Implicit motor imagery performance is impaired in people with chronic, but not acute, neck pain

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Background: People with chronic neck pain have impaired proprioception (i.e., sense of neck position). It is unclear whether this impairment involves disruptions to the proprioceptive representation in the brain, peripheral factors, or both. Implicit motor imagery tasks, namely left/right judgements of body parts, assess the integrity of the proprioceptive represention. Previous studies evaluating left/right neck judgements in people with neck pain are conflicting. We conducted a large online study to comprehensively address whether people with neck pain have altered proprioceptive representation.

Methods : People with and without neck pain completed online left/right *neck* judgement tasks followed by a left/right *hand* judgement task (control). Participants judged whether the person in the image had their head rotated to their left or right side (neck task) or whether the image was of a left hand or a right hand (hand task). Participants were grouped on neck pain status (no pain; <3 months - acute; ≥3 months - chronic) and pain location (none, left-sided, right-sided, bilateral). Outcomes included accuracy (primary) and response time (RT; secondary). Our hypotheses – that (i) chronic neck pain is associated with disrupted proprioceptive representation and (ii) the disruption is dependent on the side of usual pain, were tested with separate ANOVAs.

Results : Of 1404 participants, 105 reported acute neck pain and 161 reported chronic neck pain. When grouped on neck pain status, people with chronic neck pain were less accurate than people without neck pain (p=0.001) for left/right *neck* judgements, but those with acute neck pain did not differ from those without neck pain (p=0.14) or with chronic neck pain (p=0.28). Accuracy of left/right *hand* judgements did not differ between groups (p=0.58). RTs did not differ between groups for any comparison. When grouped on neck pain location, people were faster and more accurate at identifying right-turning *neck* images than left-turning *neck* images, regardless of history or location of pain (p<0.001 for both); people with no pain were more accurate and faster than people with bilateral neck pain (p=0.001, p=0.015) and were faster than those with left-sided neck pain (p=0.021); people with right-sided neck pain were more accurate than people with bilateral neck pain (p=0.018). Last, there was a significant interaction between neck image and side of neck pain: people with right-sided neck pain were more accurate at identifying right-sided neck turning images than people with left-sided neck pain (p=0.008), but no different for left-sided neck turning images (p=0.62).

Conclusions: There is evidence of impaired implicit motor imagery performance in people with chronic neck pain which may suggest disruptions to proprioceptive representation of the neck. These disruptions are specific to the neck (performance on hand images intact) but non-specific to the exact location of

neck pain.

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4 **neck pain**

6 Short title: Motor imagery performance in neck pain

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25 **Abstract**

26 Background: People with chronic neck pain have impaired proprioception (i.e., sense of neck

27 position). It is unclear whether this impairment involves disruptions to the proprioceptive

28 representation in the brain, peripheral factors, or both. Implicit motor imagery tasks, namely

29 left/right judgements of body parts, assess the integrity of the proprioceptive represention.

30 Previous studies evaluating left/right neck judgements in people with neck pain are conflicting.

31 We conducted a large online study to comprehensively address whether people with neck pain

32 have altered proprioceptive representation.

33 Methods: People with and without neck pain completed online left/right *neck* judgement tasks

34 followed by a left/right *hand* judgement task (control). Participants judged whether the person in

35 the image had their head rotated to their left or right side (neck task) or whether the image was

36 of a left hand or a right hand (hand task). Participants were grouped on neck pain status (no

37 pain; <3 months - acute; ≥3 months - chronic) and pain location (none, left-sided, right-sided,

38 bilateral). Outcomes included accuracy (primary) and response time (RT; secondary). Our

39 hypotheses – that (i) chronic neck pain is associated with disrupted proprioceptive

40 representation and (ii) the disruption is dependent on the side of usual pain, were tested with

41 separate ANOVAs.

