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Acute pain disrupts prospective memory cue detection processes

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ABSTRACT
Prospective memory refers to the planning, retention, retrieval, and execution of intentions for future behaviours and it is integral to the enterprise of daily living. Although prospective memory relies upon retrospective memory and executive processes often disrupted by pain, limited research has explored the influence of acute or chronic pain on the ability to complete prospective memory tasks. In the present study we investigated the influence of acute pain on prospective memory tasks that varied in their demands on executive processes (i.e., non-focal versus focal prospective memory cues). Complex-span working memory tasks were also administered to examine whether individual differences in working memory capacity moderated any negative impact of pain on prospective memory. Acute pain significantly impaired prospective memory performance in conditions that encouraged non-focal strategic processing of prospective memory cues, but not in conditions that encouraged more spontaneous focal processing. Individual differences in working memory capacity did not moderate the effect of acute pain on non-focal prospective memory. These findings provide new insights into prospective memory dysfunction created by painful experiences.

Cognitive performance is known to be hindered by acute and chronic pain with memory and attention systems among those most commonly affected (Katz, Heard, Mills, & Leavitt, 2004; Muñoz & Esteve, 2005). While most studies have focused on retrospective memory impairments (i.e., memory for past events and information; Berryman et al., 2013), limited research has examined the influence of pain on prospective memory (i.e., memory for future intentions; Gatziounis, Schrooten, Crombez, & Vlaeyen, 2018; Ling, Campbell, Heffernan, & Greenough, 2007; Miller, Basso, Candilis, Combs, & Woods, 2014). Prospective memory (PM) problems are the most frequent memory failures in everyday life (e.g., forgetting to pay bills on time, take prescribed medications, etc.; Kliegel & Martin, 2003; Unsworth, Brewer, & Spillers, 2012). Because of its importance and prevalence, remembering to perform delayed intentions at the appropriate future moment is essential for independent and successful living (Dismukes, 2008; Park & Kidder, 1996). While relatively little work has examined the impact of pain on PM, prior research has shown that many related cognitive phenomena are negatively impacted by pain, including working memory (Berryman et al., 2013), autobiographical memory (Erskine, Morley, & Pearce, 1990), memory for specific painful experiences (Noel, Chambers, McGrath, Klein, & Stewart, 2012; Redelmeier & Kahneman, 1996), and task switching (Attridge, Keogh, & Eccleston, 2016).

The negative effect that pain has on various cognitive processes holds important clinical implications. Theoretically, the diverse effects of chronic and acute pain on cognition demand a biopsychosocial model that incorporates differing perspectives on how pain leads to psychopathology (Karoly & Crombez, 2018). For example, the fear-avoidance model of chronic pain suggests that people experiencing acute painful experiences may perseverate on these painful experiences, thus leading to catastrophizing, negative affect, and depression (Vlaeyen & Linton, 2012). Perseverative effects of acute pain negatively impact several cognitive processes including working memory, retrospective memory, and potentially PM. This impact may lead to chronic negative evaluations of the source of pain, the experience of pain, and how pain will influence behaviour in future situations. This fear-avoidance loop traps some people into a vicious cycle of disability and suffering. Here, we hypothesise that individuals with higher working memory may be less susceptible to this type of interference from pain as compared to those with low working memory. This prediction emerges from research suggesting that pain hinders attention control and interrupts task-related cognitive functioning (Eccleston & Crombez, 1999; Moore, Eccleston, & Keogh, 2017).

Relatedly, neuropsychological evaluations for pain patients typically assess working memory as well as long-term retention of information to determine a patient’s mental capacity because these cognitive processes are impacted by acute and chronic pain (Mazza, Frot, & Rey, In Press). These cognitive factors are routinely implicated in successful prospective memory where people must...
encode, maintain, and retrieve intentions for future action (i.e., long-term memory functions). Moreover, recent research has shown that working memory functions are also necessary for successful PM under certain conditions (Brewer, Knight, Marsh, & Unsworth, 2010; Meeks, Pitães, & Brewer, 2015; Smith & Bayen, 2005). Given that pain negatively impacts retrospective and working memory, we reasoned that pain would also negatively impact PM, especially under demanding circumstances. Furthermore, we predicted that individuals with higher working memory capacity would be more resilient to negative effects of pain on PM.

