderating effects of anxiety, pain catastrophizing, mindfulness and divided attention on attentional modulation of pain during a cognitive task

Vanessa Tabry [ab], Maxime Lussier [bc], Philippe Brouillard [bd], Jason Buhle [e], Pierre Rainville [bf], Mathieu Roy [bg], Louis Bherer [ab]

Complete affiliation of authors

a PERFORM Centre & Department of Psychology, Concordia University
b Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal
c Department of Psychology, Université de Montréal
d Department of Mathematics and Statistics, Université de Montréal
e Department of Psychology, Columbia University (former)
f Département de Stomatologie, Université de Montreal
g Department of Psychology, McGill University

1. Introduction

Pain acts as an alarm system: it briefly disrupts ongoing activities to draw our attention towards external or internal sources of potential injury (Eccleston & Crombez, 1999). However, in some contexts pain is not a top priority, in which case it must be ignored to favour concentration on more important tasks (Legrain, Crombez, Plaghki, & Mouraux, 2013). The capacity to shut down pain when it conflicts with competing goals therefore seems to be a key factor in understanding the substantial heterogeneity in pain-related disability (Berryman et al., 2013). Indeed, there is abundant evidence for the analgesic effects of distraction by a competing task (see Table 1 for a review). However, inter-individual disparities to yield to pain's disruptive effects could also be caused by individual variations in pain sensitivity or task performance. Here, we carefully controlled for these baseline differences in order to examine characteristic patterns in the trade-off between pain perception and task performance. We predicted that traits influencing pain's threat value, such as anxiety or pain catastrophizing, might increase pain's disruptiveness by raising the relative importance of pain compared to task performance. This has in fact been demonstrated in healthy individuals (Crombez et al., 1998b, 2002; Van Damme et al., 2004; Vancleef & Peters, 2006a) and in chronic pain patients (Crombez, Eccleston, Baeyens, Van Houdenhove, & Van Den Broeck, 1999; Eccleston et al., 1997; Eccleston, 1994; Vlaeyen & Linton, 2000). Moreover, the capacity to resist distraction or to rapidly switch between tasks in order to achieve pre-defined goals is also the hallmark of executive functions (Miyake et al., 2000). Therefore, we also postulated that performance on tests measuring switching, inhibition, or divided attention abilities would be predictive of the capacity to resist pain's disruptive effects. Finally, we also examined the influence of trait mindfulness on pain's disruptive effects. Mindfulness is described as the nonjudgmental acceptance of one's thoughts, sensations and emotions (Lutz et al., 2008). Interestingly, previous studies have shown that mindfulness not only mitigates the detrimental effects of pain catastrophizing (Petter, Chambers, McGrath, & Dick, 2013), but that it also improves executive control (Teper & Inzlicht, 2013), making it a potentially important factor for explaining susceptibility to pain-related disruption.

Additionally, we also considered how pain's disruptive effects and task-induced analgesia are related to one to another. Indeed, according to limited resource models of attention (Kahneman, 1973), pain and task processing should occur at each others' expense as soon as their combined resource requirements exceed working memory capacity. Therefore, inter-individual differences in pain disruption or task-induced analgesia could be due to either bias in prioritization of task or pain, or to differences in working memory capacity. While a prioritization bias would predict a systematic shift in pain perception and task performance, limited working memory capacity would be expected to cause trial-by-trial fluctuations in pain perception and task performance, depending on which one secures the limited attentional resources on a particular trial. Alternatively, it is also possible that pain-related interference and task analgesia may not entirely depend on the same mechanism. For instance, it has been proposed that redirecting attention away from pain could block nociception at the level of the spinal cord (Sprenger et al., 2012), before it can seize working memory. In order to account for these different possibilities, we employed multi-level mediation models (Buhle & Wager, 2010) examining inter-individual differences in pain disruption, task-induced analgesia, and the trade-off between pain perception and task performance.

2. Materials and Methods

2.1 Participants

Fifty-two young adults were recruited from local universities. Screening was performed by telephone. Exclusion criteria included a history of diagnosis of neurological or psychiatric disorder, current diagnosed psychological disorder, diagnosis of chronic pain syndrome or neuropathy, history of alcohol or substance abuse, and regular (>2 weekly) use of analgesics, anticonvulsants, narcotics, antidepressants, and anxiolytics. Once initial screening completed, participants were not further screened in-person for undiagnosed psychological or psychiatric disorders. Seven participants were excluded following the first testing session because they either obtained an unrealistically low (below 45.5°C) calibrated pain stimulation temperature, the max temperature allowed elicited too little pain (less than 20/100), more than half of trials within a condition were not tolerated during the behavioural procedure, or their performance on the 2-back task was deemed too low (mean performance during calibration below A = .60). Four more participants were excluded due to technical malfunctions, failure to follow instructions, and an extended time interval between both testing sessions. Data from 41 participants (21F; mean age 24.20, age range 19-36, SD = 4.53; mean education 17.2 years, range 12-27, SD = 3.0) were thus retained for analyses. All participants completed all parts of the experiment. .

2.2 Procedure

Ethics approval was obtained from the Research ethics committee of the Institut Universitaire de Gériatrie de Montréal (CER-IUGM 13-14-034).

See Figure 2 for a recapitulative illustration of the methods. In visit one, after providing informed consent, participants completed two cognitive tasks (Dual-task and Numerical Stroop), and completed the Five-Facet Mindfulness Questionnaire. Then, they completed the sensory calibration. In visit two, taking place between one and ten days later, participants completed the Pain Catastrophizing Scale, and the State-Trait Anxiety Inventory. Then, they underwent calibration of their 2-back task performance. Lastly, they completed the final portion of the task, in which they completed cognitive task trials while receiving thermal stimuli.

2.3. Psychological measures

2.3.1. Five- Facet Mindfulness Questionnaire

Trait mindfulness is associated with having an open awareness and non-judgmental acceptance of one's emotions, thoughts and sensations on a moment-to-moment basis (Lutz et al., 2008). The 39-item five facet mindfulness questionnaire (FFMQ) is a self-report measure comprising of five dimensions: observing, acting with awareness, describing, non-judgment, and non-reacting (Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006). Statements are scored on a Likert scale from 1 (*never or very rarely true*) to 5 (*very often or always true*). For all dimensions, a higher score indicates more of the respective construct. The five factors demonstrate adequate to good internal consistency (coefficient alpha ranging from .75 to .91) (Baer et al., 2006), with similar internal consistency in French (coefficient alpha ranging from .76 to 89) (Heeren, Douilliez, Peschard, Debrauwere, & Philippot, 2011). A FFMQ global mindfulness sum was calculated omitting the observing facet, which is the least correlated with other facets in non-expert meditators (Consedine & Butler, 2014).

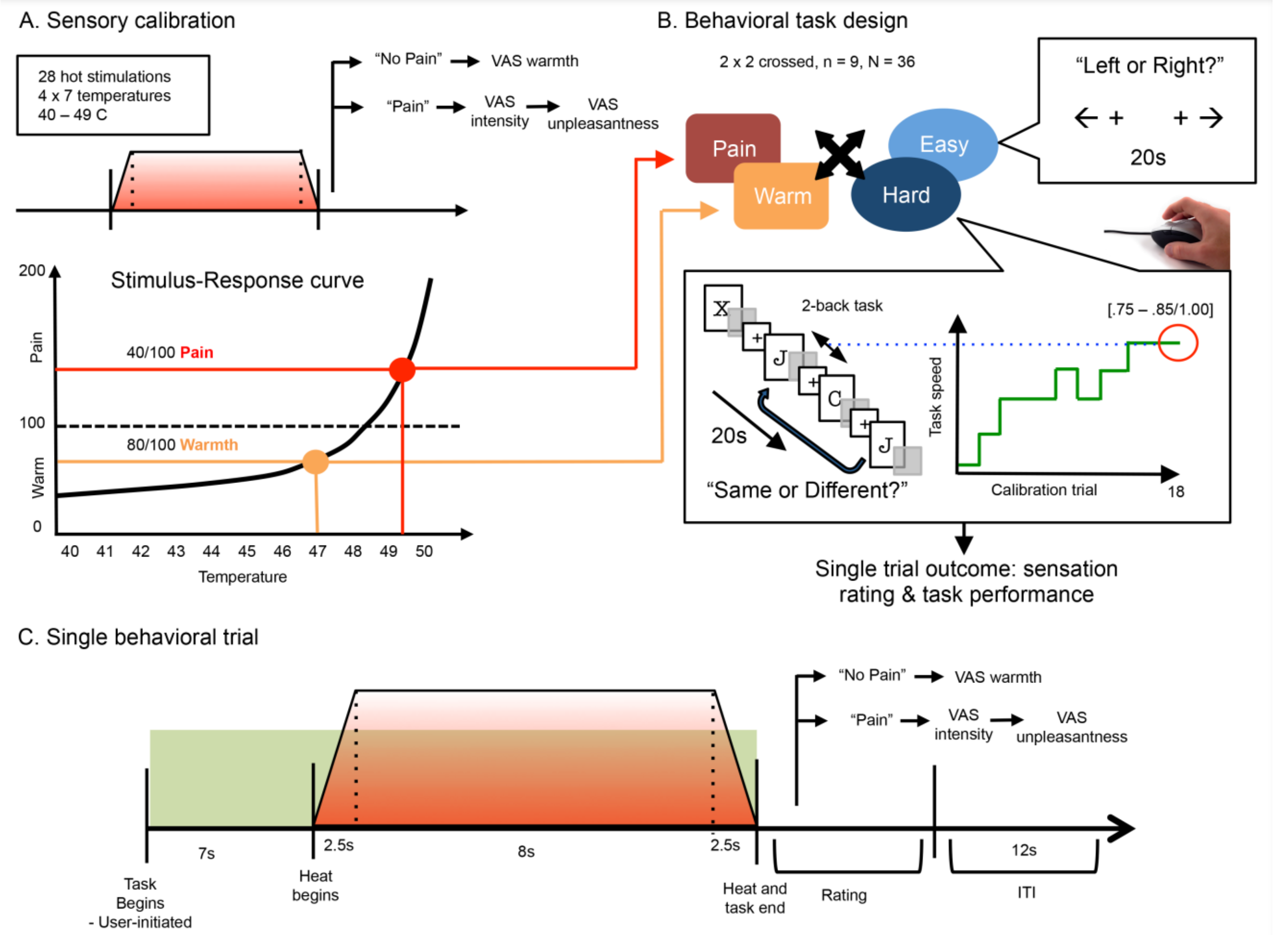

Figure 2. Sensory calibration and behavioral procedure. A. Application of thermal stimuli and evaluation of warmth and pain on rating scales. Ratings are fitted to an exponential stimulus-response curve and individual warm and pain stimulation temperatures are derived. B. Within-subjects complete crossing of two task difficulties (easy; difficult) and two thermal stimuli (Warm; Pain) derived from sensory calibration. Difficult task (*2-back)* is individually difficulty-calibrated over 18 trials using a staircase method, stabilizing performance between A = .75 and A = .85. C. Timeline of a single behavioral trial. ITI: inter-trial interval. VAS: visual analogue scale.

2.3.2. State-Trait Anxiety Inventory - Trait subscale

Trait anxiety is the relatively stable tendency to experience worry, tension, and increased autonomic activity, and those with high trait anxiety scores tend to experience more situations as threatening or dangerous (Spielberger, 1972). The Trait portion of Spielberger's State-Trait Anxiety Inventory (Spielberger, 1989) is a 20-item questionnaire that has been shown to have good psychometric properties (Spielberger, 1989) with the trait portion demonstrating good internal consistency (coefficient alpha = .89) (Barnes, Harp, & Jung, 2002). It is validated in French (Vigneau & Cormier, 2009), demonstrating excellent internal consistency (coefficient alpha = .92). Statements are rated on a Likert scale from 1 (*not at all*) to 4 (*very much so*). A higher score indicates higher trait anxiety. We selected the Trait portion only for analyses since it predicts pain-related fear traits (Quartana et al., 2009).

2.3.3. Pain Catastrophizing Scale

Pain catastrophizing is the tendency to engage in excessive negative elaborations about pain, to magnify or exaggerate its threat value, and to feel helpless in the face of pain (Sullivan et al., 1995). It has received extensive attention as a predictor of pain and associated disability (Quartana et al., 2009). The pain catastrophizing scale (PCS) is a 13-item measure comprised of three subscales: rumination, magnification, helplessness, where statements are rated on a 5-point Likert scale, from 0 (*not at all*) to 4 (*all the time*). The PCS has good psychometric properties, with the sum score demonstrating good internal consistency (coefficient alpha = .87) (Sullivan et al., 1995). It is also validated in French-Canadian, with excellent internal consistency (coefficient alpha = .91) (French et al., 2005). On all dimensions, a higher score indicates more of the respective construct.

Trait anxiety, catastrophizing and mindfulness are intimately linked. Catastrophizing has been described as a cognitive tendency employed by those with high trait anxiety (Beck, Rush, Shaw, & Emery, 1979), and accordingly they share a lot of variance (Affleck, Tenen, Urrows, & Higgins, 1992; Hirsh et al., 2007; Sullivan & D'Eon, 1990). Conversely, low trait mindfulness predicts pain catastrophizing (Mun, Okun, & Karoly, 2014b; Petter et al., 2013; Schütze et al., 2009) and trait anxiety (McCracken, Gauntlett-Gilbert, & Vowles, 2007) but is still a unique psychological construct (Day, Smitherman, Thorn, & Ward, 2014). Therefore, we test the moderating effects of trait anxiety, pain catastrophizing and trait mindfulness but occasionally employ the term "high threat sensitivity" to describe those with high trait anxiety, high catastrophizing, and low mindfulness separately.

2.4 Cognitive measures

Three cognitive mechanisms were assessed with two custom experimental tasks (Brouillard, Lussier, Parent, & Bherer, 2014) on an electronic tablet (Apple Ipad 2); they assessed divided attention, inhibition and switching. In both tasks, dependent measures are task performance (percent accurate responses) and response time (RT). RT analyses excluded trials with errors or with RT < 200ms.

2.4.1 Dual-task

Divided-attention was assessed using a dual-task paradigm (Lussier, Gagnon, & Bherer, 2012; Miyake et al., 2000), which requires execution of two independent visual discrimination tasks at once. One task required identification of one of three celestial bodies (star, planet, or moon; touch-responses on dominant-hand side of the screen), and the other task required identification of one of three animals (dog, snake or bird; non-dominant hand side). Both tasks were presented in a pseudorandom order. Pure blocks involved only trials of one of the two tasks performed alone (single pure trials, SP). During mixed blocks, either one (single-mixed trials, SM) or both tasks (dual mixed trials, DM) are presented in a random order. Participants were told to give equal priority to both tasks in the case of DM trials. In order, participants completed two pure blocks (20 SP trials each, one block for each task), two mixed blocks (40 SM, 40 DM trials each), and again two pure blocks (20 SP trials each).