42 Results: Of 1404 participants, 105 reported acute neck pain and 161 reported chronic neck

43 pain. When grouped on neck pain status, people with chronic neck pain were less accurate than

44 people without neck pain (p=0.001) for left/right *neck* judgements, but those with acute neck

45 pain did not differ from those without neck pain (p=0.14) or with chronic neck pain (p=0.28).

46 Accuracy of left/right *hand* judgements did not differ between groups (p=0.58). RTs did not differ

47 between groups for any comparison. When grouped on neck pain location, people were faster

48 and more accurate at identifying right-turning *neck* images than left-turning *neck* images,

49 regardless of history or location of pain (p<0.001 for both); people with no pain were more

50 accurate and faster than people with bilateral neck pain (p=0.001, p=0.015) and were faster

51 than those with left-sided neck pain (p=0.021); people with right-sided neck pain were more

52 accurate than people with bilateral neck pain (p=0.018). Last, there was a significant interaction

53 between neck image and side of neck pain: people with right-sided neck pain were more

54 accurate at identifying right-sided neck turning images than people with left-sided neck pain

55 (p=0.008), but no different for left-sided neck turning images (p=0.62).

56 Conclusions: There is evidence of impaired implicit motor imagery performance in people with

57 chronic neck pain which may suggest disruptions to proprioceptive representation related to the

58 neck. These disruptions are specific to the neck (performance on hand images intact), but non-

59 specific to the exact location of neck pain.

60 **Keywords:** left/right judgements, psychophysiology, Implicit motor imagery, pain, cortical body

61 representation, proprioceptive representation, working body schema

62 **Introduction**

63 Neck pain affects 10-20% of the population in any given year (Hoy, Protani et al. 2010) and

64 results in impaired movement and proprioception (i.e., the sense of where your body is located

65 is space). A recent systematic review found that people with chronic neck pain have lower

66 proprioceptive acuity than people without pain (Stanton, Leake et al. 2016). What remains

67 unclear, however, is where the dysfunction in proprioception lies. While commonly assumed to

68 be attributable to peripheral dysfunction (i.e., disrupted input from proprioceptors in the muscle,

69 ligament, and skin due to injury or the presence of nociception), other possible contributions

70 include problems with spinal processing and the encoding of proprioceptive data in the brain. In

71 fact, people with neck pain may have intact detection and transmission of proprioceptive input,

72 but have disruptions to the cortical proprioceptive representations that allow for planning,

73 executing and coordinating movements (also termed the 'working body schema' (Parsons

74 2001)). Given that different treatments can be used to target different proprioceptive

75 impairments, filling this research gap has both mechanistic and therapeutic importance.

76

77 Investigating whether impaired cortical proprioceptive representation underlies proprioceptive

78 dysfunction is challenging. Functional neuroimaging can provide key information about changes

79 in primary motor cortex representation of a movement pattern (Elgueta-Cancino, Schabrun et al.

80 2018), or in the cortical activation patterns (including functional connectivity) during tasks such

81 as imagined movements (Lotze, Montoya et al. 1999). However, to date there is no method to

82 image proprioceptive representations and thus, behavioural tasks are used. Implicit motor

83 imagery is the most established method to interrogate the cortical proprioceptive representation

84 and left/right judgements of pictured body parts is the most studied (Schwoebel, Coslett et al.

85 2002, Coslett, Medina et al. 2010, Dey, Barnsley et al. 2012, Wallwork, Butler et al. 2015) but

86 not the only approach, for example, see (Moseley and Brugger 2009). In left/right judgments,

87 people identify, as quickly and as accurately as possible, whether images of the target body-part

88   (e.g., a hand) belongs to the left-side or the right-side of the body. In completing this task, the

89   person *mentally manoeuvres* their own hand into the posture seen in the picture; a process

90   supported by via neuroimaging evidence of activation of motor related areas during the task

91   (Parsons, Fox et al. 1995, Michelon, Vettel et al. 2006). When the target body-part resides in the