Successful PM relies on a range of frontally-mediated executive processes, such as planning, goal maintenance, and interrupting/switching from irrelevant ongoing activities to execute intentions (Kliegel, Altgassen, Hering, & Rose, 2011). All of these executive functions are related to individual differences in working memory capacity and are known to be disrupted by pain (Attridge et al., 2016; Berryman et al., 2014; Moore, Keogh, & Eccleston, 2012; Moriarty, McGuire, & Finn, 2011; Okun, Karoly, Mun, & Kim, 2016). Given the prevalence of painful experiences (Breivik, Collett, Ventafridda, Cohen, & Gallacher, 2006) and the adverse effects of PM failures on daily living, it is important to understand the conditions under which pain affects PM performance. Moreover, it is critical to find possible moderators of pain’s impact on behaviour (e.g., working memory capacity).

Differences in the working memory and attention demands inherent in detecting PM cues can be conceptualised in the multiprocess view of PM (McDaniel & Einstein, 2000). In PM, information in the environment can cue the retrieval of an intended action (e.g., encountering a pill bottle cues retrieval of your intention to take medication). To mimic the demands of daily life, typical laboratory paradigms instruct participants to remember to perform a specific action upon the occurrence of a cue that occurs while they are busily engaged in an unrelated ongoing activity (e.g., press the “/” key whenever you encounter the word “doctor” while performing a lexical decision task; cf., Einstein & McDaniel, 2005). The ongoing activity does not change when the cue occurs, so for intention retrieval to happen individuals must interpret the event as a cue for action. According to the multi-process theory of PM, the detection of cues and retrieval of deferred intentions varies with the extent to which capacity-demanding (versus more spontaneous) cognitive processes are necessary for performance. For example, spontaneous PM cue detection is more likely to occur in cases where the ongoing activity fully encourages processing of relevant features of the PM cue (i.e., focal PM). Alternatively, if the ongoing activity draws attention away from the PM cue (i.e., non-focal PM), then prospective remembering is assumed to require more strategic control processes to monitor for the cue signalling the appropriateness for performing the intended action (Brewer et al., 2010; McDaniel & Einstein, 2000). For example, during a lexical-decision task, which requires semantic processing of letter strings to determine whether they constitute words, remembering to press the “/” key when the word “tortoise” is presented involves focal processing of the PM cue. However, the same task is classified as non-focal when the cue is the appearance of the syllable “tor” because the information extracted in the service of the ongoing task primarily fosters focal attention to stimuli at the word level, but not at a syllable level (Einstein et al., 2005). Therefore, while focal cues are assumed to spontaneously trigger intention retrieval, non-focal cues are assumed instead to require a more controlled approach to prospective remembering.

The notion that PM demands (such as the degree of cue-focality) influence the working memory demands for PM cue detection has promoted a more refined examinations of PM abilities in many cognitively impaired clinical populations (Foster, McDaniel, Repovs, & Hershey, 2009; Kliegel et al., 2011; Kliegel, Jäger, & Phillips, 2008; Marsh et al., 2009; Ordemann, Opper, & Davalos, 2014; Rendell, McDaniel, Forbes, & Einstein, 2007; Zuber, Kliegel, & Ilhe, 2016). Focal PM cues are typically found to enhance PM performance among older and clinical populations whose PM performance is nearly perfect under such conditions. However, more PM failures occur in non-focal PM conditions. Similarly, healthy younger adults under divided-attention conditions exhibit less PM disruption for focal than for non-focal PM tasks (Windy McNerney & West, 2007), suggesting that successful non-focal PM performance depends on some optimal level of executive functioning (for similar findings on individual differences in working-memory capacity see Brewer et al., 2010; Rose, Rendell, McDaniel, Aberle, & Kliegel, 2010). As previously noted, only two studies have explored the effects of chronic pain on PM performance and one study has examined the effects of acute pain.

Relatively few studies on pain and PM have been published. Ling et al. (2007) reported that patients with low back pain evidenced demonstrable impairments in PM using a questionnaire measure. Miller et al. (2014) used a performance measure of PM (the Memory for Intentions Screening Test; MIST) in patients with multiple sclerosis and found that pain accounted for approximately 10% of the variance in PM performance. In contrast, a recent study by Gatzounis et al. (2018) induced electro-cutaneous pain as well as threatening instructions and observed their effects on a PM task that involved subjects performing a previously-encoded intention whenever a specific cue word (i.e., a focal cue) was detected while completing a PM-irrelevant word categorisation task. Pain stimulation occurred on 14.6% of the trials and PM cues were presented on 2.65% of the trials. The investigators also assessed working memory (via reading span) and catastrophizing tendencies as possible moderators. They reported that neither threat nor pain stimulation influenced PM, nor did working memory or catastrophizing play a role in PM intention performance. A primary aim of the current
study is to address some of these inconsistencies by comparing the focal PM task used in Gatzoiunis to a nonfocal PM task that is more demanding and commonly used in the PM literature with healthy individuals.

