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Working through the pain: Working memory capacity and differences in processing and storage under pain

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It has been suggested that pain perception and attention are closely linked at both a neural and a behavioural level. If pain and attention are so linked, it is reasonable to speculate that those who vary in working memory capacity (WMC) should be affected by pain differently. This study compares the performance of individuals who differ in WMC as they perform processing and memory span tasks while under mild pain and not. While processing performance under mild pain does not interact with WMC, the ability to store information for later recall does. This suggests that pain operates much like an additional processing burden, and that the ability to overcome this physical sensation is related to differences in WMC.

Keywords: Pain; Working memory; Memory span; Individual differences.

For any who have suffered from either chronic or extreme physical pain, the disruption that these sensations cause on everyday life and behaviour is readily apparent. Completing any task, whether cognitive or motor, under even mild pain nearly always reduces the success with which that task is completed (De Gier, Peters, & Vlaeyen, 2003; Dick & Rashiq, 2007; Eccleston, 1995). Physical pain has been described as an almost constant cognitive distraction, usually coupled with other affective components that urge ‘‘escape’’ or relief from the painful stimuli (Eccleston & Crombez, 1999). If one accepts this notion of pain as cognitive distraction, those who are better equipped to deal with the extra demands of distraction should also be less affected by such sensations.

A large body of psychometric research has demonstrated reliable individual differences in how well one can simultaneously process and store information, especially under conditions that involve proactive interference or distraction (Conway & Engle, 1994; Friedman & Miyake, 2004; Kane, Bleckley, Conway, & Engle, 2001). This ability has been referred to as working memory capacity (WMC; Baddeley & Hitch, 1974). While WMC was originally conceptualised as a limited resource ‘‘buffer’’ system used to keep information available and active for consciousness (Daneman & Carpenter, 1980; Turner & Engle, 1989), more recent definitions have instead connected WMC to the ability to control or focus attention (Cowan, 2005; Kane et al., 2001), or otherwise manage executive control functions (e.g., updating, switching, or inhibition; Miyake et al., 2000). From this perspective, individual differences arise not as a result of the limited amount of resources or *capacity* of the WMC system, but instead due to the *ability* to direct behaviour in goal-relevant or otherwise appropriate ways. As such, higher-WMC individuals focus less on distracting information and are

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also more resistant to the build-up of proactive interference from irrelevant information (Engle, Tuholski, Laughlin, & Conway, 1999; Friedman & Miyake, 2004). WMC has been related to performance across several types of cognitive tasks, ranging from lower-level cognitive tasks such as Stroop performance, anti-saccade, or dichotic listening (Colflesh & Conway, 2007; Kane et al., 2001), to more complex tasks such as making metacognitive judgements and reading comprehension (Griffin, Wiley, & Thiede, 2008; Long & Chong, 2001; Sanchez & Wiley, 2006).

Investigations into the underlying neural architecture behind WMC have suggested that this memory system is strongly connected to the prefrontal cortex, specifically the dorsolateral prefrontal cortex and the anterior cingulate (Kane & Engle, 2002; Smith & Jonides, 1999). It has also been suggested that painful stimuli are processed in these same neural areas that have been associated with WMC (Bornhövd et al., 2002; Lorenz, Minoshima, & Casey, 2003; Peyron, Laurent & Garcia-Larrea, 2000).

Given these neural and functional connections, one would expect a fairly direct relationship between WMC and pain perception. Given their heightened resilience to distraction and the build-up of proactive interference (Kane et al., 2001), those who are higher in WMC should be less affected by physical pain when attempting to complete a separate task. If painful stimuli are indeed distracting, and thus competing for attention (at both a neural and cognitive level), pain information should more drastically affect performance for those low in WMC, as these individuals are less able to deal with this additional demand or distraction.

An important question is whether this relationship between WMC and performance under pain changes across different types of tasks. For example, while under pain, do high- and low-WMC individuals experience similar deficits on tasks that involve either processing or storage for later access? Interactions with task demands could provide additional insight into how pain interfaces with the cognitive system. If pain operates similarly to an additional processing burden, performance on the processing task should be slowed but just as accurate (Oberauer & Göthe, 2006). However, if pain operates as an additional memory load, one might not expect a decrease in processing performance given the divergence between the memory load (i.e., pain) and the processing task (Oberauer & Göthe, 2006).