The *task-set cost*, the relative cost of maintaining multiple executable tasks in mind at once, is calculated as the RT increment between SP and SM trial means, divided by SP mean. The *dual-task cost* is a measure of the cost of perceiving multiple stimuli and coordinating execution of two motor responses. It is calculated as the RT increment from SM to DM trials divided by mean SM RT. A higher value represented a larger cost, indicating poorer divided attention performance..

2.4.2 Numerical modified Stroop Task

The Stroop task measures inhibition of prepotent responses (Stroop, 1935), with the added fourth condition (Bohnen, Jolles, & Twijnstra, 1992; Laguë-Beauvais, Brunet, Gagnon, Lesage, & Bherer, 2013) measuring both inhibition and switching, or the capacity to alternate between different tasks (Miyake et al., 2000).

In the numerical version of the Stroop task (Sedó, 2004), the digits used were 1 to 6 inclusively, and participants responded with buttons on either side of the touch-screen (the words 'one', 'two', 'three' on the left; 'four', 'five', 'six' on the right). The trials were user-initiated. Participants completed a familiarization phase of 30 trials, involving identifying single digits. Following this, each block had 60 task trials. Block 1 involved identifying series of digits (reading condition), where the digits corresponded to the quantity present; for example, four '4's. Block 2 involved providing the number of asterisks (counting condition); for instance, five asterisks. Block 3 involved counting digits, where the quantity was incongruent with the identity of the digits (inhibition condition); for example, two '6's. Blocks 4 and 5 were similar to the inhibition condition (Block 3) in which participants were to alternate instructions, reading the digits rather than providing the number of items whenever digits appeared in a rectangle (switching condition).

Inhibition cost was calculated as the ratio of mean RT increase from the counting to inhibition trials, over counting mean RT, as follows:

$$\text{Inhibition cost} = (\text{inhibition RT} - \text{counting RT}) / \text{counting RT} \qquad (1)$$

Switching cost was obtained by dividing the mean RT increase from inhibition trials within the switching condition (non-switch trials), to switch trials (both switching to the reading instruction, and switching back to the counting instruction), by mean non-switch RT. The equation is as follows:

$$\text{Switching cost} = (\text{switch trials RT} - \text{non-switch trials RT}) / \text{non-switch trials RT} \qquad (2)$$

Costs were calculated such that a larger value represented worse performance.

2.5 Pain and warmth ratings

The rating scales were used in the sensory calibration and behavioral procedures. Immediately after stimulation ended, participants responded whether it was painful or not with a mouse click (right if 'painful', left if 'not painful'). If it was painful, participants rated pain intensity (the strength of the sensation) and pain unpleasantness (the degree to which the pain was bothersome or uncomfortable) on two visual analogue scales (VAS, (Bird & Dickson, 2001), also see Price et al., (1983)) accompanied by a numerical rating between 0 and 100. For pain intensity, the left and right anchors used were *not intense at all* and *extremely intense*; for unpleasantness, these were *not unpleasant at all* and *extremely unpleasant*. If the stimulation was not painful, heat was evaluated on a VAS with the anchors *no warmth at all* and *very hot, without pain*.

2.6 Sensory calibration

We executed sensory calibration for each participant in order to control for the effects of interindividual differences in pain sensitivity during the behavioral procedure, and as recommended previously (D. J. Moore et al., 2012). The on-screen stimuli were presented with the E-prime software package (Psychology Software Tools, Inc., 2002), and an experimenter delivered all thermal stimulations with a Medoc Thermode 9-cm^2 contact probe (TSA Neuro-sensory analyzer, Medoc Ltd. Advanced Medical System, Israel).

Participants were first briefly familiarized with the stimuli. Calibration consisted of 28 stimulations to the volar surface of the non-dominant arm. Seven temperatures (40, 44, 45, 46, 47, 48, 49°C) were presented, one to each of four sites, the order of which was determined in a pseudorandom Latin square design. Four different testing orders were used across the subjects. Heat was applied for 13s (2.5s rise and fall time from 32°C baseline, 8s plateau), during which participants watched an on-screen fixation cross; they then rated the sensation.

Sensory intensity ratings were corrected for presentation order and stimulation site effects. Pain sensitization and habituation resulting from peripheral or central adaptation processes can occur with repeated painful stimulations, and can be site-specific and site-nonspecific (Jepma, Jones, & Wager, 2014). We therefore corrected the raw pain ratings for these processes using Jepma et al.'s (2014) dynamic model, which we ran in Matlab 2012a. First, the correction derives temperature-adjusted ratings, and models the ratings as a function of site-specific and site-nonspecific adaptation processes added to an intercept. Each process is modulated by a parameter determining the strength and direction of the adaptation. Both processes also implement decay parameters that model the saturation of both effects after repeated stimulations. As such, four free parameters are estimated by random iteration of 100 initial values in an optimization function that minimizes the sum of the squared error between the observed trial-by-trial temperature-adjusted pain ratings and those predicted by the model. These four parameters are site-specific magnification, site non-specific magnification, and their respective decay coefficients. Lastly, the difference between the predicted and observed temperature-adjusted ratings is used as a correction for adaptation processes, and is applied to the raw pain ratings.

We plotted all corrected sensation intensity reports as a function of stimulation temperature on the same continuum (warmth: 0-100; pain 100-200), based on the method used in previous studies (Vachon-Presseau et al., 2013; Woo, Roy, Buhle, & Wager, 2015). Exponential curve fitting using a Matlab function permitted selection of a Warm (80/100 of warmth) and Pain (40/100 of pain) temperature for each participant. The maximal temperature of 49°C was used for the four participants for whom the predicted Pain temperatures surpassed 49°C.

2.7 2-back task

The tasks were programmed with E-Prime software package, from a script adapted from Buhle and Wager (2010). For both cognitive tasks used in the behavioral procedure, a series of characters appeared on a screen and the participant provided a response for each using a computer mouse. Each trial lasted 20s, where each character presentation consisted of a fixation cross (250ms), followed by a character (500ms), followed by a blank inter-character interval. Responses were recorded during character presentation and the blank interval. For each trial, performance accuracy was calculated as A, a non-parametric signal detection measure (Zhang &

Mueller, 2005), also previously used for a 3-back task (Buhle & Wager, 2010). A provides a measure of response accuracy independent of response bias. A is equal to .50 at random chance; 1.00 at perfect performance; and 0 when incorrect responses are provided every time. The first two letters of a series were excluded from calculation of A.

The 2-back task was used in the difficult task condition. It engages working memory (Jaeggi, Buschkuehl, Perrig, & Meier, 2010) and requires continuous performance. The task consisted of responding, for each letter in a series, whether it was identical (left-click) or different (right-click) to the one two letters previously. Letters used were C, F, J, N, Q, S, V, and X. In all trials, on average 25 % of letters (excluding the first two) were targets. Lures were used to increase the difficulty of the task and represented on average 12.5 % of letters. Lures were defined as instances where the current letter was identical to letter 1-back or 3-back.

Following instruction and practice, participants completed 18 2-back trials, without performance feedback. The blank interval duration after a letter was manipulated in a staircase procedure to maintain a task performance of $.75 > A < .85$. The starting interval duration was 2583ms. If performance on two subsequent trials was above $A = .85$, the post-letter interval duration was decreased for the following trial. If performance on two subsequent trials was below $A = .75$, interval duration was stepped up for the following trial. In order to maintain constant total trial duration, faster trials contained more letters. At the end of the calibration procedure, the final post-letter interval duration was derived as the participant's task speed parameter. This was done to ensure that the task remained equally challenging and engaging across participants.

2.8 Behavioral Procedure

The behavioral procedure consisted of 36 trials lasting approximately 50s each. A trial involved completing one of two cognitive tasks (Easy, Difficult) while receiving a thermal stimulus (Warm, Pain); immediately following the end of the task and stimulus, the participant rated their sensation. The 2-back task was used as the Difficult task. The Left-Right task was used in the Easy task condition. The task consisted in responding to a series of left- (left-click) or right-pointing (right-click) arrows on the screen. The proportion of left-responses was the same as that of targets in the 2-back task. The design crossed both levels of cognitive task difficulty and heat levels in a within-subjects design, resulting in four conditions with nine trials of each type. These were presented in a pseudorandom order, which was the same for each participant. Participants were given no instruction regarding prioritization of the task or pain.

We aimed to administer to participants stimuli that would invoke equal baseline pain and warmth intensities, and equal subjective 2-back task difficulty level. Therefore, the 2-back calibration speed was used as the post-character blank interval duration for both cognitive tasks, and the Warmth and Pain stimuli were derived from the sensory calibration. Dependent variables for each trial were task performance A and pain intensity; pain unpleasantness reports were not included in the current analyses.

2.9 Analyses

For the psychological and executive functions moderators, outliers were identified according to the outlier labeling rule (Hoaglin, Iglewicz, & Tukey, 1986; Hoaglin & Iglewicz, 1987; Tukey, 1977), which involves removing cases that were outside the interquartile range (IQR) Q3 - Q1 by a factor larger than 2.2 times the IQR. No participants were excluded using this rule.

Pain ratings from the behavioral procedure were subjected to the same correction procedure applied to sensory calibration ratings. As such, pain ratings were regressed on task condition, and we used the residual of the regression to estimate the magnitude of correction. As such, we corrected the pain ratings for the effects task condition prior to estimating the site-specific and site-nonspecific correction parameters. We then subtracted these estimated adaptation effects from the raw pain rating scores.

2.9.1 Subject-level effects

In order to test the hypotheses that pain would impede task performance on the difficult task and that the difficult task would inhibit sensation in the Pain condition, we performed means difference tests on heat-pain intensity and on task performance. These were paired-samples *t*-tests for normally distributed variables and Wilcoxon rank-sum tests for non-normally distributed variables.

2.9.2 Trial-level effects

In order to examine trial-by-trial interactions between task performance and pain, we performed multilevel mediation analyses on all behavioural trials (MacKinnon, 2008). It has been argued (Zhao, Lynch Jr., & Chen, 2010) that a statistically significant direct effect of the predictor on outcome variable is not required for mediation to apply; therefore, we performed mediation tests regardless of the significance of effects found on subjects-level analyses.

Multilevel analyses resolves violation of the assumption of independence of observations for mediation (MacKinnon, 2008) when examining nested data. Multilevel mediation analyses derive average group-level means (in our case, participant means) and use them to estimate regression slopes and intercepts for nested individual trials. Including second-level moderators allows testing of their contribution to slopes and intercepts within each individual. We expected these analyses to yield results that were slightly different from means-difference analyses, because in the case of multilevel analyses, between-subjects variance is relegated to the 2nd-level rather than conflated with error variance.

Applied to our paradigm, equations for multilevel moderated mediation are:

Y (outcome) predicted by X (predictor)

Trial-level 1:

$$Y_{ij} = c_j X_{ij} + e_{ij} \tag{3}$$

Subjects-level 2:

$$c_j = c_2 Mod_j + \gamma_{00} + u_{0j} \tag{4}$$

Y predicted by X and M (mediator)

Trial-level 1:

$$Y_{ij} = c_j' X_{ij} + b_j M_{ij} + e_{ij} \tag{5}$$

Subjects-level 2:

$$c_j' = c'_2 Mod_{0j} + \gamma_{00} + u_{0j} \tag{6}$$

$$b_j = b_2\, Mod_{0j} + \gamma_{00} + u_{0j} \tag{7}$$

M predicted by X

Trial-level 1:

$$M_{ij} = a_j X_{ij} + e_{ij} \tag{8}$$

Subjects-level 2:

$$a_j = a_2 Mod_{0j} + \gamma_{00} + u_{0j} \tag{9}$$

Where e is trial-level error variance for the *i* th trial of the *j* th participant, u is subjects-level error variance, γ is grand mean, Mod is the tested subject-level moderator, and a_j ,b_j ,c_j ,c_j' are trial-level standardized mediation regression coefficients. The values of e, u, β and γ vary across the three main mediation equations, even though notation does not make this explicit. a_2, b_2, c_2 are second-level regression coefficients.

The mediation analyses were performed with 'mediation.m' Matlab script, available online (http://wagerlab.colorado.edu/tools). We tested the significance of mediation paths with a bias-corrected bootstrap test (Efron & Tibshirani, 1993) with 10 000 bootstrap samples to test each of the a, b, and ab path coefficients. First, we tested whether reported sensation mediates the effect of the effect of stimulation level on task performance. Next, we tested whether task performance mediated analgesic effects of task difficulty on reported sensation. In both mediations performed, the mediator and the dependent variable were z-transformed. Testing time interval in days, pain threshold, and task calibration interval were entered as covariates from each moderator prior to running the general linear models. In all tests, alpha level for significance was set to .05.

3. Results

3.1. Descriptives

Response time measures for the Stroop task and Dual-task are presented in Figure 3. For each participant, we averaged response time for each dual-task trial type over left- and right-hand responses, and used these mean measures to calculate cognitive costs. Descriptive statistics for sensory calibration results, psychological and cognitive variables and 2-back calibration results are presented in Table 2. Summary of analyses performed is presented in Figure 4.

We compared STAI-T scores to normative values for men and women in the population. Norms for STAI-T scores in women in the general population are 34.8 (*SD*: 9.2), while for men

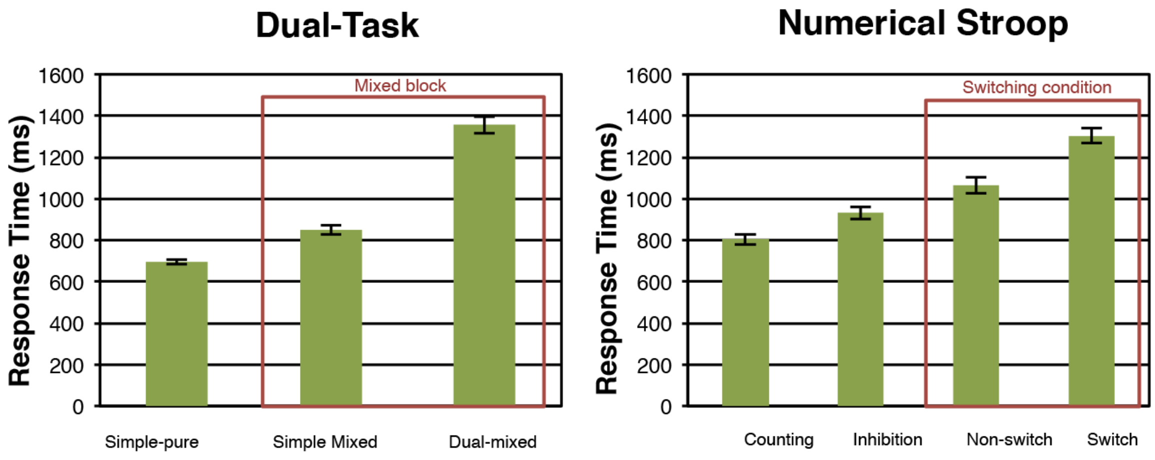

Figure 3. Numerical Stroop and Dual-task raw response time (RT) means for the different trial types. RT means excluded erroneous trials or those with RT < 200ms. Error bars depict standard error.