Given the specific nature of the cognitive impairments caused by pain, and based on the above framework, the present study investigated the influence of experimentally-induced acute pain on PM tasks varying in the demands of executive control required for prospective remembering (i.e., cue-focality). We hypothesised that acute pain would impair non-focal, but not focal, PM performance. Further, if the expected pain-related PM decline for non-focal tasks is indeed a consequence of shared executive resources, the effect of acute pain on non-focal PM performance should decrease as working-memory (WM) capacity increases (Rose et al., 2010). This account predicts that individual differences in working memory capacity should moderate the effects of pain on non-focal PM. Critically, however, this account also predicts that individual differences in WM capacity should not be associated with focal PM performance. A final goal of the current work was to examine how pain influences individuals’ metacognitive judgements about PM performance. This goal was accomplished by asking participants to make postdictions regarding the impact of pain on their PM performance at the end of the experiment. Specifically, we were interested in the degree to which participants were metacognitively aware of any negative impacts of pain on their own PM performance.

Methods

This study was approved by the Human Research Institutional Review Board at Arizona State University.

Participants and design

Over the course of two semesters, a total of 239 young adults (104 females) from Arizona State University participated in this study ($M_{age} = 22$ years, $SD = 2.25$). We collected the data with no a priori power calculation nor any stopping rule based on significance of the findings. In fact, the study ended with a sample size deemed appropriate based on our experience conducting many individual differences studies of this nature at the end of the second semester of data collection. After providing consent, each participant was tested individually in sessions that lasted approximately 75 min and all participants completed a battery of pain-related questionnaires (including the Mindful Attention Awareness Scale (MAAS); Positive and Negative Affect Schedule (PANAS); Profile of Chronic Pain and the Perception of Pain Scale); a set of three automated complex-span working-memory tasks (Operation-span; Symmetry-span and Reading-span; see Oswald, McAbee, Redick, & Hambrick, 2015; Unsworth, Heitz, Schrock, & Engle, 2005 for full task details) and a PM task. All participants reported no existing chronic pain experience. The information collected from the pain-related questionnaires was not relevant to the current study and will not be further discussed.

We implemented a 2 (PM condition: focal versus nonfocal PM) $\times$ 2 (Pain condition: pain versus no-pain) mixed-factorial design to assess whether cue-focality interacted with pain to produce selective PM deficits. The PM task involved two between-subjects conditions (focal and nonfocal). Of the 239 participants, 101 participants (62 females) were randomly assigned to the focal condition and 138 (42 females) to the non-focal condition. Acute pain was induced by having participants place their non-dominant index finger into a pressure algometer while performing the PM task using their dominant hand (Figure 1). The two levels of Pain (Pain and No-pain) were manipulated within-subjects and counterbalanced such that all participants completed the PM task both in pain and not in pain. Importantly, all of the results reported in the current study are unaltered when controlling for the counterbalancing factor of putting the participants in pain during the first versus the second block. The lack of a counterbalancing effect indicates that the acute painful experience did not have any detectable and lasting effects on PM when participants transitioned to no pain blocks.

Materials

Pain manipulation and assessment

Pain intensity was rated on a numerical rating scale where 1 stands for “No pain/physical discomfort” and 10 for “The most intense pain/physical discomfort ever”. Each participant rated their level of pain at three points during the study: (1) upon arrival on the day of testing (Baseline rating); (2) after performing all WM tasks (Pain rating); and (3) before performing the PM task in the No-pain condition (No-pain rating). In order to ensure sufficiently intense nociceptive input, the weight for the Pain condition (Pain rating) was determined by having the experimenter add weight to the algometer until the participant reported between 6–7 on the pain scale (note that participants were blind to this pain threshold determination). For both Pain and No-
pain conditions, the subject’s index finger remained in the algometer device during the entire PM task. However, in the No-pain condition the experimenter removed all weight from the algometer.