To address these questions a study was conducted which examined the performance of high- and low-WMC individuals while under both mildly painful and non-painful conditions. To examine whether physical pain affects one's ability to either process or maintain information for later recall differently, separate processing and memory span tasks were also evaluated.

METHOD

Participants

A total of 40 undergraduates in an introductory psychology course at a large public university were solicited for participation. This experiment was approved by the university institutional review board to ensure that all participants were treated ethically. Participants were recruited from a larger overall sample ($N = 285$) of native English speakers who had already completed the AOSPAN task (described below). Participants were informed that they would be asked to use alcoholic mouthwash as directed by the manufacturer prior to obtaining their consent to participate in the study. At the start of the experiment all participants reported that they were not currently experiencing any physical pain (e.g., headaches, toothaches, etc.).

Materials

Working memory capacity measure. A computerised assessment of WMC, Automated Operation Span (AOSPAN; Unsworth, Heitz, Schrock & Engle, 2005) was used in this experiment. AOSPAN is a computerised analogue of the original Operation Span task developed by Turner and Engle (1989), and has been shown to be both reliable and diagnostic for assessing differences in WMC (Unsworth et al., 2005).

In AOSPAN participants are required to evaluate the correctness of a series of simple maths equations, which range in trial size from three to seven maths equations. After each presented equation participants are given a letter to remember for a later test. After completing each trial participants are asked to select the presented letters, in the correct order of presentation, from a matrix of 12 possible choices.

Participants completed three sets of each trial size, which resulted in 75 overall individual items. The AOSPAN session was self-paced and lasted (on average) approximately 20 minutes, and all administration and scoring was consistent with the recommendations of Unsworth et al. (2005).

Only participants whose total score on the AOSPAN task fell within either the upper or lower 25% of the distribution of the larger overall sample were recruited to complete the remaining portion of the study at a later time. Thus this study employs an extreme groups design relative to WMC. A simple comparison does confirm that the low-WMC group ($M = 41.05$, $SD = 10.82$) did perform significantly lower on the AOSPAN task than the high-WMC group ($M = 68.80$, $SD = 2.38$) $t(38) = 11.21$, $p < .001$, and at levels consistent with previous findings on the AOSPAN task (Unsworth et al., 2005).

Processing task. In order to evaluate processing performance, participants were given a list of 24 simple algebraic maths problems—e.g., $(5 \times 1) + 6 \; = ?$—and asked to solve as many problems as possible in 45 seconds. These maths problems were adapted from the original OSPAN task developed by Turner and Engle (1989), and thus have been considered previously as effective examples of a simple processing task. Processing performance was evaluated in terms of both the overall number of problems solved correctly, and the number of errors made. As participants were not penalised for guessing, errors and the overall number of problems solved correctly are considered related but independent measures of processing performance, albeit assessed with the same task.

Memory span task. In the memory span trials participants were given a list of 20 words (again adapted from the original OSPAN task, Turner & Engle, 1989), and were asked to study these words for 45 seconds. Participants were then asked to recall these words after a short 30-second delay. Memory span performance was evaluated in terms of the overall number of words recalled, and also the number of incorrect words (or intrusions) produced.

Pain rating questionnaire (PRQ). Participants completed a pain rating questionnaire (PRQ) after each trial which rated their physical pain on a scale of 1–10, with 1 being no pain (operationalised as ‘‘sitting in a comfortable chair watching your favourite TV programme’’), and 10 being extreme pain (operationalised as ‘‘burning your hand on a hot pan on the stove’’). While ‘‘burning your hand on a hot pan’’ obviously does not represent the most extreme pain possible, this anchor point was chosen to avoid floor effects given the modest manipulation of physical pain utilised here. In the current experiment this PRQ measure demonstrated a high degree of reliability when estimating the degree of physical pain across trials (Cronbach’s $\alpha = .93$).

Procedure and design

This experiment consisted of a 2 (pain) × 2 (WMC) × 3 (task) factor design. Both pain and task were run within-participants, netting a total of six trials overall for each participant. Performance was then compared across high and low WMC groups.