92   midline, such as for the neck and back, the task has been adapted and a judgement is made

93   about whether the person in the image has their head or trunk rotated or laterally flexed to the

94   left-side or right-side. Performance (accuracy) in this task is likely to be dependent on an intact

95   neural proprioceptive representation for the target body-part, i.e., the neural representations that

96   coordinate, plan and execute movement (Bray and Moseley 2011), although recent work has

97   questioned whether this occurs as strongly for body parts that reside in the midline - see Alazmi,

98   Gadsby et al. (2018). Notably, because real movement is not permitted during these task,

99   peripheral/spinal contributors to proprioception are limited (although see Silva, Loubinoux et al.

100   (2011) for evidence that some peripheral contribution still exists), thus the task is thought to

101   primarily target cortical proprioceptive representations.

102

103   Previous work evaluating implicit motor imagery performance in people with neck pain has

104   found conflicting evidence. People with recurrent neck pain (n=30) were significantly less

105   accurate than pain-free controls on a neck left/right judgement task (Elsig, Luomajoki et al.

106   2014), but people with chronic whiplash associated disorders (n=64) were not different from

107   controls (Pedler, Motlagh et al. 2013). However, Elsig et al (2015) evaluated performance only

108   on a neck left/right judgement task, making it unclear whether the impaired performance is

109   specific to the painful body part (discrete dysfunction of neck proprioceptive representation), or

110   merely represents impaired spatial performance (regardless of the body part image used) or

111   indeed impaired central nervous system processing. Given this uncertainty and the relatively

112   modest sample sizes of previous work, it is key to evaluate implicit motor imagery performance

113   in people with neck pain using a larger sample to comprehensively explore the presence and

114   nature of any dysfunction.

115

116   Here we describe a large, online study recruiting a representative sample of people with neck

117   pain and healthy pain-free controls who performed left/right judgements of neck rotation and of

118   hands. First, we extended past work by investigating the contribution of pain duration and pain

119   location on task performance, as has been investigated in people with and without back pain

120   (Bowering, Butler et al. 2014). Second, we evaluated whether impairment on the left/right

121   judgement task is location- ~~or movement-~~specific. In people with pathological arm pain, impaired

122   performance on a hand left/right judgement task is specific to images that correspond to their

123   painful hand (Moseley 2004). It is unknown if a similar effect would occur in people with neck

124   pain (e.g., left sided-pain, impaired performance only on images of left neck rotation), but if

125   present, it would suggest a more nuanced dysfunction in proprioceptive representation than

126   previously realised.

127

128   We had two main aims: to determine whether *neck pain and its duration* are associated with

129   impaired left/right neck rotation judgement performance (Aim 1), and to determine whether the

130   *location/side of neck pain* is associated with impaired performance for left-turning and right-

131   turning neck rotation images (Aim 2). Within Aim 1, we included an analysis with left/right hand

132   judgements as we wanted to determine whether people with neck pain are less accurate on

133   left/right neck rotation judgements, but not left/right hand judgements, than healthy controls. If

134   performance was also reduced in a hand task, this would imply a more global problem. This

135   would demonstrate that any problems with neck motor imagery are not specific to the neck and

136   may therefore simply reflect forced-choice response time impairment (i.e., generally poor at the

137   task). For Aim 1, we hypothesised that the presence and duration of neck pain would affect

138   performance in a left/right *neck* rotation judgement task, but not a left/right *hand* judgement task.

139 Specifically, we hypothesised that people with chronic neck pain would be less accurate and

140 take longer to respond to images in the left/right neck judgement task than people with no neck

141 pain or people with acute neck pain (*Hypothesis 1*). For Aim 2, we hypothesised that the usual

142 location of neck pain would affect performance to images showing neck rotation towards their

143 painful side (i.e., people with left-sided neck pain would be less accurate and take longer to

144 respond to images of necks turning to the left and vice versa; *Hypothesis 2*).