**Complex-span working memory tasks**

**Operation span**

Participants solved a series of math operations while trying to remember a set of unrelated letters. Immediately after the letter was presented the next operation was presented. When recall was required, letters from the current set could be recalled in the correct order by clicking on the appropriate letters. One trial of each set-size (3–7) was presented, with the order of set-size varying randomly. Consistent with prior research, the dependent variable for all of the complex-span measures was the proportion of correct items recalled in the correct serial position.

**Symmetry span**

Participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task, participants were shown an 8 × 8 matrix with some black squares. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. After each symmetry judgment, participants were presented with a 4 × 4 matrix with one of the cells filled in red. At recall, participants were required to recall the sequence of red-square locations in the preceding displays in the order they appeared by clicking on the cells of an empty matrix. Set-size ranged from 2–5, with one administration for each set-size.

**Reading span**

Participants read a set of sentences while trying to remember a set of unrelated letters. For each sentence, participants determined whether the sentence made sense or not (half of the sentences made sense). After each sentence decision, participants were presented with a letter for recall at the end of the set. At recall, letters from the current set-size ranged from 3–7, with one administration for each set-size.

**Prospective memory task**

The parameters of this task and the word and nonword stimuli follow a well-validated PM paradigm known to manipulate executive demands within a PM task while holding all other task demands equal (Brewer et al., 2010; see Figure 2). Participants first received instructions for the lexical-decision task. They were told that their task was to decide, as quickly and accurately as possible, whether a string of letters formed valid English words or not by pressing one of two keys (“J” and “F” keys, respectively). Word and nonwords were presented one at the time and stayed on the screen until participants responded. Participants were also told to press the spacebar (with their thumb) when a “waiting” message appeared between each trial, which triggered presentation of the next lexical-decision trial. After a 20-trial practice block, participants encoded the PM intention. For both focal and nonfocal PM conditions, the participants were told that we were also interested in their ability to remember to perform a specific future action. Therefore, in addition to performing the lexical-decision task, participants were instructed to make a special key press (“/” key) during the “waiting” message whenever they encountered a PM cue. In the focal condition the cue was the specific word (“DOCTOR”) which appeared 8 times in the context of the ongoing task, and for the nonfocal condition the cue was the syllable (“TOR”) which also occurred 8 times in the context of the ongoing task but in different words. The two PM conditions were exact replications of one another, and only the nature of the PM cues differed between them.

For both conditions 8 PM cues occurred once every 25 trials beginning on trial 25 and ending on trial 200. Each PM block consisted of a total of 208 lexical-decision trials, and participants performed two blocks (one block in Pain and one in No-pain). PM performance was defined as the proportion of cues successfully responded to with a “/” response during the “waiting” message immediately following the cue. After the experimenter was satisfied that participants fully understood all the instructions, a 10-min distractor task was administered (i.e., a visual puzzle-task). In PM paradigms, instituting delays (filler distractor tasks) between intention encoding and execution is crucially important to remove the intention from primary memory and prevent the prospective task from becoming a vigilance task (Einstein & McDaniel, 1990). Therefore, following this delay, the experimenter asked the participant to place their finger into the algometer and initiated the first block of the PM task without making any reference to the PM task. Depending on the counterbalancing order, participants performed the first PM block either in Pain or No-pain. After completing the first PM block, and before participants initiated the second block, all participants rated their pain level with all weight removed from the algometer (No-pain rating). This last pain rating is important to insure that participants that performed the first PM block in Pain initiated the second PM block reporting not being in pain. The experimenter then either added the weights (or kept all weight removed) from the algometer, and participants initiated the second PM block in the Pain or No-pain condition.

At the end of the experiment, all participants completed a PM post-experimental questionnaire that asked them to recall the intended action and PM cue (Scullin, Bugg, McDaniel, & Einstein, 2011). The use of this type of questionnaire is suggested in the PM literature to confirm participant’s understanding of the PM task and to disentangle retrospective memory failures (i.e., failures remembering the intention content, or what action to
perform and when to perform it) and actual PM failures (i.e., failures remembering the intention itself, or that one needs to do something at a certain point in the future; Ellis & Kvalishvili, 2000; Scullin et al., 2011). Participants were also asked to make metacognitive judgments about whether pain to affect their PM ability by rating the perceived difficulty of remembering to perform the PM intention while they were in pain versus no-pain. Ratings were made in an 8-point Likert scale ranging from 0 "Not difficult at all" to 8 "Extremely difficult". These judgements may provide insight into compensatory strategies developed by participants to mitigate perceived negative impacts of acute pain.