Pain was induced by having participants swish 20mL of alcoholic mouthwash (21.6% by volume) for 45 seconds at a rate of 1 swish per second. This manipulation was expected to induce mild levels of physical pain that, although disruptive, would not physically harm or incapacitate the participants to a degree where they would be unable to complete the subsequent performance tasks. This manipulation produces a dull, throbbing pain within the mouth of the individual (caused by the alcohol irritating the sensitive gum tissue), more consistent with the symptoms of chronic pain rather than a relatively sharp, quick sensation of pain that is more synonymous with transient or acute pain (Loeser & Melzack, 1999). In the no-pain trials participants instead swished 20mL of distilled water for the same time period. While under either pain or no pain, participants also completed one of three possible tasks. The first type of task was the baseline rating task. In the baseline task participants were simply asked to close their eyes, clear their mind, and swish either mouthwash or distilled water (based on counterbalancing condition). Importantly, participants were not asked to do anything else in the baseline task. After the time was up, participants completed the PRQ and then completed the second baseline trial with the second liquid. This task was designed to provide a baseline estimate of the amount of physical pain induced by the mouthwash manipulation, and these baseline trials were always completed first.

After completing the two baseline trials, participants repeated the same general procedure except while also completing either the processing or memory span tasks. Whether participants completed the processing or memory span task next was counterbalanced, as was the order of the pain trials within each task. Finally, word and maths problem lists were also completely randomised within tasks, and participants completed the PRQ after each trial.

To reiterate, this procedure resulted in six trials overall for all participants: baseline, processing, and memory span trials under mild physical pain and an additional trial for the same three tasks, but this time under no pain. Trials were run back to back, and there was no discrete break given between the different tasks. All participants were run individually in a quiet room, which contained only a sink and a table with chairs.

RESULTS

Pain ratings

As a manipulation check, pain ratings were compared across all trial types. Results indicate that alcoholic mouthwash ($M = 4.30$, $SD = 2.05$) produced significantly higher levels of physical pain than distilled water ($M = 1.23$, $SD = .48$) in the baseline trials, $F(1,\ 39) = 111.10$, $p < .001$, $\eta_p^2 = .74$. For this baseline trial there was no difference ($F < 1$, $p > .05$) in the magnitude of perceived pain across low- ($M = 4.00$, $SD = 2.08$) and high-WMC ($M = 4.60$, $SD = 2.04$) individuals. Thus it appears that the mouthwash manipulation was not affecting each WMC group differently, and produced similar levels of physical pain in each group.

This pattern was also consistent across the processing and storage trials. In the processing trials mouthwash ($M = 4.88$, $SD = 2.27$) was rated as significantly more painful than water ($M = 1.48$, $SD = .91$), $F(1,\ 39) = 97.16$, $p < .001$, $\eta_p^2 = .71$. In the memory storage trials mouthwash ($M = 4.75$, $SD = 2.13$) was again rated as more painful than distilled water ($M = 1.28$, $SD = .55$) $F(1,\ 39) = 116.30$, $p < .001$, $\eta_p^2 = .75$. While it appears that swishing alcoholic mouthwash does not produce extreme physical pain (even as defined here), this manipulation did successfully induce mild physical pain in these participants relative to baseline ratings.

Processing performance

In terms of simple maths processing (Table 1), it appears that mild pain reduces overall performance, $F(1, 38) = 6.71$, $p < .01$, $\eta_p^2 = .15$, relative to a no-pain control. There was no reliable effect of WMC and no interaction (Fs < 1.18, $p > .05$) on processing performance. This suggests that pain reduces the number of correct answers provided overall, and this processing deficit does not interact with WMC.

To evaluate processing accuracy, the number of maths errors made on the processing task was also analysed. Error analyses revealed that differences in processing performance were not due to severe disruption of mental calculation. Participants maintained a very high level of processing accuracy ($>$ 94% on average) across all trials, and there were no reliable differences between pain trial, WMC group, and no interaction (Fs < 1, $p > .05$). This suggests that physical pain does not reduce processing *accuracy*, but instead reduces the *rate* at which problems are attempted or completed, which in turn affects the overall score.