Table 2

Descriptives and intercorrelations of calibration parameters and psychological and cognitive factors from experimental study

Measure	Mean (*SD*)	1	2	3	4	5	6	7	8	9	10	11
Sensory calibration												
1. Pain threshold (°C)	46.20 (1.24)	—	.99***	.91***	.16	.06	.14	.11	-.11	.02	.11	-.10
2. Warm temp (°C)	45.04 (1.52)		—	.84***	.18	.10	.08	.11	-.11	.00	.11	-.07
3. Pain temp (°C)	47.91 (.82)			—	.07	.01	.26	.16	-.02	.09	.15	-.15
Psychological factors												
4. PCS	14.02 (10.69)				—	.43**	-.59	.20	-.15	.22	.11	.05
5. STAI-T	39.34 (10.13)					—	-.66***	.09	.19	.11	.06	.22
6. FFMQ	103.22 (17.20)						—	-.23	-.12	-.17	.00	-.20
Executive functions												
7. Dualtask cost	0.72[a] (.16)							—	.33*	.04	.12	.06
8. Taskset cost	0.21[b] (.09)								—	-.14	.36*	.05
9. Stroop inhibition cost	0.16[c] (.08)									—	-.28	.10
10. Stroop switch cost	0.30[d] (.11)										—	-.04
2-back calibration												
11. task character interval (ms)	579 (347)											—

Note. PCS = Pain Catastrophizing Scale, PCS sum score ranges from 0 to 52. STAI-T, State-trait Anxiety Inventory - Trait, STAI-T score ranges from 20 to 80. FFMQ, Five-Facet Mindfulness Questionnaire, FFMQ Act with Awareness, Describe, Nonjudge, Nonreact sum score ranges from 32 to 160.

[a] $t(40) = 29.18$. [b] $t(40) = 14.67$. [c] $t(40)=13.31$. [d] $t(40) = 15.81$. all $p < 0.001$.

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

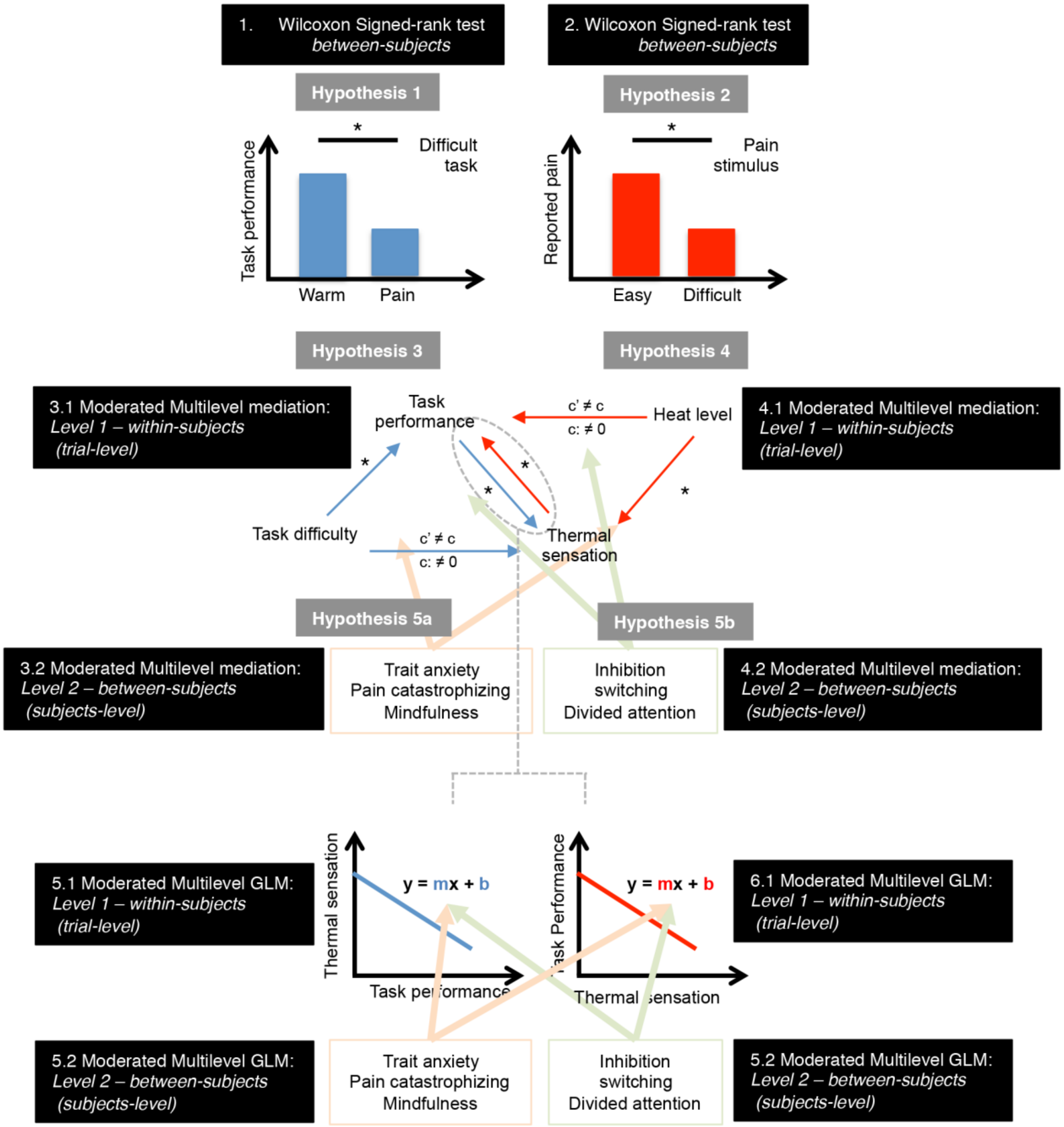

Figure 4. A depiction of proposed analyses for the experimental study.

it is 34.9 (*SD*: 9.2) (Spielberger 1983). Our mean scores were 42.9 (*SD*: 10.7) for women (n = 21) and 35.6 (*SD*: 8.5) for men (n = 20); scores for the women in our sample were higher than normative scores for women for the STAI-T. Typical scores for people with diagnosed anxiety fall in the range of 47 to 61 (Antony 2001). In our sample, eight participants had STAI-T scores of 47 or above (range 47-62), suggesting undiagnosed anxiety disorder in 19.5% of our sample. Similarly, three of our participants have scores meeting the clinically meaningful threshold for pain catastrophizing (respectively, 31, 33, 48). Seventy percent of pain patients with scores of 30 or above remain unemployed in the year after injury (Sullivan, 1995) . However, in order to maintain a representative sample, and since neither the STAI-T nor the PCS are considered diagnostic tools, we did not exclude any participants based on these measures. This decision is discussed below.

At shortest and longest final 2-back calibration intervals achieved (range: 159 -1750 ms), a trial contained 22 and eight letters, respectively. Warm temperature, pain temperature, and pain threshold were highly correlated with one another, as expected. Pain catastrophizing and anxiety were positively correlated, and both were negatively correlated with mindfulness, also as expected. The task calibration and sensory calibration parameters did not correlate with our psychological and executive functions variables of interest, meaning that any outcomes predicted by these variables cannot be related to baseline differences in stimulation temperature or cognitive task character presentation speed. Finally, as expected, Stroop inhibition, switching, dual-task and task-set costs were all significantly different from zero (Table 2), indicating that the executive task conditions indeed incurred additional cognitive processing compared to their control conditions (Stroop inhibition score: $t(40) = 13.31$, 95% CI [.14, .18]; Stroop switch score:

$t(40) = 15.81$, 95% CI [.20, .26]; Dual-task cost: $t(40) = 29.18$, 95% CI [.55, .63]; task-set score: $t(40) = 14.67$, 95% CI [.18, .24]. all $p < .001$).

3.2. Manipulation checks

In order to confirm that the 2-back task was indeed more difficult than the LR task, we first verified the average task accuracy difference between the 2-back task and the LR task. Because task performance was highly skewed and kurtotic, we used the nonparametric Wilcoxon signed-rank test to test the difference between 2-back task and LR task performance. Performance was significantly higher on the LR task (*Mdn* = .995) than on the 2-back task (*Mdn* = .853; $z = 5.58$, $p < .001$, $r = .62$).

In order to confirm that Pain stimuli were indeed felt more strongly than Warm stimuli, a paired-samples t-test was performed for sensation between warm and pain tasks. Pain stimuli were perceived more intensely during both tasks (2-back, $t(40) = 19.47$, $p < .001$, Cohen's d = 3.04; LR, $t(40) = 23.81$, $p < .001$, Cohen's $d = 3.72$).

3.3 Subject-level effects

See Figure 5 for a depiction of mean pain and performance in each behavioral condition, and Table 3 for detailed outcomes. We first examined the effects of stimulus intensity on 2-back performance. Since performance was highly skewed and kurtotic, nonparametric Wilcoxon signed-rank tests were used in order to test mean differences between Warm and Pain conditions. There was no significant difference in performance between the Warm (*Mdn* = .876) and Pain (*Mdn* = .853) conditions, ($z = 1.67$, $p = .096$, $r = .18$). We then examined the effects of task difficulty on reported pain in the Pain condition using a paired-samples t-test. Significantly lower sensation was reported for the 2-back task versus the LR task ($t(40) = 4.18$, $p < .001$, Cohen's

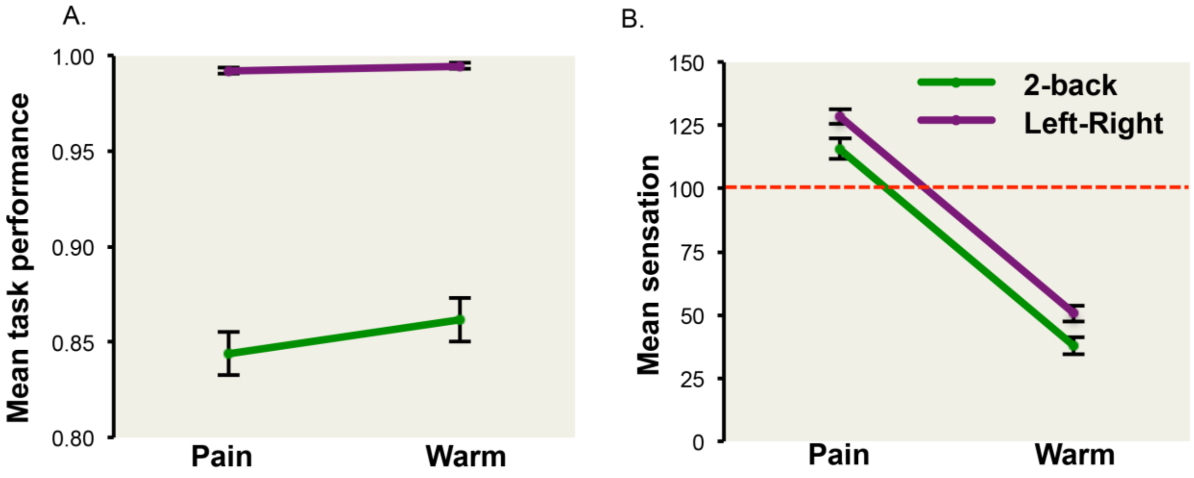

Figure 5. Task difficulty and heat level effects on mean performance and repeated sensation on the Left-Right and 2-back tasks. Red line indicates pain threshold. Task performance measure is A, a measure of target detection sensitivity ranging from A= .5 (random chance) to A = 1.0 (perfect detection). Error bars represent standard error.

Table 3.

Behavioral procedure outcomes for pain and warm stimuli, and 2-back and Left-right tasks

			Pain			Warm		
		N	*M* (*SD*)	Min	Max	*M* (*SD*)	Min	Max
2-back	Sensation	41	115.81 (25.73)	46.38	163.91	37.89 (21.98)	9.30	100.30
	Performance	41	.84 (.07)	.71	.96	.86 (.07)	.71	.96
Left-Right	Sensation	41	128.56 (19.52)	63.67	165.53	50.59 (20.28)	6.79	102.49
	Performance	41	.99 (.01)	.96	1.00	.99 (.01)	.95	1.00

Note. Mean sensation (warm and pain) intensity ratings and task performance in the four behavioral task conditions. Heat & pain sensation ratings are on the same scale such that 0-100 represent heat reports, and 100-200 represent pain reports.

d = .65). In order to examine the relationship between the above effects, we tested the correlation between Task-induced Analgesia (mean sensation for Pain*LR task - Pain*2-back) and Pain-induced Interference (mean performance for Warm*2-back - Pain*2-back). Those who displayed high Task-induced Analgesia experienced low Pain-induced Interference (*r* = -.349, *p* = .025); in other words, they prioritized the task.

3.4 Multilevel mediation models

Next, we examined trial-level relationships between task performance and reported sensation. Subject-level analyses would indicate whether a higher stimulation temperature interrupts task performance and whether a more difficult task reduces pain. However, this does not indicate whether temperature-related performance interruptions are due specifically to higher pain, and whether task-difficulty analgesia is due to higher task performance. In a sharedresource model, task performance and pain perception should theoretically compete, where performance is a measure of task engagement: analgesia should occur on trials where task performance is high, and conversely performance interference should occur in trials where pain perception is high.