145

146 **Methods**

147 Participants

148 The current study is based on data collected as part of a large, online cross-sectional study,

149 from which characteristics of the task and normative data have been published (Wallwork,

150 Butler et al. 2013). That study collected data from a convenience sample of 1737 participants,

151 from 40 countries, who were recruited via email, using the Neuro Orthopaedic Institute (NOI,

152 Adelaide, Australia) mailing list, and via social media. Access to a computer with internet access

153 was required to participate. Ethical approval was granted from the University of South Australia

154 Human Research Ethics Committee (Protocol ID HS13-2009). All participants provided informed

155 consent online, as per the Declaration of Helsinki.

156

157 Questionnaires

158 Participants completed an online questionnaire, providing details on their age, gender, and

159 handedness (Wallwork, Butler et al. 2013). This study concerns participant responses to

160 questions about neck pain. If a participant reported neck pain, they also answered questions

161 about the duration of their neck pain, the side of neck pain (left, right or bilateral), and whether

162 their neck pain was evoked by neck movement (left, right or bilateral).

163

164 Left/right judgement tasks

165 Once participants had completed the baseline questionnaire, instructions on how to complete

166 the left/right judgement tasks using the Recognise platform (Neuro Orthopaedic Institute,

167 Adelaide, Australia; www.noigroup.com) were provided. Two sets of images (head/neck; hands)

168 were used for testing and the images in each set were presented in a randomised order. The

169 first set displayed images of people's head and upper torso with their head rotated either

170 towards their left side or their right side (i.e., left and right neck rotation, respectively). The

171 second set displayed images of left and right hands. Participants were instructed to make a

172 judgement on whether the person in the image was rotating their neck to their left or right side,

173 or whether the hand was a left hand or a right hand, respectively. Participants were advised to

174 make a left-sided response by depressing the 'a' key with their left index finger and to make a

175 right-sided response by depressing the 'd' key with their right index finger. Participants were

176 instructed to make a decision as quickly and as accurately as possible and to avoiding

177 guessing. They were informed that they would have a maximum of five seconds per image to

178 respond before the test was automatically advanced and the next image was shown.

179

180 Two trial images (either of a left and a right neck rotation or of a left and a right hand) preceded

181 formal testing in order to orientate the participant to the keyboard commands – data were not

182 recorded on these images. The formal test included five left/right judgement tasks, each

183 involving 40 images. The first four left/right judgement tasks displayed images of a head and

184 torso (left/right neck rotation judgements), the fifth task displayed images of hands (left/right

185 hand judgements). The images were randomly presented to be left and right rotation (neck

186 images) or sides (hand images) with images rotated at: 0°, 90°, 180°, and 270°. Each task

187 comprised 50% male models and 50% female models, both aged in their early 20's wearing

188 plain black clothing. All left images were mirrored reflection of right images and each participant

189 received all the images (order randomised). See Figure 1 for sample images.

190

191   *INSERT FIGURE 1A-F HERE*

192

193   Data processing

194   Left/right judgement performance was analysed using the data from the second and fifth

195   left/right judgement tasks. The first and third tasks were included in as methodological controls

196   for task features and the fourth task was included to address a separate question that was

197   unrelated to the aims of the present study. Specifically, the first left/right judgement task (neck

198   images) was included to familiarise participants with the task and to allow for a known learning

199   effect (Boonstra, de Vries et al. 2012). The third task (identical to task 2) was included as a

200   backup in the situation that people with pain had difficulty completing task 2 and there were

201   significant missing data. Because there were sufficient data available for task 2, we decided

202   (prior to analysis) to not include data from the third task to minimise potential participant fatigue

203   that was likely to occur given it was the third repetition of neck images. The fourth task was a

204   separate task that included contextual images (with various backgrounds and distractions). Data

205   from the fifth left/right judgement task (hand images) were analysed as a control because the

206   task involved implicit motor imagery of a remote body part, and the use of new images (hands

207   versus necks) reduced potential for fatigue.