**Results**

For all statistical analyses, a conventional alpha level of .05 was used and counterbalancing had no effect on any of the dependent variables so that factor was excluded (ps > .05).

**Descriptive statistics**

Average performance for all WM tasks can be found in Table 1. WM task performance was similar to previously reported research from our laboratory and from other laboratories (Oswald et al., 2015; Redick et al., 2012). Also, estimates of skew and kurtosis were at reasonable levels (Kline, 2015).

### Table 1. Descriptive statistics for subjective pain ratings.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Focal PM (N = 101)</th>
<th>Nonfocal PM (N = 138)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M (SD)</td>
<td>M (SD)</td>
</tr>
<tr>
<td>Baseline</td>
<td>1.52 (0.5)</td>
<td>1.56 (0.5)</td>
</tr>
<tr>
<td>No-Pain</td>
<td>1.55 (0.9)</td>
<td>1.58 (0.7)</td>
</tr>
<tr>
<td>Pain</td>
<td>6.66 (2.4)</td>
<td>6.9 (1.8)</td>
</tr>
</tbody>
</table>

Notes: Pain intensity was rated on a numerical rating scale where 1 stands for "No pain/physical discomfort" and 10 for "The most intense pain/physical discomfort ever".

### Table 2. Descriptive statistics for all working memory tasks.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean</th>
<th>SD</th>
<th>Skew</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ospan</td>
<td>16.90</td>
<td>5.00</td>
<td>-1.322</td>
<td>1.527</td>
</tr>
<tr>
<td>Rspan</td>
<td>15.84</td>
<td>3.89</td>
<td>-567</td>
<td>.037</td>
</tr>
<tr>
<td>Symspan</td>
<td>10.01</td>
<td>2.75</td>
<td>-538</td>
<td>-215</td>
</tr>
</tbody>
</table>

**Lexical decision task accuracy and response latencies**

Before conducting the analysis on PM performance, we examined mean lexical decision latency scores (averaged across trials that did not contain PM cues) as a function of pain (between subject variable) and PM condition (cue focality manipulated within subjects). In line with previous research, results of this analysis showed that response latencies were slower in the non-focal (M = 959, SE = 14) than focal (M = 829 ms, SE = 16) possibly reflecting increased monitoring for PM cues in the non-focal condition, F(1, 237) = 39.954, p < .001, η² = .144. There was also a significant main effect of pain condition, reflecting faster lexical decision latencies when individuals were placed in pain (M = 959, SE = 14) than when they were not in pain (M = 914, SE = 12), F(1, 237) = 19.710, p < .001, η² = .077. Finally, there was a significant PM condition × Pain interaction, F(1, 237) = 17.053, p < .001, η² = .067. Planned comparisons confirmed that pain...
reduced latencies in the non-focal PM condition (M = 921, SE = 14) versus (M = 998, SE = 15), t(137) = 5.760, p < .001, but not in the focal PM condition (M = 827, SE = 17 versus (M = 830, SE = 18), t(100) = .269, p = .789.

Similarly, we report an analysis of lexical decision task accuracy (averaged across trials that did not contain PM cues) as a function of pain (between subject variable) and PM condition (manipulated within subjects). There was no difference in lexical decision accuracy between the nonfocal (M = .92, SE = .01) and focal conditions (M = .91, SE = .01), F(1, 237) = 3.604, p = .059, $\eta^2_p = .015$. There was a significant main effect of pain on lexical decision accuracy, reflecting worse ongoing task performance when individuals were placed in pain (M = .91, SE = .01) compared to when they were not in pain (M = .92, SE = .01), F(1, 237) = 17.469, p < .001, $\eta^2_p = .072$. There was not a significant PM condition × Pain interaction, F(1, 237) = 3.604, p = .059, $\eta^2_p = .015$.