We tested two different multilevel mediation models. The results of the two mediation models tested are reported in Figure 6. The first model tested the hypothesis that trial-by-trial fluctuations in task performance explain the effects of task difficulty on reported sensation, incorporating Pain trials only (Task analgesia model: task difficulty → performance → perceived warmth/pain). The second model tested the complementary hypothesis that trial-by-trial fluctuations in thermal sensation explain the effects of heat level on performance, using 2-back trials only (Pain disruption model: heat level → perceived warmth/pain → performance). As recommended by Baron & Kenny (Baron & Kenny, 1986), we began by testing whether

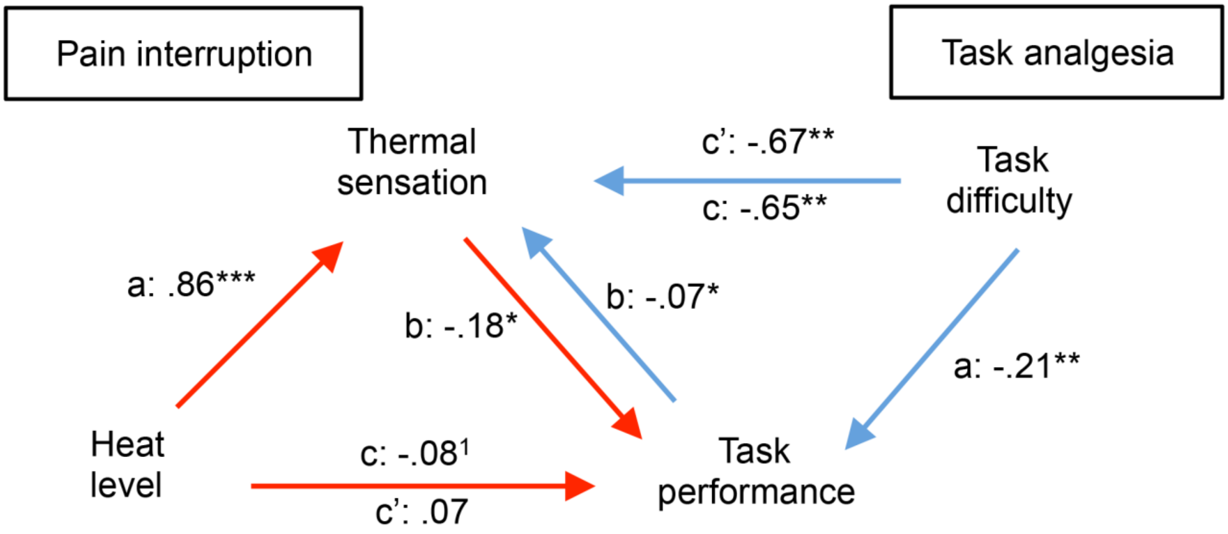

Figure 6. First-level mediation models of the effects of task difficulty on sensation and of heat level on task performance. In red, mediation of the effect of heat level on task performance by pain intensity for 2-back trials only. In blue, mediation of the effect of task difficulty on reported sensation by task performance for Pain trials only. a,b,c,c’ are mean standardized regression coefficients for the illustrated relationships.

*** $p < .001$. ** $p < .01$. * $p < .05$. ^{1} $p < .07$

moderation provided a more parsimonious explanation of the relationship between each model's predictor, mediator, and dependent variables. For both models, the interaction (cross-product) between the predictor and the mediator didn't significantly predict the residual variance in the dependent variable after controlling for the predictor and mediator main effects (Task analgesia model: *beta* = 24.56, z = .09, *p* = .466; Pain disruption model: *beta* = 4.24×10^{-4}, z = .58, *p* = .280), suggesting an absence of moderation in both models.

In the Pain disruption model in the 2-back trials alone (Figure 6, in red), we found that heat level had a near-significant negative effect on task performance (total effect standardized regression coefficient, c = -.08, *z* = 1.85, *p* = .064). In addition, we found a significant positive effect of heat level on perceived sensation (a = .86, *z* = 4.07, *p* < .001), and a marginally significant negative effect of sensation on task performance, after controlling for heat level (b = -.18, *z* = 1.91, *p* = .056). The effect of heat level on task performance disappeared completely after controlling for perceived sensation (direct effect, c' = .06, *z* = .84, *p* = .39), indicating full mediation. The mediated effect of heat level on on performance by sensation was near significant (indirect effect, ab = -.12, *z* = -1.82, *p* = .069). It has been argued that there need not be a statistically significant to-be-mediated effect (total effect c) to justify testing a mediation (Zhao et al., 2010). Thus, the marginal interruptive effect of thermal stimulation level on task performance was fully explained by the effects of stimulation level on reported sensation. Note that the total effect in the pain disruption model is analogous to the test of the effect of heat level condition on mean performance above using the nonparametric test, returning a significance level of *p* = .096, indicating a trend. For the regression analyses performed in the mediation test, the significance level returns a lower *p*-value because, while between-subjects variability in the nonparametric test contributes to error variance in the statistical test, in the multilevel regression analyses the between-subject variability is attributed to a term at the second level of analysis (u in multilevel mediation equations above), where it does not contribute to trial-level error variance

In the Task analgesia model in Pain trials alone (Figure 6, in blue), we found a significant negative effect of task difficulty on reported sensation (total effect c = -.65, $z = 3.25$, $p = .001$). We also found a significant negative effect of task difficulty on performance (path a = -.21, $z = 3.20$, $p = .001$), and a marginally significant effect of task performance on reported sensation, after controlling for task difficulty (path b = -.07, $z = 1.94$, $p = .052$). The effect of task difficulty on reported sensation strengthened slightly when statistically controlling for the performance-mediated effect (direct effect c' = -.67, $z = 3.14$, $p = .002$), indicating a suppression effect (MacKinnon, Krull, & Lockwood, 2000). The mediated effect of task difficulty on sensation by performance was significant (indirect effect, ab = .01, $z = 2.39$, $p = .017$). Hence, performance partially mediated the distractive effect of task difficulty level on reported sensation, but in the direction opposite of the direct effect of task difficulty on sensation. Indeed, the total effect of task difficulty (path c) was composed of an analgesic non-performance-mediated effect (direct effect, c') and an anti-analgesic performance-mediated effect (indirect effect, path ab). To summarize, high task performance controlling for all other factors was analgesic, but when paired with the typical performance decrement during the harder task (path a), the total mediation had a positive contribution to reported sensation (performance counter-analgesia), an effect that partially counteracts the analgesic direct effect of task difficulty.

Performing at one's best in the 2-back x pain condition resulted in a 11.46/100 (*SD* = 37.48) point predicted decrease in pain, compared to worst performance in that condition. We also predicted the performance difference associated with individual extremes in pain perception.

One's most painful trial was linked with a 0.04/1.00 (*SD* = .16) predicted performance decrease from that for the least painful trial.

3.5. Pain at different task performance levels

In order to better understand the relationship between sensation and performance for Pain trials, we plotted sensation for all Pain trials across subjects in Figure 7. Reported sensation is highest for 2-back trials performed at A < .6, and for A = .1. To examine the relationships between the mediated pathways, we examined the correlations between ab paths. Those who displayed higher performance-related reduction of analgesia also experienced more sensation-mediated task-interruption (*r* = -.347, *p* = .026).

3.6 Moderation of trial-level mediation effects

Next, we wanted to verify whether our psychological and executive functions factors of interest moderated individual trial-level dynamics between task performance and reported sensation. For both multilevel mediation models, we included seven second-level (subject-level) moderators in order to examine their effects on first-level (trial-level) mediation dynamics: trait anxiety, pain catastrophizing, mindfulness, dual-task cost, task-set cost, Stroop inhibition cost, Stroop switching cost.

The results of both second-level mediation models are presented in Table 4. In the Pain disruption model, the inhibitory effect of sensation on performance, controlling for heat level (b path) was significantly increased by trait anxiety, significantly decreased by mindfulness, and marginally increased by pain catastrophizing. This inhibitory effect was also reduced by high task-set cost, indicating that those with a worse task-set ability displayed a weaker disruptive

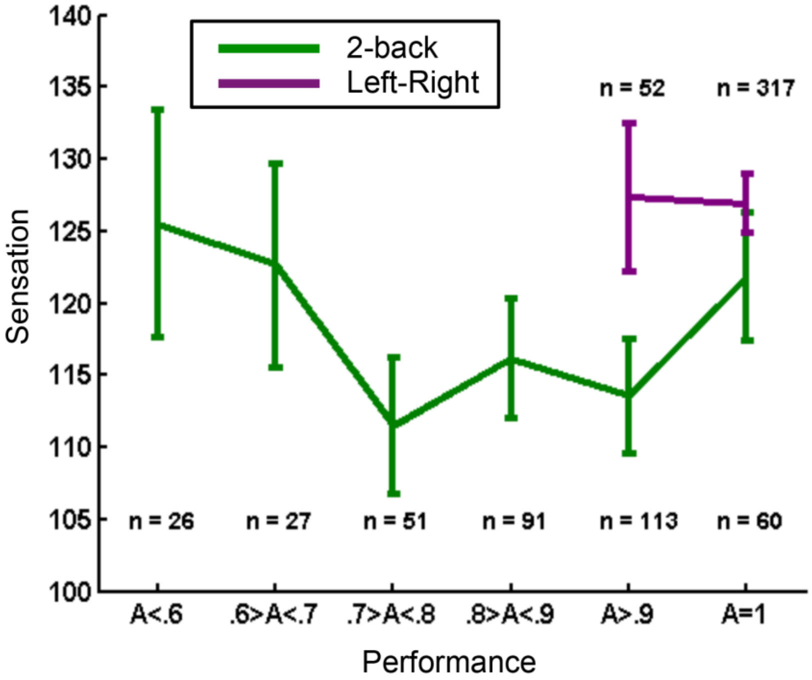

Figure 7. Reported sensation as a function of task performance in Pain trials, pooled together across participants and split into performance bins. A = 1 represents perfect performance and A = .5 represents performance at random chance. n values are total number of trials in the corresponding performance bins. For the Left-Right condition, performance was always above .9. Error bars represent standard error.

Table 4

Standardized regression coefficients for 2^{nd}-level threat-sensitivity and executive functions moderators of first-level mediations.

Mediation 1: Heat level - sensation - performance (2-back trials alone)

	a_2	b_2	c'_2	c_2	ab_2
Psychological variables					
Pain catastrophizing	9×10^{-5}	-.181*	.149^1	.034	-.135*
Trait anxiety	.002	-.175*	.128	.015	-.126^t
Trait mindfulness	-6×10^{-4}	.208*	-.218**	-.042	.163*
Executive functions					
Stroop inhibition cost	-.003	-.020	-.031	-.023	-.009
Stroop switch cost	.023	.094	-.044	.052	.083
Dual-Task cost	-.020	-.017	-.010	.014	.007
Task-Set cost	.012	.243**	-.156	.005	.178**

Mediation 2: Task difficulty - performance - sensation (Pain trials alone)

	a_2	b_2	c'_2	c_2	ab_2
Psychological variables					
Pain catastrophizing	.050	-.069*	-.008	.004	.006
Trait anxiety	.113*	-.064*	.001	.002	-.001
Trait mindfulness	-.049	.094*	.002	-.008	-.007
Executive functions					
Stroop inhibition cost	.043	-.014	6×10^{-4}	.007	-3×10^{-4}
Stroop switch cost	-.021	-.001	-.018	-.019	-2×10^{-4}
Dual-Task cost	.020	.009	-.046*	-.030	.010
Task-Set cost	.027	.071	-.050	-.076*	-.013*

Note. Coefficients are tested on individual first-level mediations depicted in Figure 6.

*** $p < .001$. ** $p < .01$. * $p < .05$. ^{1} $p < .07$.

effect of reported sensation on task performance. The net effects on the mediation (ab path) term were that high anxiety, pain catastrophizing, and task-set cost all separately predicted a larger sensation-mediated impact on performance, while mindfulness predicted a smaller sensation-mediated effect on performance. There are no moderating effects on the total effect of heat level on performance. Neither dual-task, Stroop inhibition nor switching costs moderated any first-level effects**.** In addition, task-set cost moderated the total effect of task difficulty, such that those with worse task-set ability displayed a larger analgesic effect when performing the difficult task. Finally, dual-task cost negatively moderated the direct effect of task difficulty, in that those with a better dual-task ability experienced smaller analgesic effects of task difficulty, regardless of performance.

3.7 Moderated multilevel General linear models

We next wanted to corroborate our above results, and to verify whether the psychological and executive factors also predicted mean sensation or performance; in other words, whether the factors moderated the intercepts of the sensation-performance functions. Indeed, the multilevel mediation models above suggest that the negative relationship between reported sensation and task performance is moderated by several psychological and executive functions factors; however, such effects could be due to moderation of first-level slopes, or first-level intercepts of the tested regressions. Therefore, two multilevel general linear model analyses on were completed. Second-level standardized regression coefficients of the moderators on first-level slopes and intercepts are depicted in Table 5.

First, trial-level effects of reported sensation as a predictor and task performance as an outcome for Pain trials alone were verified. Then, trial-level effects of task performance as a

Table 5

Standardized subject-level regression coefficients applied to first-level mediation terms

	General linear model: sensation → performance					
	Slope			intercept		
	beta	*t*	*p*	*beta*	*t*	*p*
Psychological Factors						
Pain Catastrophizing	-3 x 10^{-5}	-1.44	0.030	3 x 10^{-4}	0.70	0.593
Trait Anxiety	-3 x 10^{-5}	-1.41	0.051	-2 x 10^{-4}	-.42	0.657
Mindfulness	2 x 10^{-5}	1.85	0.060	5 x 10^{-5}	0.21	0.866
Executive Functions						
Dualtask cost	1 x 10^{-4}	-0.07	0.904	-0.045	-1.13	0.235
Task-set cost	0.004	1.65	0.004	-0.096	-2.34	< .001
Stroop inhibition cost	-7 x 10^{-4}	-.20	0.875	-0.077	-1.17	0.314
Stroop switching cost	0.002	0.94	0.351	-0.023	-0.46	0.639

	General linear model: performance → sensation					
	Slope			intercept		
	beta	*t*	*p*	*beta*	*t*	*p*
Psychological Factors						
Pain Catastrophizing	-4.47	-2.15	0.143	0.076	0.47	0.622
Trait Anxiety	-2.24	-0.966	0.356	0.211	1.24	0.233
Mindfulness	2.98	2.26	0.019	-0.148	-1.47	0.133
Executive Functions						
Dualtask cost	14.69	0.11	0.869	-3.87	-0.26	0.704
Task-set cost	357	1.46	0.029	-11.3	-0.61	0.522
Stroop inhibition cost	-11.1	-0.036	0.875	-12.1	-0.54	0.678
Stroop switching cost	-4.57	-0.027	0.963	-6.29	-0.33	0.884

predictor and reported sensation as an outcome were verified. Second-level moderators were included in the model, and each moderator was first statistically controlled for testing time interval in days, pain threshold, and task calibration stimulus interval. Similar moderation effects were found on slopes as were found on b-paths in mediations above. In addition, task-set cost significantly reduced the 1st level intercept of the effect of sensation on performance, indicating that worse task-set ability significantly reduced mean performance on 2-back-Pain trials.