208

209   Participants' data were excluded if the second and fifth left/right judgement task were not

210   completed in their entirety. Consistent with previous literature, response times were calculated

211   only for images for which the response was correct and data from images were excluded if the

212   response time was less than 500ms as this was considered too short of a time to make a

213   judgement response and therefore would likely represent a guess (Kunde 2001). Further, if the

214   response time for eight consecutive images reached this 5 second limit (i.e., the participant

215   timed-out) then the data from those images were excluded because it was assumed the

216   participant was distracted or the internet/computer failed. We included all other responses that

217   were 5 seconds (i.e., timed-out response) as it was assumed the participant simply took that

218   long to respond or was unsure about that particular response. Last, data sets were excluded

219   where participants did not provide necessary information for covariate analysis (age, gender,

220   handedness) or group allocation (i.e., neck pain). At the completion of data processing, there

221   were 1404 complete participant datasets.

222

223   Group allocation

224   Participants were grouped based on: (1) duration of pain (i.e., no pain; pain for less than 3

225   months considered "acute pain"; pain for 3 months or more considered "chronic pain"); (2)

226   location of pain (i.e., left-sided neck pain, right-sided neck pain, bilateral neck pain and no neck

227   pain).

228

229   Statistical analysis

230   All statistics were performed using SPSS 23.0.0 (SPSS, Chicago, IL, USA). Accuracy and

231   response time data were both tested for normality. Accuracy of responses were not normally

232   distributed and as a result were log transformed. The log transformed accuracy values met

233   normality criteria (as assessed by visual inspection of P-P plots and non-significant Shapiro-Wilk

234   statistic) and were used for all analyses. Thus, for accuracy data, the analysis results were back

235   transformed to provide group specific data (mean, 95%CI). The back transformed mean

236   differences and their 95%CIs were not reported, because the difference between logarithms of

237   two geometric means results in a logarithm of their ratio, not of their difference (Bland and

238   Altman 1996). Age, gender and handedness are known to affect left/right neck judgement

239   performance (Wallwork, Butler et al. 2013); response time increases with age, is greater in

240   females, and is greater in left-handed people, and accuracy reduces with age. Therefore, these

241   variables were considered in all analyses and included as co-variates where appropriate.

242   Further, a linear regression was performed using accuracy and response time to assess for a

243 possible speed-accuracy trade-off (i.e., faster performance but incorrect response) which would

244 suggest improper performance of the task. In all analyses, the alpha level was set at 0.05, with

245 a Holm-Bonferroni correction used for all multiple comparisons (Holm 1979).

246

247 To determine whether *neck pain and its duration* is associated with impaired left/right judgement

248 performance (*Aim 1*), univariate ANOVAs were conducted (one each for accuracy and response

249 time) for neck images, with a between-subjects main effect of Pain Duration (no pain, acute pain

250 and chronic pain) and Age as a covariate. If a significant main effect, independent t-tests were

251 used to make specific between group comparisons. Identical analyses were completed for

252 left/right judgement performance on hand images (control).

253

254 To determine whether the *location of neck pain* is associated with impaired performance for

255 responses to left-turning and right-turning *neck* images (*Aim 2*), accuracy and response time

256 were separately investigated using a 2 (within-subjects main effect of Side of Head Turn in

257 Image: left-sided turning images and right-sided turning images) by 4 (between-subjects main

258 effect of Location of Pain: no pain, left-sided pain, right-sided pain, bilateral pain) repeated

259 measures ANOVA. Such an analysis allowed us to determine if those with bilateral pain were

260 equally impaired for left vs right images as well as explore whether or not there were task-based

261 features that influenced performance, regardless of the presence or location of neck pain.