**Prospective memory performance**

The proportion of PM cues successfully responded to was submitted to a general linear model (GLM) with PM condition (focal, non-focal) as the between-subjects factor and pain condition (pain, no-pain) as the within-subjects factor. Replicating previous work (e.g., Brewer et al., 2010; Einstein et al., 2005) more PM cues were detected in the focal (M = .95, SE = .02) than in the non-focal condition (M = .57, SE = .02), F(1, 237) = 157.378, p < .001, $\eta^2_p = .399$. There was also a significant main effect of pain condition, reflecting worse PM performance when individuals were placed in pain (M = .72, SE = .02) compared to when they were not in pain (M = .80, SE = .02), F(1, 237) = 25.807, p < .001, $\eta^2_p = .098$. However, this main effect was qualified by a significant PM condition × Pain interaction, F(1, 237) = 14.173, p < .001, $\eta^2_p = .060$. Follow up analysis showed that the main effect of pain was significant in the nonfocal condition with participants performing higher in the no pain (M = .63, SE = .02) than in the pain condition (M = .50, SE = .02), t(137) = 5.526, p < .001. In contrast, in the focal condition, participants’ performance in the no pain condition (M = .96, SE = .02) did not differ from that in the pain condition (M = .95, SE = .03), t(100) = 1.596, p = .114. As hypothesised, pain selectively affected highly demanding PM tasks (Figure 3). It should be noted that performance in the focal condition was at high levels, which could limit the opportunity to observe an effect of pain in this condition. The observed pattern of results is however consistent with previous research using similar focal cues to the ones used here (Brewer et al., 2010; Einstein et al., 2005). Also, we conducted pairwise comparisons after removing participants from focal conditions who detected all of the cues and the pattern of results did not change, i.e., we still did not find an effect of pain on focal PM performance, t(38) = 1.617, p = .114.

Results from the PM post-experimental questionnaire revealed that both focal and non-focal PM conditions elicited nearly perfect post-test recall, and only two participants from the focal condition failed to recall the PM intended action. Thus, it seems likely that the PM failures described above were due to problems in detecting the cues rather than retrieving the intended action when the cue occurred (i.e., PM problems), rather than to retrospective memory failures for the task demands.

**Correlations and moderation analysis**

Correlations between all WM capacity measures (Ospan, Rspan and Symspan) ranged between .22 and .45, all ps < .05. Therefore, z-scores were created for each task and these measures were averaged together to create a single WM capacity score. Consistent with previous research (Brewer et al., 2010), WM capacity positively correlated, albeit weakly, with nonfocal PM performance, r = .18, p < .05, but not with focal PM, r = .03, p > .05. The WM capacity score was therefore included as a covariate in the GLM analysis using only data from the non-focal PM condition and an interaction between WM capacity and pain on PM performance was assessed to test for moderation. WM capacity was predictive of nonfocal PM, F(1, 135) = 4.49, p < .05, $\eta^2_p = .03$, replicating previous work (Brewer et al., 2010; Rose et al., 2010). Contrary to our predictions, however, individual differences in WM capacity did not moderate the decline in nonfocal PM performance under acute pain conditions, F(1, 135) = .001, p = .998, indicating that high and low WM participants were similarly affected by pain. Thus, pain seems to impact non-focal PM performance through some alternative mechanism.

**Perceived difficulty**

To evaluate metacognitive aspects of PM performance in this experiment, the same 2 (PM condition: focal vs. nonfocal) × 2 (Pain condition: pain vs. no pain) mixed-factorial ANCOVA was conducted on subjective ratings of PM task difficulty with WMC as a covariate. Participants in the non-focal condition perceived the PM task to be significantly more difficult than participants in the focal condition.
condition, $F(1, 236) = 50.281, p < .001, \eta^2_p = .176$. There was also a significant main effect of pain condition, $F(1, 236) = 198.652, p < .001, \eta^2_p = .457$, that was qualified by a significant interaction with PM condition, $F(1, 236) = 43.901, p < .001, \eta^2_p = .157$. This interaction reflects that, participants in the non-focal, but not focal, condition felt that pain made the PM task more difficult.

Interestingly, when the composite WM capacity score was entered as a covariate on only the non-focal PM condition, the ANCOVA revealed a significant interaction of WM and pain condition, $F(1, 135) = 40.978, p < .001, \eta^2_p = .233$. To examine the nature of this interaction, we did a median split of the data based on WM performance which showed that this interaction is driven by the fact that high WM capacity participants did not believe that the pain manipulation had an impact on the proportion of non-focal cues participants responded to successfully ($M = 5.86$), whereas low WM capacity participants were more sensitive in their retrospective judgments regarding the negative impact of the acute pain exposure ($M = 2.67$), $t(66) = 8.03$, $p = .049$ and $t(69) = 11.312$, $p < .00$, respectively. The fact that high-WMC participants showed similar decreases in non-focal PM performance in the pain condition relative to low-WMC participants may therefore reflect that these participants did not perceive any greater difficulty in PM remembering while they were in pain.