In order to visualize the moderating effects of our factors of interest, we plotted performance as a function of reported sensation in 2-back trials, and reported sensation as a function of performance in Pain trials, in two separate plots in Figure 8. Each function was plotted twice, using the trial outcomes of the upper and lower 25 percentiles for each moderator (*n* = 9 for each) in order to illustrate the differences.

4. Discussion

Our aim was to examine the interruptive effect of pain on task performance and the analgesic effect of a challenging task on thermal sensation, and to investigate the moderating effects of threat-sensitivity and executive functions on the individual relationships between task performance and pain. We summarize our findings as follows. First, a challenging task inhibited pain significantly compared to an easy task, which is consistent with our first hypothesis (Hypothesis 1). Second, painful stimuli did not interrupt task performance more than warm stimuli, a result that does not confirm our second hypothesis (Hypothesis 2). Third, upon testing the mediation of the analgesic effect of task difficulty by task performance, we found that task performance tended to partially counteract the analgesic effect of a challenging task, indicating a

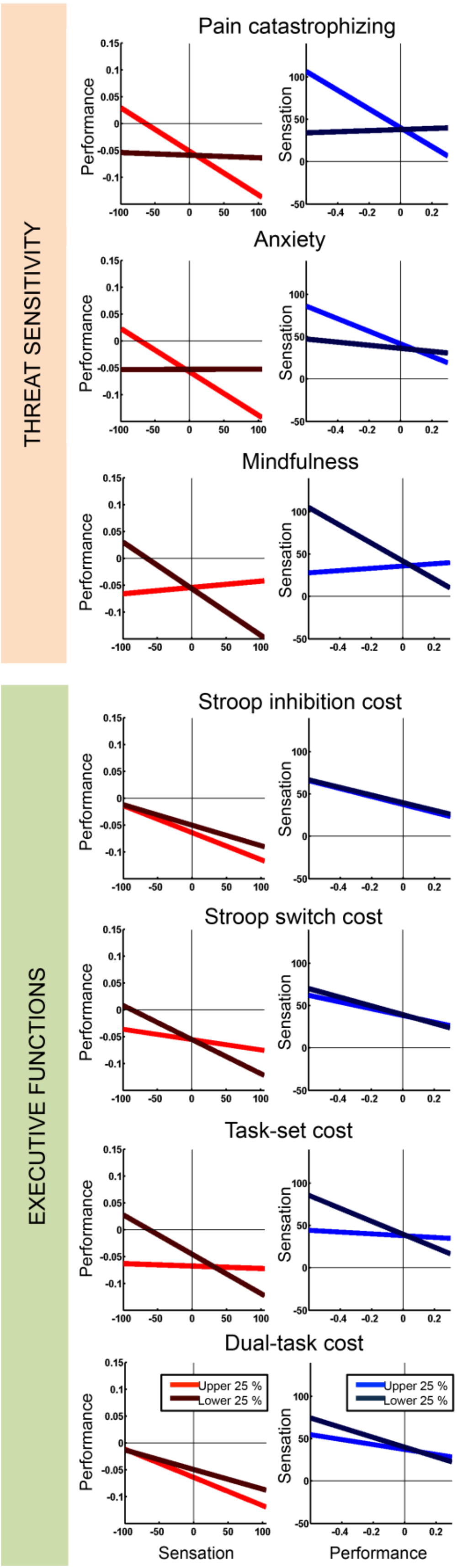
THREAT SENSITIVITY
Pain catastrophizing
Anxiety
Mindfulness
EXECUTIVE FUNCTIONS
Stroop inhibition cost
Stroop switch cost
Task-set cost
Dual-task cost
Performance
Sensation
0.15
0.1
0.05
0
-0.05
-0.1
-100
-50
0
50
100
-50
-0.4
-0.2
0.2
Upper 25 %
Lower 25 %
Sensation
Performance

Figure 8. Effects of psychological and executive functions moderators of interest on individual bidirectional sensation-performance relationships. Lighter lines depict the pain-sensation functions for the top 25 percentile individuals (*n* = 9) within the indicated moderator; darker lines depict the functions of the bottom 25 percentile participants (*n* = 9). In red, performance as a function of sensation in an individual trial (2-back trials alone), controlling for the effects of heat level; in blue, sensation as a function of performance (high-pain trials alone), controlling for the effects of task difficulty level. Depicted relationships are both mediator-outcome b paths depicted in Figure 3.

*** $p < .001$. ** $p < .01$. * $p < .05$. $^1 p < .07$.

suppression effect. This partly supports our hypothesis (Hypothesis 3). Fourth, reported thermal sensation completely explained a small task-interruptive effect of stimulation level on task performance, which supports our hypothesis (Hypothesis 4). Further, all of the tested psychological variables potentially influencing the threat value of pain as well as one measure of divided attention predicted a sharper trade-off between reported sensation and task performance; the presence of moderation effects is in line with our hypothesis (Hypothesis 5). Specifically, high trait anxiety, high pain catastrophizing, low trait mindfulness, and better dual-task ability predicted a higher pain-relieving effect of high task performance, and also a higher task-interruptive effect of high reported pain.

4.1 Task-related analgesia

The analgesic effect of our challenging task is consistent with a large body of experimental literature (see Buhle & Wager (2010) for a review). In fact, our results demonstrate two separable effects of a challenging task on pain. Attempting to complete a difficult task, regardless of performance, was analgesic. This effect was slightly counteracted by a small but significant mediation by task performance, which we explain as follows: while high performance considered on its own is pain-inhibitory, performance typically dropped during the harder task, partly countering analgesia due to task difficulty alone. Concentration on a task is proposed to shield from distraction by attenuating processing of background information, and rendering the attentional focus more steadfast (Sörqvist & Marsh, 2015). In particular, some have proposed that actively holding in working memory the features of pain-unrelated stimuli, as would be the case for the 2-back task, prevents processing of a nociceptive distractor (Legrain et al., 2013).

4.2 Heat level task interruption

The effect of a painful stimulus on a challenging task was fully explained by reported sensation, supporting the idea that pain interferes with task processing by acting as an attentional capture (Eccleston & Crombez, 1999). However, our pain-interruptive effects are marginal, and therefore only partially consistent with significant pain-related disruption of a higher task-load 3-back found by Buhle and Wager in a similar design (Buhle & Wager, 2010). Our results are nevertheless consistent with previous experimental work (Coen et al., 2008; Dick et al., 2006; Petrovic et al., 2000; Seminowicz & Davis, 2007a; Veldhuijzen et al., 2006), which typically failed to demonstrate pain-interruptive effects despite the intuitive sense that such effects should exist (Eccleston & Crombez, 1999). This is likely due to several factors, notably frequent emphasis on prioritizing task performance in pain-task paradigms, the use of distractor tasks of insufficient complexity (Keogh et al., 2013), and the difficulty reproducing clinical pain threat in the laboratory, where threat may largely mediate the effects of clinical pain on impairment (Leung, 2012).

4.3 Pain-performance relationships

Those for whom the challenging task inhibited pain more were less impacted by pain stimuli in terms of their task performance. We liken this individual variability to the A-type (attention dominates) and P-type (pain dominates) characterizations proposed by Erpelding and Davis (Erpelding & Davis, 2013). Further, those who experience large sensation-mediated interference also experienced stronger performance-mediated counter-analgesia. The added value of the performance- and sensation- mediated relationships is the indication at least part of the trade-off occurs in indices of attentional processing, rather than or in addition to in lower-order effects preceding recognition. Our results therefore are in support of the shared resource model of attentional modulation of pain (Kahneman, 1973; Seminowicz & Davis, 2007a).

It is paradoxical that the lowest pain levels were reported for trials performed near the calibrated level, rather than for perfectly performed trials. Sörqvist and Marsh (2015) distinguish concentration, or the degree of absorption, from effort, which is the 'mental energy' applied, where concentration may require varying degrees of effort. It is possible that at near-perfect performance, one achieves a self-maintaining flow-state of reduced effort but high concentration (Nakamura & Csikszentmihalyi, 2002). Conversely, at moderate performance, timely detection and recovery from errors may require more controlled, effortful resource allocation. Several studies have shown that more difficult task conditions have stronger analgesic effects (Buhle & Wager, 2010), which leads us to speculate that effort in particular plays a large role in suppression of pain by task challenge.

4.4 Moderation by threat sensitivity and executive functions

We found that the trade-offs between pain and performance, which are pivotal for explaining the models, were moderated by threat sensitivity traits and executive functions. While it is already known that some of the psychological traits affect task analgesia and pain disruption, none have examined their effects on the relationship between these processes. In our experiment, high anxiety and catastrophizing and low mindfulness further polarize the performance-sensation trade-off when controlling for task difficulty and heat level, respectively. This has the net effect of increasing sensation-mediated task disruption, consistently with literature demonstrating increased pain interruptive effects by threat instruction (Crombez et al., 1998a; Van Damme et al., 2008), catastrophizing (Crombez et al., 1998b, 2002; Schrooten et al., 2013), and fear of pain (Keogh et al., 2001; Roelofs et al., 2004). Indeed, pain catastrophizing has been characterized as a pronounced attentional bias toward sensory and affective pain information (Quartana et al., 2009), and those high in trait anxiety exhibit an increased attentional bias toward bodily threat (Sagliano, Trojano, Amoriello, Migliozzi, & D'Olimpio, 2014). In turn, management of increased threat is proposed to recruit some 'common-pool' attentional resources (Pessoa, 2009), which in shared-resource model would leave little remainder for task processing. Conversely, mindfulness promotes non-reactivity to and disengagement from targets of attention (Lutz et al., 2008), and in our task paradigm likely reduces the tendency to fixate on exogenous pain interruptions. It therefore seems fitting that it would reduce one's susceptibility to interruption by pain. In our experiment, it is surprising that threat sensitivity affected only the indirect impact of heat level on performance, but not the total effect. This may be due to the heat level's effects being small in the first place.

In theory, these individual differences in the trade-off between reported sensation and task performance could be driven by either reduced pain when performance is high, reduced performance when pain is high, or a combination of both. According to the moderation graphs, for all psychological variables the third possibility applies, since neither mean performance nor mean pain are affected by the variables, but specifically the relationship between the two. Therefore, threat sensitivity increases both the degree to which pain interrupts task performance as well as analgesia caused by performing well on the task. This is counterintuitive; we wouldn't expect threat-related psychological variables to increase task analgesia as well. How, then, do threat-related psychological variables increase performance analgesia?

We propose that threat-sensitive individuals must deploy more effort to resist distraction due to the intrusive nature of pain, setting them near a "breaking point" in performance. The stronger attentional pull of pain threat along with a motivation to seek shielding from pain may push those high on threat sensitivity to draw on extra resources in order to perform the task (Inzlicht & Schmeichel, 2012). That threat-sensitivity predicts more effortful performance is supported by the link between catastrophizing and perfectionism (Rudolph, Flett, & Hewitt, 2007), the disposition to strive for flawlessness and set excessively high performance standards, along with overly critical self-evaluations (Flett & Hewitt, 2002). This in turn would lead to increased analgesia, although effort self-reports are needed to support this idea. However, despite our effects of threat-sensitivity on the pain-performance trade-off, neither performance-mediated nor total distraction analgesia were affected. This is at odds with the literature (Campbell et al., 2010; Roelofs et al., 2004; Verhoeven et al., 2010) showing that pain-related fear traits and catastrophizing reduce the effectiveness of a distraction task. In those cases, higher pain in catastrophizers may explain its effects on distraction effectiveness. However, the present study controlled for individual differences in pain sensitivity and did not find such mean effects.

Interestingly, the challenging task was more pain-inhibitory for those with worse divided attention ability than for those with better divided attention. Individuals with a larger dual-task cost, the cost associated with perceiving two stimuli and coordinating two responses, showed a larger analgesic effect of the challenging task, irrespective of performance. For individuals with a larger task-set cost, the cost of maintaining multiple executable tasks in mind at once, net analgesia was increased since the counter-analgesic mediated effects of performance were reduced. It does seem that for participants with worse divided attention ability, prioritizing a challenging task may incur a (fortunate) cost to pain processing. Conversely, divided attention costs did not predict performance interruption due to heat level, although higher task-set costs reduced the sensation-mediated interruptive effects. This effect is driven by a tendency for those with large task-set costs to perform worse on average along all levels of pain, in particular at low and moderate sensation levels. Our effects may indicate that those who have difficulty efficiently maintaining several task-sets in mind have a more general difficulty juggling pain and task, irrespective of pain intensity. The role of divided attention measures in individual pain-task dynamics may reflect costs associated with a saturation of executive processing capabilities in a limited-resource model.

An examination of scores of our sample on the STAI-T reveals that 19.5% of our sample falls in the typical range for people with diagnosed anxiety disorder, despite our initial exclusion of diagnosed psychological disorder. Indeed, globally, approximately half of all cases of anxious disorder go medically undetected, with only one third of the detected cases being correctly diagnosed (Lecrubier et al., 2001) . Nevertheless, anxiety scores for our sample fall somewhere in the middle of a wide prevalence range found previously in the literature. On the lower end, in an undergraduate sample in the United States (N = 2843) prevalence of anxiety disorder was found to be as low as 4.2% (6.1% in females, 2.2% in males), as detected by the Patient Health Questionnaire (PHQ) (Eisenberg, Gollust, Golberstein, & Hefner, 2007). Another study in a British undergraduate sample (N = 1197) found that 17.3% met psychiatric cutoffs on the General Health Questionnaire-28 screening tool measuring somatic symptoms, anxiety, insomnia, and depression, with 97.1% of the psychiatric sample meeting anxious disorder criteria (Macaskill, 2013). A study conducted in Norwegian students (N = 1750) with the General Health Questionnaire found that 21% presented clinically significant psychological distress (Nerdrum, Rustøen, & Rønnestad, 2006). Next, a study conducted on undergraduates in Ohio (N = 374) found that 25% presented moderate-to-severe anxiety on the Depression Anxiety and Stress Scale (DASS-21) (Beiter et al., 2015). Finally, on the upper end a study conducted in a Turkish undergraduate sample (N = 1617) found that 47.1% of respondents presented moderate to severe anxiety on the DASS-42 (Bayram & Bilgel, 2008). Anxiety appears to be more common in university students than in the general population, estimated to have a prevalence of 12% based on a large Ontario sample of individuals 15-64 years of age (Offord et al., 1996). This is argued to be due to a constellation of factors co-occurring during university years, namely the financial burden of debt, pressures due to exams and academic deadlines, isolation and marginalization experienced by international students, and stresses associated with initial transition and adaptation to university setting, among others (Nicky Stanley, 2009). Importantly, the STAI-T is not considered a diagnostic tool for an anxiety disorder and is intended for use as a continuous measure of generalized anxiety. Therefore, in the interest of maintaining a representative sample, we did not exclude any participants on the basis of this measure.