262 Therefore, in addition, to specifically evaluate the effect of lateralised pain on performance,

263 repeated measures ANOVAs were completed comparing only those with lateralised neck pain

264 (left-sided neck pain versus right-sided neck pain) for performance (accuracy and response

265 time) on left-sided turning and right-sided turning neck images.

266

267 Given that people with neck pain could have neck pain in one location (i.e., left side neck pain),

268 but experience pain with a movement in the opposite direction (i.e., experience left-sided neck

269   pain when rotating the neck to the right), we ran a sensitivity analysis classifying participants

270   into groups based on the direction of neck rotation which induced their pain. This was

271   completed to ensure that we did not miss a potential effect of the location of neck pain (see

272   Supplementary).

273

274   **Results**

275   Of the1737 people who completed the online task, 333 were excluded due to incomplete data

276   for the neck pain questionnaires. This resulted in a sample of 1404 participants from 35

277   countries. In Test 2, 546 of the 56160 single responses (i.e., <1% of responses) were eliminated

278   and in Test 5, 601 of the 56160 single responses (i.e., ~1% of responses) were eliminated due

279   to too short of a response time or 8 consecutive timing-out responses. Participant demographics

280   are shown in Table 1.

281

282   *Insert Table 1 here.*

283

284   Accuracy-response time trade off

285   People who responded faster were also more accurate ($p<0.001$, $R^2=0.123$). That is, there was

286   no accuracy-response time trade-off.

287

288   Aim 1: The effect of neck pain and its duration on left/right judgement performance

289   **Accuracy:**

290   **Neck images**: Controlling for age, there was a main effect of Pain Duration ($F_{2,1400}= 6.36$,

291   $p=0.002$, partial $\eta^2 = 0.009$) on accuracy of identifying direction of head turn (see Figure 2A).

292   People with no pain (89.1%, 95%CI 88.1% to 90.1%) were more accurate ($p=0.001$) than

293   people with chronic neck pain (83.9%, 95%CI 81.2% to 86.7%), but were no different ($p=0.14$)

294   from people with acute neck pain (86.2%, 95%CI 82.9% to 89.7%). Further, there was no

295   difference in accuracy for judgements of neck images between those with acute neck pain and

296   those with chronic neck pain (p=0.28).

297   **Hand images:** Controlling for age, there was no main effect of Pain Duration ($F_{2,1400}$= 0.539,

298   p=0.58, partial η^2 =0.001) on accuracy for left/right judgements of hand images (see Figure 2B).

299   People with no pain had a mean accuracy score of 87.3% (95%CI 86.7% to 88.1%), while

300   people with acute and chronic neck pain had a mean accuracy score of 86.3% (95%CI 84.1% to

301   88.7%) and 86.7% (95%CI 84.7% to 88.5%), respectively.

302

303   *Insert Figure 2A-2D here*

304

305   **Response time:**

306   **Neck images:** Controlling for age, there was no main effect of Pain Duration ($F_{2,1400}$= 1.511,

307   p=0.221, partial η^2 =0.002) on response time for judgements of images of necks (see Figure

308   2C). People with no pain were no faster at identifying an image of a neck than those with acute

309   pain (mean difference: -61.5ms, 95%CI -156.9 to 33.9ms) or those with chronic pain (mean

310   difference: -53.7ms, 95%CI -133.9 to 26.4ms) and those with acute pain were no different than

311   those with chronic pain (mean difference: 7.7ms, 95%CI -110.4 to 125.9ms).

312

313   **Hand images:** Controlling for age, there was no main effect of Pain Duration ($F_{2,1400}$= 1.491,

314   p=0.225, partial η^2 =0.002) on response time for hand images (see Figure 2D). People with no

315   pain were no quicker at making judgements than those with acute pain (mean difference: -

316   73.5ms, 95%CI -183.6ms to 36.5ms) or those with chronic pain (mean difference: -59.1ms,

317   95%CI -151.5ms to 33.4ms), and those with acute pain were no quicker than those with chronic

318   pain (mean difference: 14.5ms, 95%CI -121.9ms to 150.9ms).