TABLE 1
Processing and memory performance (M(sd)) by Trial and WMC Group

	Processing performance	*Processing errors*	*Memory performance*	*Memory errors*
Pain				
Low WMC	15.55 (4.38)	.70 (.86)	4.65 (1.93)	1.60 (.99)
High WMC	16.45 (3.86)	.90 (.97)	7.85 (2.52)	.60 (.75)
Overall	16.00 (4.10)	.80 (.91)	6.25 (2.74)	1.10 (1.01)
No-pain				
Low WMC	16.80 (4.06)	.80 (1.06)	7.30 (2.08)	.85 (.67)
High WMC	18.25 (3.16)	.85 (.99)	8.60 (1.88)	.70 (.92)
Overall	17.52 (3.67)	.83 (1.01)	7.95 (2.069)	.78 (.80)

$n = 20$ participants in each WMC group.

Memory span performance

In terms of memory span performance, again physical pain produced a significant deficit in the number of words correctly recalled, $F(1, 38) = 16.37$, $p < .001$, $\eta_p^2 = .30$. However, there was both a significant main effect of WMC, $F(1, 38) = 18.68$, $p < .001$, $\eta_p^2 = .33$, and a significant interaction between pain condition and WMC, $F(1, 38) = 5.11$, $p < .05$, $\eta_p^2 = .12$ (Figure 1). Post-hoc analyses (with a Bonferroni adjustment) suggest that while high-WMC individuals do not demonstrate a decline in performance in memory span tasks under mild pain, $t(19) = 1.18$, $p > .05$, low-WMC individuals are much more susceptible to the effects of physical pain, $t(19) = 4.83$, $p < .001$.

To test whether pain impacts the number of memory errors committed, the number of intrusions (or incorrect words recalled) was also analysed. Results indicate that while physical pain creates more intrusions overall, $F(1, 38) = 4.28$, $p < .05$, $\eta_p^2 = .10$, pain specifically produces more intrusions for low-WMC than high-WMC individuals, $F(1, 38) = 7.31$, $p < .01$, $\eta_p^2 = .16$ (Figure 1). This resulted in low-WMC individuals also producing more intrusions overall, $F(1, 38) = 7.06$, $p < .01$, $\eta_p^2 = .16$.

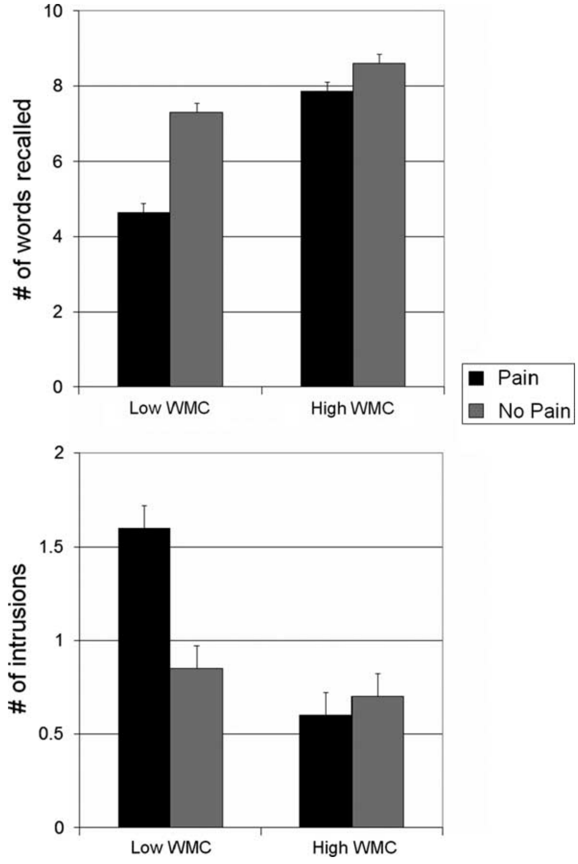

Figure 1. Memory span performance by pain trial and WMC. Error bars represent the standard error of the mean.