Similarly, three participants exhibited pain catastrophizing sum scores deemed 'clinically meaningful'. This cut-off represents the 75th percentile in normative samples of chronic pain patients, and is derived from a sample of injured workers. Seventy percent of those with clinically meaningful scores remain unemployed one year post-injury, and describe themselves as totally disabled. However, it is not clear whether catastrophizing assessed in pain-free individuals is a good predictors of later impairment in clinical contexts (Quartana et al., 2009). So far, studies on the clinical value of catastrophizing are done in patients with injury or ongoing pain and catastrophizing measures taken typically refer to such pain. However, pain catastrophizing as measured in pain-free samples still is predictive of pain felt in painful procedures one (Sullivan & Neish, 1999) and 10 weeks later (Sullivan et al., 1995).We therefore opted to retain all such participants in the interest of maintaining a representative sample.

4.5 Limitations

Our study has some limitations. First, our lack of sufficient statistical power prevented us from employing factor analyses to examine the moderating effects of composite psychological and executive functions variables. Second, contrary to our assumption in the current study, our sensation reports necessarily reflect sensation memory rather than momentary experience. As such, it could be interesting to investigate whether task-related analgesia reflects disrupted pain memory rather than inhibiting pain experience itself (Christenfeld, 1997), especially considering that catastrophizing (Lefebvre & Keefe, 2002) and anxiety (Noel, Chambers, McGrath, Klein, & Stewart, 2012b) have been found to modulate memory for pain. Third, we did not examine the effects of motivation in our paradigm, although it is known to play a role in attention allocation in competing task paradigms (Inzlicht & Schmeichel, 2012) and in attentional pain modulation (Van Damme, Legrain, Vogt, & Crombez, 2010; Verhoeven et al., 2010). Future studies are warranted to verify whether motivation are involved in the effects of high-threat traits and executive functions on attentional modulation of pain. Attentional mechanisms are now believed to play a role in the pathogenesis and maintenance of some chronic pain cases (Eccleston et al., 1997; Pincus & Morley, 2001; Vlaeyen & Linton, 2000). Indeed, the findings that pain-related fear traits (Leeuw et al., 2007) and executive functions (Attal et al., 2014) both predict pain and related disability hint that some measures of susceptibility to pain-related disruption may predict pronounced attentional bias and impairment in the face of clinical pain. Based on such predictions, attentional training in early clinical phases could potentially curb the deleterious effects of attentional biases on pain patients.

General Discussion

Our first objective was to examine analgesic effects of a challenging task and the task-interruptive effects of pain. We next aimed to test trial-by-trial dynamics between task performance and pain perception, and the way in which psychological factors and executive functions moderated these individual dynamics. In order to verify these effects, we administered warm and painful thermal stimuli to young adults while they completed cognitive tasks of low and high difficulty; pain ratings and task performance were sampled for each trial. We measured trait anxiety, pain catastrophizing and mindfulness with questionnaires, and we tested inhibition, switching and divided attention ability with cognitive tasks adapted to electronic tablet. We employed multilevel analyses to examine trial-level variations in pain perception and task performance. We will summarize our results with respects to our hypotheses.

First, the painful stimuli did not significantly impact mean performance on the working memory task (rejection of Hypothesis 1). This is consistent with previous experimental findings (see review Table 1) that often fail to find a significant impact of pain on task performance. However, given that the n-back task has previously been found to be impacted by pain (Bingel et al., 2007; J Buhle & Wager, 2010; Moore et al., 2012 task 4), we expected as such in our case. It is possible that the pain levels we applied were not high enough to disrupt the task. Indeed, Buhle and Wager (2010) used higher levels of pain, i.e. up to 80/100 in their most painful condition, which might explain their larger effects of pain on task performance. As well, the task they used was a higher-load 3-back task, where more difficult tasks are thought to be more easily disrupted (Keogh et al., 2013). Second, the challenging working memory task inhibited pain significantly more than the simple attentional task (confirmation of Hypothesis 2), which is consistent with a large body of literature on the analgesic effects of challenging tasks (see review

Table 1). We see these results as complementary and indicating that in our experiment, participants tended to prioritize performance on the task over attending to pain. While we gave no instruction to prioritize either the pain or the task, we suspect that participants more frequently favoured the task given the implicit emphasis on it via the time spent practicing and calibrating the 2-back task prior to pairing with pain. In addition, the structure of our task trials likely reduced the interference effects of pain. Indeed, administering the pain stimuli after several seconds of task might have blunted its impact on performance, since focused attention to another task has been found to reduce capture by incoming sensory stimuli, in part by engaging top-down inhibition of sensory processing at the spinal or brainstem level (Sörqvist & Marsh, 2015; Sprenger et al., 2012). If we had designed our trials otherwise, by presenting the cognitive task first or both the task and pain simultaneously, participants might not have had the time to become engaged in the task and mean pain interference effects would have been larger. As it stands, our task design favoured performance on the task at the expense of pain processing.

Second, we tested whether high task performance explains the analgesic effect of the difficult task on pain stimuli on a trial-by-trial basis, and we explain our results as follows. The more difficult task leads to a significant reduction of pain rating (path c). These effects are nuanced, and can be decomposed into two parts: 1. Regardless of task performance, engaging in the difficult task was analgesic in itself (path c'). 2. We then found an inhibitory effect of task performance on pain perception (path b), after controlling for the effect of task difficulty. However, since performance on the harder task tended to worsen (path a), the analgesic potential of high performance tended to be un-recruited. Consequently, on average the performance-mediated effect of the difficult task (path ab) slightly countered the analgesia caused by engaging in the task. Indeed, the mediation of the effect of task difficulty on reported sensation by task performance is suppressive, as evidenced by the increased analgesic effect of the task when the mediation by performance is factored out (suppression effect, MacKinnon, Krull, & Lockwood, 2000; partial support of Hypothesis 3). Performance on the easy task was often near perfect (see Table 3); if performance was similar or even higher on the harder task, the mediation term would be negative ($a > 0 * b < 0$), thereby adding supplemental performance-mediated analgesia to the direct analgesia of the challenging task (c'). Although it may seem paradoxical that the total mediation effect by task performance is counter-analgesic rather than analgesic on its own, its subcomponents (paths a and b) are in the directions we would expect: it is sound for a harder task to incur lower task performance (negative path a), and we expected higher task performance to inhibit pain (negative path b). Hence, when multiplying the two negative regression coefficients to obtain the mediation effect, a positive mediation term (and suppression effect) is obtained. Our finding of an analgesic effect of task performance (path b) is nevertheless consistent with those of Buhle and Wager (2010), who found a similar result in their multilevel mediation analyses.

Third, we verified whether the small mean impact of pain on performance on the difficult task was explained by the intensity of reported thermal sensation for that trial. In this test, we found a near-significant interruptive effect of the pain stimulus on the 2-back task (path c). In addition, as expected, application of the pain stimulus provoked more pain than the warm stimulus (path a), which in turn inhibited task performance (path b). Reported pain fully explained the interruptive effect of a pain-inducing stimulus for that trial (confirmation of Hypothesis 4), suggesting that a noxious stimulus exerts its interruptive effect by virtue of pain proper (the conscious experience) rather in an earlier pre-attentional bottleneck, from nociception alone (physiological processing of a noxious stimulus, without resulting in the conscious percept of pain). The fact that reported pain predicts disruption is consistent with the results of Buhle and

Wager (2010), and is in line with existing proposals that pain interruptive by virtue of its ability to demand attention (Eccleston & Crombez, 1999).

Fourth, traits suggesting sensitivity to threat, namely high anxiety, high catastrophizing and low mindfulness, did not decrease the analgesic effect of the challenging task, nor the interruptive effect of the painful stimulus (no c path moderation; rejection of Hypothesis 5a). Instead, our results are more nuanced. High anxiety, high catastrophizing and low mindfulness each increased the degree to which sensation mediated the effect of a painful stimulus on a task (negative moderation of ab path); and increased the counter-analgesic effect of task performance on total analgesia by the difficult task.

Fifth, low inhibition and switching costs (suggesting better inhibition and switching ability) did not increase task analgesic nor pain interference (no c path moderation), nor did they moderate any of the mediation terms. The only factor that influenced the mean analgesic effect of the difficult task on pain was divided attention ability, namely task-set cost: interestingly, the challenging task was more pain-inhibitory on average for those with a weaker ability to divide attention between two tasks (partial support of Hypothesis 5b). No psychological factor influenced total task-analgesia or pain-interruption (c paths of mediation models, Figure 6).

Trade-off between pain processing and task performance

For the individual trials in which pain was reported as more intense, task performance was lower. Conversely, in better-performed trials, subsequent pain reports were lower. It therefore seems that high task performance and high pain perception are mutually inhibitory.

Despite the lack of mean PI (c path), our results still help clarify this unstable effect, because we deconstructed the attentional effects that, when combined in the right contexts, give rise to mean

TA and PI effects (Hypotheses 1 & 2). Given that the mediation by reported sensation fully explains the total effect, then using stronger or more threatening pain might have driven the total PI effect to significance. Hence, our analyses help bring an extra nuance to the results of previous inconsistent results. Specifically, although on average noxious stimuli might not have interfered with tasks in previous studies (Table 1 review), when pain was *felt* highly, it was interruptive, It is also possible that, in studies that did not find pain interference effects, task analgesia operated most strongly. This is corroborated by our finding that those who experienced lower pain interference exhibited higher task analgesia, which might have also been the case in previous work, although this is not reported.

Moderating effects of threat-sensitivity

Threat sensitivity is used here to describe high anxiety, high pain catastrophizing, and low trait mindfulness. Indeed, the three measures are correlated in our study, such that anxiety positively predicts pain catastrophizing, and mindfulness negatively predicts anxiety and pain catastrophizing. The current discussion on literature will focus mostly on catastrophizing since, to the best of our knowledge, the roles of mindfulness and anxiety have not been examined in the literature with regards to their effects in pain-task paradigms.

We had expected those who were more threat-sensitive to have more difficulty resisting interruptions by the pain stimuli to the difficult task. However, threat sensitivity did not increase mean pain interruption, nor did it influence mean task analgesia (no c-path moderation in either mediation model, Figure 6). The failure to modulate pain interruption is nevertheless consistent with results of two existing studies on the moderating effects of catastrophizing that control for individual differences in pain sensitivity (Keogh et al., 2013; Moore et al., 2013), as we have. In these studies, catastrophizing and threat did not influence pain interruption and task analgesia.

Conversely, the studies that did find effects of catastrophizing (Crombez et al., 1998a, 1998b, 2002) did not correct for individual differences in pain sensitivity, nor report whether catastrophizers were more sensitive to pain at baseline. Combined with our findings, this suggests that catastrophizers may fare worse in pain-task paradigms because they feel more pain, which in turn should be interruptive to task performance. This would explain why calibrating the stimulation temperatures individually such that all participants receive the same pain levels eliminates the effect of catastrophizing on task analgesia and pain interference. However, pain catastrophizing did not predict lower pain thresholds in our sample, and indeed tends to be a bad predictor of experimental pain thresholds (Quartana et al., 2009), which casts doubt on this proposal. Instead, it is possible that, although pain catastrophizing does not affect pain threshold, it may affect sensitivity at higher pain levels. Also, studies finding moderating effects of catastrophizing might have done so because they used electrocutaneous stimuli, which may be more disruptive than heat pain, especially for those with high threat sensitivity, given their startling nature and higher aversiveness (Rainville et al., 1992) and their known tendency to provoke anticipatory anxiety (Cornwell, Echiverri, Covington, & Grillon, 2008).

Despite the finding that threat-sensitivity did not influence mean task analgesia and mean pain interference, , we found that it had more nuanced effects. Specifically, it moderated the trial-level effects of fluctuations of *reported* pain, and of *performance* on the challenging task. Indeed, threat sensitivity increases not only the interruptive effect of reported pain on task performance, but also the analgesic effect of performance - interestingly, performance inhibits pain more in threat-sensitive individuals, which appears counterintuitive. Our proposed explanation is that being more sensitive to pain threat tends to increase 1. motivation to seek shielding from pain threat, possibly by absorption in the task and 2. motivation to avoid errors on the cognitive task. These may push those high on threat sensitivity to draw on extra resources in order to perform the cognitive task (Inzlicht & Schmeichel, 2012). That threat-sensitivity predicts more effortful performance is supported by the finding that catastrophizing predicts higher perfectionism (Rudolph et al., 2007), which is the disposition to strive for flawlessness and set excessively high performance standards for oneself, along with overly critical self-evaluations (Flett & Hewitt, 2002). This in turn would lead to increased analgesia, although effort self-reports are needed to support this idea. However, according to our experiment, at a particular 'breaking point' of pain intensity, despite one's best efforts, pain inhibition by performance 'loses'; pain interruption becomes the predominant process. Such impacts in threat sensitive individuals are consistent with previous descriptions of catastrophizing and anxiety; pain catastrophizing is proposed to involve a pronounced attentional bias toward sensory and affective pain information (Quartana et al., 2009), and trait anxiety increases attentional bias toward bodily threat (Sagliano et al., 2014). Since management of increased threat is proposed to recruit some 'common-pool' attentional resources (Pessoa, 2009), in a shared-resource model this would leave little remainder for task processing. In sum, pain catastrophizing and trait anxiety further polarize the trade-off between task performance and pain processing, likely because of a mechanism of threat avoidance that fails when the pronounced attentional bias to threat becomes too strong to suppress and tips the scale.