Thus, high-WM capacity individuals may not have engaged in compensatory strategies to ensure successful intention fulfilment that resulted in decreased PM performance under acute pain conditions leading to the absence of the intended moderating effect of WM capacity on pain’s effects on PM (see Einstein & McDaniel, 2007 for a similar argument). While this latter analysis is exploratory in nature, it underscores the importance of evaluating individual differences in PM through the lens of metacognitive monitoring and control processes in future studies.

**General discussion**

Given the ubiquity of pain and PM demands in everyday life, and considering that both pain and unsuccessful PM performance disrupt daily living, it seems remarkable that only three studies have investigated the effects of pain on PM performance. Drawing from the multi-process-theory of PM, our study aimed to provide a more refined examination of the nature and extent of PM impairment due to acute pain. To this end, we used a well-validated paradigm known to manipulate PM demands, and compared PM performance while participants were under experimentally-induced pain compared with no pain.

As hypothesised, we found that pain impaired event-based PM in conditions that place high demands on the executive processes required for successfully detecting the PM cue (i.e., non-focal PM). In contrast, we replicated Gatzounis et al. (2018) in showing that pain does not impair focal PM cue detection. These results are consistent with experimental research showing no impoverished PM performance, even under highly demanding divided attention-conditions, when individuals rely on focal targets to cue them to perform some future action (Marsh, Hancock, & Hicks, 2002; Windy McNerney & West, 2007). These results also dovetail with prior research showing that cue-focality reduces age and clinical-related PM deficits (Foster et al., 2009; Kliegl et al., 2008; Rendell et al., 2007).

Theoretically, our findings not only confirm a specific prediction of the multi-process-view for PM retrieval, but they also support the prediction of a mediational mechanism proposed in a recent process-model of the clinical neuropsychology of PM (Kliegl et al., 2011). Namely, that PM deficits in a specific populations only emerge if there is a mismatch between PM demands (e.g., high level of controlled demands as found in nonfocal tasks) and the available cognitive resources (e.g., impaired executive control).

Studies of both experimentally-induced acute and chronic pain have demonstrated a detrimental effect on more complex-tasks such as divided-attention, task switching and memory updating tasks, but not on less cognitively demanding tasks (Moore et al., 2012; Moriarty et al., 2011). Given the current debate about whether pain-related cognitive interference is dependent on task-related factors and what sort of tasks are most susceptible to disruptive pain effects (Buhle & Wager, 2010; Veldhuijzen, Kenemans, de Bruin, Olivier, & Volkerts, 2006), our results extend previous findings by providing the first evidence that acute painful experiences can have deleterious effects on PM, but only under certain conditions (i.e., highly demanding PM tasks). These effects were obtained with a group of participants under experimentally-induced acute pain. Based on these results and those reported by Ling and colleagues (Ling et al., 2007) and Miller and colleagues (Miller et al., 2014), there seems to be an open line of inquiry regarding chronic pain populations and their PM abilities under focal versus nonfocal conditions.

Although individual differences in working-memory capacity were positively correlated with nonfocal (but not focal) PM performance, working memory capacity did not moderate the pain-related decline in nonfocal PM performance. Also, the correlation between working memory and PM was smaller than previously reported findings which is important to note. This finding suggests that the interruptive function of acute pain on nonfocal PM appears to be modulated by factors other than goal maintenance (Crombez, Eccleston, Baeyens, & Eelen, 1998; Karoly & Crombez, 2018).

As a potential explanation for the lack of moderation of pain’s effects on PM via WM, it is worthy of note that high and low WM participants differed in their metacognitive ratings of the perceived difficulty of the nonfocal PM task under pain. This may have altered their approach to the experiment and ultimately hindered our ability to find the intended moderating effect. Another possibility involves our assessment of WMC. Specifically, we assessed it using a reduced subset of the number of trials in the
complex-span tasks, and in so doing, we may have reduced the variance in WMC scores, thus decreasing our power to detect a moderation effect (Oswald et al., 2015). Considering the high prevalence of pain in the general population (Breivik et al., 2006; Karoly & Ruehlman, 2007), our findings of pain-related PM impairment underscore the need for further investigation into the potential mechanisms that may underlie these effects. This work will be important for developing training and support interventions that can help mitigate pain’s impact on day-to-day cognitive functioning where goal attainment is hindered.