This pattern of memory span results suggests that an enhanced ability to focus attention can attenuate memory deficits while under conditions of mild pain. While an overall reduction of memory performance was observed, this reduction is most steep for those low in WMC, and nonsignificant for high-WMC individuals. Further, analysis of memory errors suggests that, unlike in the processing tasks, mild physical pain impeded the ability to remember information by also causing more erroneous information to be recalled, specifically for those low in WMC.

DISCUSSION

While pain has been shown previously to impact cognitive performance, this study was designed to explore whether these performance decrements could indeed be moderated by differences in WMC. The results of this study do corroborate the intuitive suggestion that even mild physical pain can impede the successful completion of other unrelated tasks. This pain handicap appears to affect both cognitive processing and also the storage of information for later recall. However, while processing deficits do not appear to be related to WMC, maintenance of information for later recall appears to be closely linked to how well participants can focus their attention. Individuals high in WMC appear to be relatively unaffected by the onset of physical pain in the storage trials; however those low in WMC are less able to store information for later recall in the face of similarly painful stimuli.

Further, a closer examination of processing accuracy also suggests that pain is not just a general distraction, but also specifically an additional processing burden for the cognitive system. Consistent with previous findings that have examined the relationship between simultaneous processing tasks and WMC, painful stimuli reduced overall processing performance, but not accuracy (Cowan, 1995; Oberauer & Göthe, 2006). This suggests that pain sensations are being processed in parallel with the mathematical operations, which naturally slows the overall rate at which mathematical operations can be carried out. This informs the memory deficit observed in the low-WMC group, as it is possible that having to process the additional painful stimuli changed the otherwise simple storage task into a complex span task. As such, it is not surprising that these results mirror group differences found on any other complex span task typically used to assess WMC (see Conway et al., 2005, for a further discussion of the distinctions between complex and simple span tasks).

These findings also suggest that individuals are continually processing their current physical state, specifically when under pain, and this somatosensory information is made repeatedly available to influence the cognitive system during the painful event. This is consistent with current understanding of the nociceptive system in which pain-sensing fibres do not adapt quickly, but instead continue sending signals for a prolonged period of time and in fact increase over time (Melzack & Wall, 1965). The pervasion of this noxious sensation into consciousness, through repetition, makes much sense as it encourages retreat or avoidance of further physical harm (which is likely ongoing, and thus producing the sensation).

Similarly, the current findings are also consistent with previous results that have examined how mental (but not physical) intrusions relate to the attentional or executive system (Eysenck, Derakshan, Santos, & Calvo, 2007; Friedman & Miyake, 2004). It has been suggested that the ability to suppress unwanted or intrusive thoughts primarily requires participants to resist the build-up of proactive interference (PI) over time (Friedman & Miyake, 2004). Importantly, complex span tasks (like the AOSPAN task used here) have also been found to closely tap the executive ability of individuals to resist this build-up of PI (Kane et al., 2001; Miyake et al., 2000). This suggests that the executive system is capable of dealing with this intrusive stimulus (whether it be physical pain or an unwanted thought) by repetitively eliminating it from the WM system in order to preserve primary task performance (Eysenck et al., 2007; Friedman & Miyake, 2004). Unfortunately, it also suggests that those who are less able to resist this build-up of PI are more likely to be unable to put these painful sensations or thoughts out of mind.

In conclusion, these results support the notion of pain as cognitive distraction, and further suggest that those who are better equipped to deal with these intrusive sensations are less affected by these painful sensations. This study also suggests that distracting stimuli need not exist only on a cognitive level, but instead that any distracting stimulus (whether it be somatosensory or a result of cognitive task demands) is processed and dealt with by the WM system. While the results of this experiment are somewhat limited, given the modest number of overall participants and both the simplicity of the method used to induce pain and the tasks used to evaluate performance, these results do still suggest that pain perception does interact with individual characteristics to influence observable performance.

On a more practical note, this work also highlights the need for effective pain management, especially for those individuals who suffer from chronic pain and are forced to work through this pain to successfully function in their jobs, care for their family, or perform otherwise everyday tasks. Future work should also consider exploring other potential interactions between more complex cognitive processes and physical pain, preferably on larger and more diverse samples.

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