In our paradigm, mindfulness exerts the opposite effect of that of trait anxiety and pain catastrophizing, in that it reduces the pain-performance trade-off. In other words, higher mindfulness appears to promote a more diffuse distribution of attention between performance and pain, consistently with the idea that mindfulness training predicts the development of a wider and more diffuse attentional field (Lutz et al., 2008). According to our data, for those who are more mindful, focusing on task performance does not necessarily preclude processing of pain, and vice-versa. Specifically, if pain is not judged as threatening, it will attract less attentional resources, thereby rendering it less interruptive to task performance; conversely, lower pain threat may translate into a reduced motivation to seek shielding from pain by the cognitive task. It may also be that mindfulness reduces the tendency to become absorbed in a task to the point of total inhibition of distractors. Indeed, mindfulness promotes awareness and a wide monitoring of experience without explicit engagement (Lutz et al., 2008), which in our experiment may manifest as a reduced analgesic effect of high task performance. In any case, higher mindfulness scores seems to predict the ability to process pain and task more easily simultaneously, where both are less mutually inhibitory. It is not clear whether high mindfulness acts on pain-task paradigms solely by virtue of its shared component with catastrophizing and anxiety, or whether the unique portion of mindfulness (Day, Smitherman, Ward, et al., 2014) also plays a role. Indeed, a study found that some subscales of FFMQ, notably *act with awareness, non-judge* and *non-react,* are related to pain catastrophizing, and that these relationships become no longer significant after controlling for the common factor of worry via the Penn State Worry Questionnaire (Day, Smitherman, Ward, et al., 2014); the common component of the FFMQ and the PCS seems to be their ability to predict worry. The FFMQ still has at least one unique component that is distinct from the PCS (Day, Smitherman, Thorn, et al., 2014), which is captured by the *observe* and *describe* subscales. These may indeed play a moderating role in our sample, which lead us to opt to test the roles of mindfulness and pain catastrophizing separately, using sum scores for each in order to reduce the amount of tests we perform. To our knowledge, there are no studies examining the role of mindfulness in paradigms similar to ours. Future research would be required with larger samples to test the unique or shared contributions of catastrophizing and trait mindfulness subscales along with trait anxiety in similar pain-task paradigms.

Based on our results, those who are highly threat sensitive may be particularly resistant to task interruption at low levels of pain, but may be more vulnerable to disruption at high levels of pain, than those with low threat sensitivity. Despite our attempts to clarify previous findings, we do not come to a clear consensus about whether threat-sensitivity benefits or worsens outcomes in pain-task paradigms. Our results do, however, help clarify how attention is influenced by threat sensitivity. We can speculate that the costs for threat-sensitive individuals at high pain levels, particularly above those provoked in the experiment are larger than the benefits they have at low levels. However, pain-performance relationships across ranges of pain not tested in our study may not be linear, and as such we cannot confidently make such conclusions based on our data. It may also be that attentional modulation of pain becomes gradually dysfunctional as pain becomes more persistent over time, where initial attentional biases conferred by catastrophizing and anxiety may play important mediating roles (Liossi, 2012; Van Damme et al., 2010). We nevertheless demonstrate that threat-sensitivity factors exert effects on attentional modulation of pain without influencing sensitivity to pain.

Moderating effects of executive functions

Worse divided attention ability as indicated by larger task-set cost on a divided attention task, predicted a larger mean analgesic effect of a challenging task on pain (moderation of c-path in task analgesia model). Our effects suggest that those who have more difficulty maintaining several task-sets in mind have a more general difficulty juggling pain and task performance at the same time, irrespective of pain intensity. It is counterintuitive that weaker cognitive ability predicts a better outcome on pain-task paradigms. However, divided attention measures in individual pain-task dynamics may reflect costs associated with a saturation of executive processing capabilities in a limited-resource model, where having a high task-set cost implies that a cost is incurred for both task performance and pain processing when pitted together. Given that participants were likely to prioritize the cognitive task (since much emphasis prior to the behavioral procedure was placed on understanding and performing well on the 2-back task in our experiment), a task-oriented priority might have incurred larger costs to the alternate task of pain monitoring (thereby reducing pain perception) in those with larger task-set costs. Paradoxically, those with larger task-set costs, then, benefit because they are unable to effectively divide their attention beyond the prioritized cognitive task. We do not see the converse effect, i.e. that the painful stimulus was more interruptive than the warm stimulus, nor that higher pain impacted task performance more for those with larger task-set costs - in fact, it was the opposite, where worse divided attention predicted a smaller impact of pain on task performance (moderation of b-path in pain interference model). This was specifically because task performance was not as high across all pain levels in those with larger task-set costs, as indicated by multilevel moderation of the intercept (mean task performance) in individual trials by task-set cost (Table 5). In sum, those with worse divided attention benefit from larger task analgesia, but also have smaller impacts of pain on task performance, because their performance low to begin with, even at low levels of pain.

Some have proposed that task switching should improve pain management by virtue of its ability to promote effective allocation of attentional resources in daily life management of pain (Boggero et al., 2015), but we found that did not apply to our findings. Divided attention ability may play more of a role in our case, and this may be because our paradigm itself represented a dual-task: participants had to monitor their pain to be able to provide summary reports, all the while performing on the task (Seminowicz & Davis, 2007b). If participants were told to explicitly ignore the pain and were not asked to report its intensity, it's possible that inhibition and switching would play larger roles. In sum, while inhibition and switching abilities did not predict outcomes on the pain-task paradigm, divided attention predicted individual dynamics as well as mean analgesia caused by the more challenging task, suggesting that attention allocation between a task and pain is subject to influence by individual differences in certain executive functions, but not others.

Models of attention applied to a pain-task paradigm

Typically, previous authors have referred to a shared-resource model of attention (Kahneman, 1973) as best capturing the dynamics of pain-task paradigms (Eccleston & Crombez, 1999; Legrain et al., 2013; Seminowicz & Davis, 2007a). According to such a model, all targets of attention will compete for shared resources, whether or not they rely on shared mechanisms. Performance on some attentional tasks will decline if the combined attentional demands exceed the capacity limits, which vary as a function of arousal. Figure 10 depicts our proposed attentional model, where the gray inner circles represent the central executive, which follows a capacity model of attention. Indeed, we found that task performance (attention to the task, in blue), is inversely proportional to reported pain (attention to the pain, in pink), which is support for a shared-resource model. Note that although one process at a time takes up the majority of the capacity, there is still remaining capacity for the other to be carried out to a lesser degree (panels A and B). However, the magnified task-interruptive effect of reported pain and analgesic effect of performance in those who are more threat sensitive implies that such individuals have a smaller working capacity. Accordingly, in those with high threat sensitivity

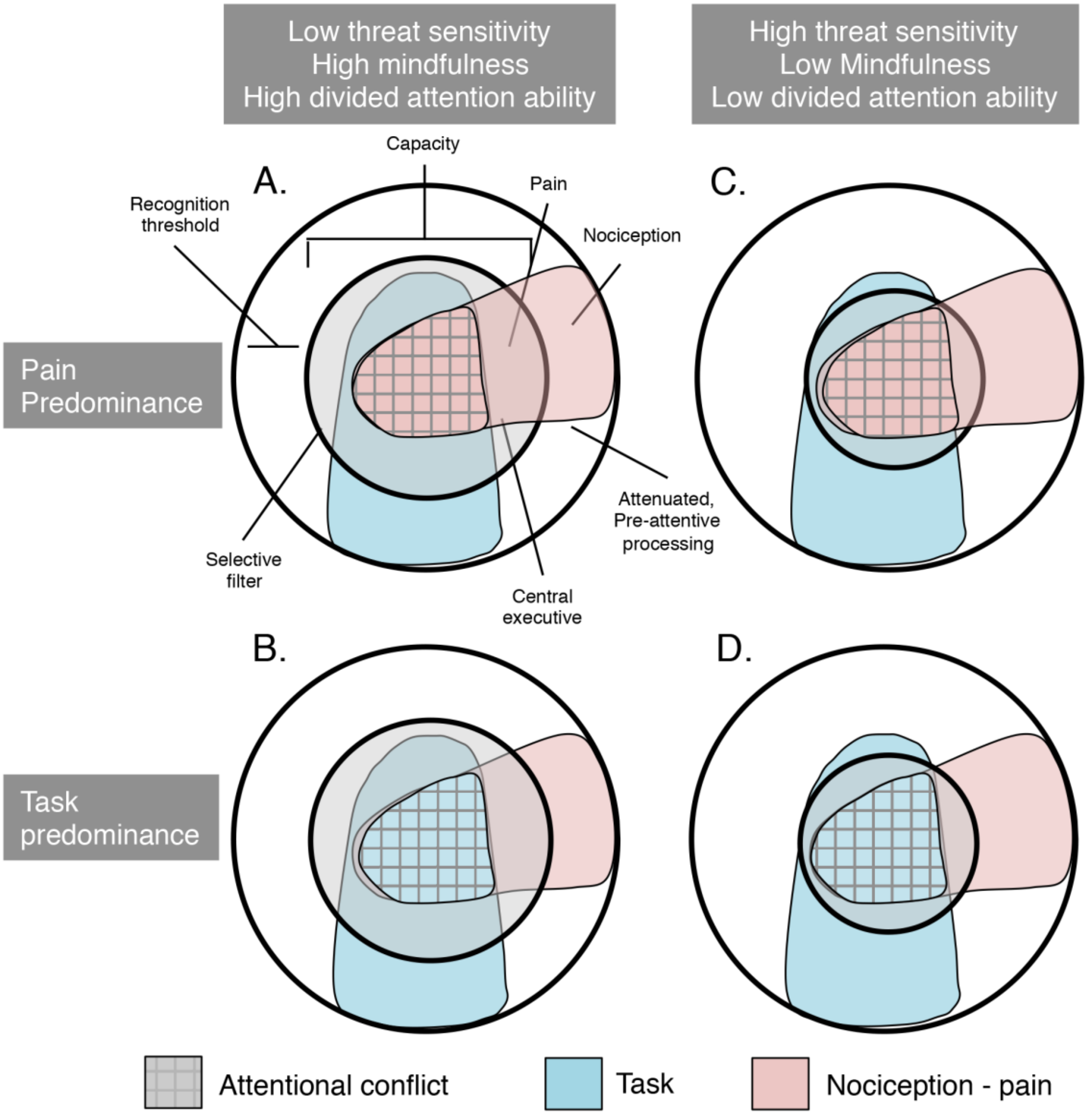

Figure 9. Proposed model combining a shared-resource model in and Treisman's attenuation model to explain attentional processing of thermal pain and a concurrent challenging task. The checkered regions of attentional overlap allocated either to the task or to pain, depending of internal (temporal precedence of pain/task, performance drop on the task, pain spikes) and external factors (motivation, distractions, irrelevant cognitions) leading to either pain or task predominance. A. Pain predominance in a high-capacity individual. Although task performance is predominant in the central executive, some pain is still felt. B. Task predominance in a high-nd low divided attention, (panels C and D, with smaller inner circles representing capacity), when

one process is predominant, there is little remaining space for the other. This is consistent with Kahneman's proposal that while moderate levels of arousal are best for performance, very high levels (as may be the case in the highly threat-sensitive) are detrimental (Yerkes & Dodson, 1908). Conversely, better divided attention would widen one's processing capacity limits; similarly, higher mindfulness may be associated with larger executive capacity (Chiesa et al., 2011).

However, the above model does not account for how pain enters the attentional field in the first place. We propose that prior to the executive stage described above, incoming stimuli are first attenuated. According to the Treisman attenuation model (Treisman, 1964), an unattended stream of incoming sensory stimuli is not blocked, but rather, it is attenuated in strength. If the unattended stream reaches a certain threshold for recognition, then attenuation is lifted and it will intrude into the attended stream. The threshold is permanently low for certain signals, such as one's own name, for example, or stimuli that are of high relevance for survival. Recognition threshold can also be contextually manipulated. As such, one prediction is that at high levels of concentration, the recognition threshold for unattended streams is higher, such that a higher level of nociception is required for it to intrude into the attentional field in the form of pain. The implication of the presence of an Attenuation model prior to reaching the central executive is that it adds an additional level of selection at a lower level of processing. Indeed, one study found that during concentration on one task, brainstem responses to a stream of auditory distractors was attenuated (Sörqvist & Marsh, 2015).

A strength of having a dual system combining at least two levels of selection is that it accounts for the multiple levels at which incoming signals can be modulated by attention. Such a model therefore implies that incoming streams of information are modulated first at a lower level (at the spinal, brainstem or thalamic level), at the nociceptive, 'pre-experiential' level of pain, and then at a higher level (SI and later), after pain has been felt. Indeed, attention has been found to modulate nociception from the level of the spinal cord, to SI, and the anterior cingulate cortex (Villemure & Bushnell, 2002), while pain catastrophizing, on the other hand, seems to modulate pain at the supraspinal level (Rhudy et al., 2009; Terry, Thompson, & Rhudy, 2015) but not lower. One flaw of a dual-model is related to the methodological difficulties in identifying which signals are parsed and selected at each part of the model. Another is that the model is more complex: the levels of selection may interact. For instance, it may be that attenuation by the lower-level Treisman model is caused by processes in the central executive. In order to test the dual-aspect of such a model, it would be necessary to use spinal imaging or electrophysiology and fMRI combined with behavioral measures to verify the levels at which pain is modulated by attention. Care must also be taken to avoid reverse inference in any conclusions made about the model.

Relation between threat sensitivity factors and executive functions

Discussion so far has implied that the effects of executive functions and threat-related psychological factors are separate. However, it is likely these factors interact, in that that rumination, anxiety, and worry occupy or deplete executive functions (Solberg Nes et al., 2009). Watkins & Brown (2002) showed that rumination reduced performance on an executive random number generation task in a sample of depressed individuals. Accordingly, in our sample, higher *rumination* scores on the PCS subscale predicted larger dual-task cost ($r = .318$, $p = .043$), indicating that those who ruminate more tend to have more difficulty dividing attention between two tasks; but no differences in task-set cost ($r = -.166$, $p = .300$) nor in Stroop inhibition or switch costs ($r = .192$, $p = .230$; $r = .088$, $p = .585$, respectively). We propose an additional nuance. As we previously mentioned, an attentional model of catastrophizing and anxiety posits that the trait is manifested as facilitated attentional processing of threat-related stimuli (Cisler et al., 2009). More specifically, anxiety is known to increase bottom-up capture of emotionally negative or motivationally relevant stimuli (Moser, Becker, & Moran, 2012; Pérez-Dueñas, Acosta, & Lupiáñez, 2009). As such, catastrophizing and anxiety may involve a difficulty overcoming internal (ruminative thoughts, feelings of helplessness) and external (nociceptive or threat-related cueing stimuli) attentional orienting to threat, increasing its probability of being prioritized against a competing task. Accordingly, one can conceptualize orienting to threat as a distraction impulse to be controlled, and executive capacity as the effortful controller. Inzlicht and Schmeichel (2012) proposed that the outcome of an attempt to exert self-control is dependent on the relative strengths of the impulse to be controlled and of the control mechanism itself. Applied to our context, the way pain threat is handled by executive functions should be dependent on at least two parameters - the strength of the impulse to attend to pain threat, and the capacity limits of executive functions responsible for attention allocation. If catastrophizing about a distractor becomes an attentional priority, there may be little left over for the concurrent executive task, especially if executive functions are weak. Having robust executive functions may be able to ensure the resiliency of attentional activity despite high catastrophizing and anxiety. Conversely, having worse executive functions may increase the likelihood that even low levels of catastrophizing about pain will tax the attentional system. However, very few published findings are available addressing this question. More research is needed to test whether stronger executive functions protect from the effects of threat-related psychological traits on the interruptive effect of pain.