The present experiment examined the role of acute pain on prospective memory—a topic that has received little empirical attention. By studying acute pain induced experimentally in healthy college-age volunteers, we ruled out extraneous factors (such as the influence of age-related medical conditions, drug effects, and personality differences) while carefully tracking short-term cue-detection processes. Strong acute pain that is not modified by a cognitive or pharmacologic intervention yielded PM disruption on in nonfocal conditions but not in focal conditions.

Furthermore, numerous studies of the placebo effect in pain have demonstrated the intricate connection between sensory processing (nociception) and cognition (Moriarty et al., 2011; Pancyr & Genest, 1993), with the meaning, interpretation, or appraisal of pain now widely understood as possessing as much or greater predictive power as the raw, interoceptive experience of pain or distress itself (Crombez, Vervaet, Baeyens, Lysens, & Eelen, 1996). As placebo treatments pivot on the creation of a positive expectancy of pain relief (Price, Finniss, & Benedetti, 2008) and as such expectancies are basically predictions or simulations of future state changes, the link between felt pain and dimensions of prospective processing deserves expanded empirical attention. Because PM is a form of episodic future thinking (Brewer & Marsh, 2010; Szpunar, Nathan Spreng, & Schacter, 2014) and because individuals in pain tend, over time, to develop deficits pertaining to the cognitive control of attention, planning, and memory for delayed task execution, the systematic study of pain and PM has the potential to contribute to both basic and applied cognitive and clinical psychology (cf., Karoly, 2018; Seligman, Railton, Baumeister, & Sripada, 2013).

There are several limitations of the current study that highlight important directions for future research in the domain of pain and PM. The sample consisted of university students (18–35 years of age) which leaves open the question about whether a different pattern of results might be found with other populations (e.g., older adults, chronic pain patients, and various other clinical group that exhibit PM deficits). The influence of acute and chronic pain on future-oriented behaviours like PM is an important avenue for future research in these groups and we hope the methods in the current study turn out to be useful for researchers. Another limitation of the current study is that the experimental paradigm unfolded over a short time period, used non-personally relevant cues, and had no consequences for PM success or failure. These factors all have important influences on PM and may interact with pain in theoretically meaningful ways. One more important shortcoming of the current study is that no ongoing task words were repeated in a manner similar to how the focal cue repeated, and thus the lack of an effect of pain on the focal condition is somewhat ambiguous (i.e., cues in the focality condition also differed in terms of item-repetition perhaps explaining the lack of an effect of pain on PM in this condition). This issue should be addressed in future research. Finally, another interesting area for future research is in time-based PM. Future studies should examine the impact of pain on other forms of PM (e.g., time- and activity-based PM). For example, the impact of pain on time-based PM can be examined from the perspective of temporal gate models of time perception. Specifically, it is our prediction that pain will adjust attentional gating processes leading to shifts in time perception (Block & Zakay, 1997). This pain-induced shift in attention should greatly impact time perception and therefore time-based PM.

We believe that the incorporation of experimental data along with theories of PM is a crucial step toward understanding how and why pain adversely affects daily functioning. The current research provides new insights into the existing literature on pain-related cognitive impairment. Specifically, it points to a specific cognitive function that is disrupted by acute pain: the ability to remember to execute delayed intentions. The effects of PM failures on quality of life are not minor. Emerging literature suggests that PM deficits predict functional dependence in everyday capacity above and beyond impairment in other cognitive abilities (Park & Kidder, 1996; Woods et al., 2009). For example, failures to notice prompts to take prescribed medications are likely to result in poor treatment adherence and clinical outcomes. Therefore, if we can better understand which specific task characteristics influence PM performance under varying pain conditions, we can improve our ability to predict which individuals are most at risk for PM disruption. Importantly, the results of this study may suggest particularly effective strategies for improving PM performance under acute pain conditions, such as using an approach of prominent, external cues that reduce executive demands and automatically prompt PM cue detection (McDaniel & Einstein, 2007). Accordingly, future studies might extend the current laboratory finding to a more naturalistic PM task.

Disclosure statement
No potential conflict of interest was reported by the authors.

References