Alternate explanations of results

Current discussion has assumed that pain reports reflect pain experience directly. Given that pain reports are given after the end of the noxious stimulation, they necessarily reflect *memory* for pain rather than rather than *direct* experience of pain. Indeed, it has been shown that pain reports given directly after pain stimulation reliably reflect pain reports given during the stimulus (Koyama, Koyama, Kroncke, & Coghill, 2004). However, It is possible that an ongoing cognitive task reduces the efficacy of subsequent pain memory retrieval, by serving as an interference task to the storage of experiential momentary samplings of pain perception (Bancroft, Hockley, & Servos, 2013) - and that degree of absorption or effort expended in the task increases this effect. If this is true, task-related analgesia in our study is the result more of a deficit in pain memory than of inhibition of the sensory experience itself. Christenfeld (1997) found that memory for pain intensity on a cold pressor task was reduced after a 10-min delay if a high-load distraction was given during pain compared to pain reports immediately after pain, suggesting that pain memory is subject to interference. Similarly, pain reports given after the termination of pain may differ from ongoing pain experience. Further, negative affect has been found to play a role in pain memory accuracy in chronic (Jamison 1989, other) and acute (Gedney et al. 2004) pain. In addition, catastrophizing (Lefebvre & Keefe, 2002) and anxiety (Noel et al., 2012b) have been found to modulate memory for pain. Assessing pain experience versus pain memory involves certain methodological difficulties, because interrupting a participant mid-task to probe experiential pain will require pulling attention away from the concurrent task and onto the pain, thereby cancelling the effects of distraction, and also would necessarily measure retention of the past few moments of pain. This does not detract from the usefulness of testing the pain-task paradigms, because memory for pain is considered an important determinant for future pain schemas and subsequent medical decisions (Bryant, 1993; Noel, Chambers, McGrath, Klein, & Stewart, 2012a).

Limitations and future considerations

Several limitations pertain in the current study. First, the multilevel models used are very complex, making their results more difficult to understand and to generalize to new contexts. The sizes of many of the effects in the current study are small, in particular the interruptive effects of pain stimuli on task performance and by extension, the moderating effects of the tested factors on these effects. We also employ multiple tests of statistical significance, using multiple moderators on several mediation paths, with no correction for the number of tests, making it likely that Type I errors were made. For these two reasons, it is important to interpret our study results with caution. In addition, we considered a few alternatives for the moderation tests on our seven moderators of interest. A principal components analysis, ideally involving all the subscales of the PCS and the FFMQ, would have allowed us to detect with more precision the clustering of variables and their conjoined and individual contributions to our model. However, we had an insufficiently large sample to test such effects, even with the sum scores of the PCS and FFMQ. Even without using a principal components analysis, employing all subscales would have been ideal, because it is likely that certain subscales of catastrophizing and mindfulness weigh more importantly in affecting attentional modulation. Some individual mindfulness subscales tend to better predict health indices than total mindfulness, as summed in our study (Consedine & Butler, 2014). For instance, the *observe* subscale, excluded from our mindfulness sum score because it is not well correlated with the other subscales in novice meditators (De Bruin, Topper, Muskens, Bögels, & Kamphuis, 2012), is likely to predict higher attention to pain, while *non-react* may predict more pain disruption given that, among all the subscales, it most predicts low anxiety, depression, and use of healthcare. However, we preferred to use sum scores in order to avoid running too many tests. We also avoided entering all the moderators together at the second level in order to avoid issues related to multicollinearity. Future work with similar paradigms testing moderation of related constructs would benefit from larger sample sizes, where the ratio should be at least with at least 10 observations per variable entered into a principal components analysis.

Next, calibration of individual thermal stimulus temperatures took place on a different day than behavioral testing, and the time that elapsed between testing sessions was variable. This leads us to call into question the validity of the pain sensitivity measures from time 1 to time 2. Indeed, a study found that a group of 50 healthy participants demonstrated moderately variable heat pain thresholds in a 1-week interval (Wylde, Palmer, Learmonth, & Dieppe, 2011). In our case, this spacing was done to reduce physiological adaptations to pain (Hollins, Harper, & Maixner, 2011), and cognitive fatigue from repeated cognitive testing. An alternate solution would have been to complete sensory calibration on the same day, but to include a break before the behavioral portion of the experiment. Another would be to include a brief verification procedure with pain stimuli presented alone prior to behavioral testing to confirm the validity of pain calibration results over time.

A few limitations apply to research on pain interference and task analgesia processes in general. First, one reason why many may have not reliably demonstrated pain interference effects experimentally is because the pain levels required to measurably impact task performance may approach maximum tolerated levels. In other words, participants are likely to ask to cease any intense pain stimulus as it begins to seriously impact task performance, thereby invalidating task performance measures and typically causing that particular task trial to be excluded from analyses. As such, in our experiment, a few trials (a total of nine throughout all participants) were excluded for this reason. In a clinical context where pain is not as easily relieved, however, it is more likely that inescapable pain exerts interruptive effects.

Next, as described above, a pain-task paradigm in which participants are required to monitor pain with the aim of providing reports can be described as a dual-task paradigm, which is not representative of encounters with pain in daily life. In experiments such as ours, one is tasked with the challenge of both ensuring optimal task performance while periodically or continuously sampling pain experience in order to formulate a final pain score. The demand of actively monitoring pain may pose its own attentional constraints, since rarely is one expected to provide pain scores in everyday life. Seminowicz and Davis (2007a) distinguish pain *perception* from pain *evaluation,* invoking the Heisenberg uncertainty principle to propose that once one has begun to evaluate a pain perception, the perception becomes transformed. Notably, pain monitoring may increase pain perception. Indeed, attention to pain increases summary pain reports when pain is terminated (Arntz, Dreessen, & Merckelbach, 1991). Ideally, randomly prompting participants to report pain after approximately of the trials might have led them to monitor their pain less in general, as participants would not know when a rating would be requested of them. This technique has been employed by Seminowicz and Davis (2007b) to this end.

It is likely that highly pain catastrophizing individuals are under-represented in experimental pain research, due to a recruitment bias that would dissuade them from participating. Indeed, our sample mean catastrophizing sum score was lower than that found for a large undergraduate sample that was not receiving pain (14.0 points compared to 18.6 points (Sullivan et al., 1995). With a more representative sample, we would expect pain interference effects to be magnified, consistently with current knowledge on catastrophizing. However, the effects of threat sensitivity on pain interference and task analgesia for pain levels above those used in the study may be nonlinear. A simple online questionnaire study assessing willingness to participate in different kinds of mock pain studies (i.e., involving different types of noxious stimuli) as a function of pain catastrophizing would allow us to help capture the extent of this recruitment bias.

We here address work that attempts to categorize individuals as exhibiting A-type (attention, or task, dominates) or P-type (pain dominates) behavior, and to bring to light some notable flaws that cast doubt on their methodology and conclusions. Seminovicz, Mikulis & Davis (2004) gave young adults a Stroop task and concurrent pain via transcutaneous electrical stimulation of the median nerve, and split their sample according to whether participants performed faster during painful stimulation ('attention dominates', or A-type) than with no stimulation, or slower ('pain dominates', or P-type). Two follow-up studies were then carried out with the same methodology (Erpelding & Davis, 2013; Seminowicz & Davis, 2007b). The authors argued for the existence of distinguishable individual tendencies to favor pain or a task when presented concurrently, reflecting potential vulnerabilities to pain interference. These conclusions were even included in a Ted-Ed on pain by one of the authors (Davis, 2014). However, it is vital to note that there exist several flaws, both in the methodologies of the studies and in conclusions made. First, in all studies the authors do not test whether performance was significantly impacted (P-type) or improved (A-type) by pain in either group, as absolute RT deviations from the no-pain condition could be very small and due to random chance. Indeed, mean deviations seem to vary from as little as 10ms to 1200ms between Pain and No Pain conditions, and it would be more reasonable to conceptualize RT changes in response to pain as continuous rather than binary. Next, the difficulty of the Stroop task was not individually calibrated, leading to the possibility that individual task skill differences might have affected pain perception, given our findings of task analgesia by a harder task. Decreased pain perception in turn might have allowed better performance on the task; however, the authors do not report the relation between A- and P-type group membership and reported pain levels. In addition, in Erpelding & Davis (2013), the Stroop trials from which mean A- and P-type scores were derived comprised of only a single 60s block of 24 task trials for each of the No Pain and Pain conditions, suggesting that any differences in task performance might have been the product of a one-time momentary fluctuation of attention. Additionally, order effects due to counterbalancing of Pain and No Pain conditions might have affected membership to A- or P-type group and were not reported. Finally, and most importantly, evidence of sustained trait A- or P-type behavior across time, different tasks, and modalities of noxious stimuli has not yet been reported. The first step in establishing whether behavior on such experimental paradigms are predictive of pain impairment in clinical settings, long-term, is to test whether individual TA and PI patterns have good test-retest reliability across several testing times and multiple tasks. Indeed, repeating our experimental paradigm over a set period of time within subjects may be a first step in establishing clinical validity of individual behavior on our pain-task paradigm.

We make some final proposals for future work in accordance with points discussed above. First, future work should examine whether stronger executive functions can rescue from the effects of high threat sensitivity. Second, motivation is known to play a role in performance on competing tasks (Inzlicht & Schmeichel, 2012), pain processing (Van Damme et al., 2010), and on pain-task paradigms (Verhoeven et al., 2010); it might be more ecological to measure the effects of a motivation in a future experimental study, or to use monetary rewards for high performance to probe the effects of inducing motivational incentives.

From experimental to clinical implications

Our findings may be extended, with parsimony, to some clinical contexts. First, in our study, pain experienced when completing the difficult task was on average 13 points lower on a scale of 100 than when completing the easy task, and could be further reduced by up to a mean of 11 additional points for perfect performance. While at best this pain reduction is still under the reduction of 30/100 deemed clinically significant (Bird & Dickson, 2001), in our case the pain changes took place on a short time scale - tens of seconds - and suggest that more immersive, motivating, or complex tasks could lead to clinically effective distraction from pain. Further, our results indicate that one's tendency to be sensitive to pain threat and one's divided attention ability influence the way attention is manipulated and allocated between pain processing and task processing in the global attentional workspace on a moment-to-moment basis. Our results do not directly capture the common notion that those who are more threat sensitive fare worse in pain, but suggest that they may even benefit in some cases. Indeed, Schreiber et al. (2014) found that chronic pain patients who catastrophize experienced more analgesia from a distracting task. This is reminiscent of our finding that higher task performance was more pain-inhibitory in, and leads us to speculate that for individuals with catastrophizing levels not assessed in the study, and who are experiencing acute or chronic pain, we would find larger task analgesic effects, but also larger interference effects of pain. There may yet exist an as yet untapped potential for threat sensitive individuals in particular to benefit from cognitive distraction. Finally, our results demonstrate the intuitive notion that concentrating on an alternate task reduces pain. Distraction from pain is already used in several clinical contexts where pharmacological analgesia is not recommended or applicable. For example, virtual reality immersion has been shown to effectively reduce surgical pain (Morris, Louw, & Grimmer-Somers, 2009).

However, generalizability of experimental results to clinical context is riddled with many barriers to overcome. First, generally, the primary task paradigm does not sufficiently emulate real-life pain contexts. It would be useful to conduct a similar study where the onset of pain was unpredictable and potentially threatening, with rewards contingent on effective performance. Second, pain-free individuals to whom we have administered pain are likely to be vastly different from chronic pain patients. Chronic pain is known to be accompanied by a constellation of co-occurring symptoms and patterns, including anxio-depressive symptoms (Dersh et al., 2002), sleep problems and reductions in every occupational activity (Choinière et al., 2010), and pathological central pain regulatory mechanisms (Woolf, 2011). This being said, how can we bridge the gap between the current experimental work and clinical outcomes? We can begin by testing its predictive value in acute or sub-acute pain patients. Although this poses its own methodological issues (e.g., how to stimulate versus release pain from one minute to the next) in some cases it is possible to manipulate the pain and pain threat in a patient with physical positions of the body, as has been done by Vangronsveld et al. (2007) in whiplash patients.

General conclusions and final contribution to the field.

Although we have called into question the representative nature of the current study participants of pain patients, it's important to remember that, while pain becomes a lifelong affliction for some, it always has a beginning. Statistically, out of the forty-one studied here, eight are likely to go on to eventually develop chronic pain in adulthood, with this number reaching near thirteen in old age (Reitsma, Tranmer, Buchanan, & Vandenkerkhof, 2011). Capturing how exactly this unwanted guest is first handled in a person's mind before it becomes wrought into the fabric of everyday life is crucial to understanding how patients eventually manage pain, or alternatively, how it manages them.

As for Dave Grohl, some clues regarding his psychological make-up might help explain how, on the day he broke his leg onstage, he kept his head up. He is known for "treating fans like gold", regularly donating to many charities, leaving large gratuities, as well as repeated displays of humility, kindness, and a generally cheery attitude (Maloney, 2012); indeed, he is often referred to as "The Nicest Man in Rock". As a final clue, he regularly sees a therapist to "help him understand band problems, getting older, problems with the volume of work and general life changes", suggesting mental groundedness (James, 2016). Being well-balanced and kind to others may make Dave Grohl better respond to adversity, and these traits may overlap with those that helped him propel to stardom and cope with the stresses and insecurities involved in being at the center of such a fickle industry. This may not be a surprise, coming from the man who, after witnessing his band-mate Kurt Cobain commit suicide, was motivated to found his own band soon after, and with a positive attitude: "When Kurt died, I woke up the next day and thought, 'I’m lucky to be alive.' [...] I felt the most important thing was just appreciating being alive, good day or bad day" (Kellmurray, 2016). The show must go on.

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