319

320 Aim 2: The effect of location of neck pain on judgements to left turning and right turning neck

321 images

322 **Accuracy:**

323 When considering neck pain in all locations (none, left, right, bilateral), there was a main within-

324 subjects effect of Direction of Image Head Rotation ($F_{1,1345} = 57.44$, p<0.001, partial η^2 =0.041)

325 and a main between-subjects effect of Location of Pain ($F_{3,1345} = 4.34$; p = 0.005, partial η^2

326 =0.010), but no Direction of Image Head Rotation x Location of Pain interaction ($F_{3,1345}= 2.07$,

327 p=0.103. partial η^2 =0.005). Post-hoc analyses revealed that people were less accurate at

328 identifying a left-turning neck than a right-turning neck (p<0.001), that people with no pain were

329 more accurate than people with bilateral pain (p=0.001), and that people with right-sided pain

330 were more accurate than people with bilateral pain (p=0.018; see Figure 3A).

331

332 *Insert Figure 3A and 3B here*

333
334 When comparing accuracy in only those people with lateralised neck pain (i.e., only left- or right-

335 sided neck pain), there was a main effect of Direction of Image Head Rotation ($F_{1,150} = 37.7$,

336 p<0.001, partial η^2 =0.201), but no between-subjects effect of Side of Pain ($F_{1,150} = 2.53$; p =

337 0.11, partial η^2 =0.017). There was also a significant Direction of Image Head Rotation x Side of

338 Pain interaction ($F_{1,150}= 7.81$, p=0.006, partial η^2 =0.050). To explore the interaction effect, post-

339 hoc tests evaluated the effect of image in each group and the effect of group for each image. In

340 regards to the former, post-hoc tests confirmed that both those with left-sided pain and right-

341 sided pain were less accurate for left-turning images than right-turning images (p=0.018 and

342 p<0.001, respectively). In contrast, post-hoc tests exploring the effect of group for each image

343 show that accuracy was no different between groups for *left-turning* neck images ($t_{1,150} = -0.504$,

344 p=0.62), whereas for *right-turning* neck images those with right-sided neck pain were

345 significantly more accurate ($t_{1,150} = -2.70$, p=0.008; 93.1%, 95%CI 89.9% to 96.2%) than those

346   with left-sided neck pain (87.3%, 95%CI 84.5% to 90.2%; see Figure 4A). Overall, this suggests

347   that people with right-sided neck pain have a larger difference in accuracy between right- and

348   left-turning images than do people with left-sided neck pain, and this larger difference is driven

349   by improved performance for right-turning neck images.

350

351   *Insert Figure 4A and 4B here*

352

353   **Response time:**

354   Similar to accuracy findings, there was a main within-subjects effect of Direction of Image Head

355   Rotation ($F_{1,1347}$= 18.60, p<0.001, partial η^2 =0.014) and a main between-subjects effect of

356   Location of Pain ($F_{3,1347}$= 3.51, p=0.015, partial η^2 =0.008), but no Direction of Image Head

357   Rotation x Location of Pain interaction ($F_{3,1347}$= 1.56, p=0.20, partial η^2 =0.003). Post-hoc

358   analyses revealed that people were faster at identifying a right-turning neck image than a left-

359   turning neck image (mean difference= -52.02ms, 95% CI= -75.68ms to -28.36ms, p<0.001), and

360   that people with no pain were faster at responding to images than people with left-sided neck

361   pain (mean difference = -32.6ms, 95% CI -245.4ms to -19.8ms, p=0.021) and people with

362   bilateral neck pain (mean difference = -231.4ms, 95%CI -231.3ms to 25.2ms, p=0.015; see

363   Figure 3B). When only those with lateralised neck pain (left- or right-sided pain) were included in

364   the analysis, findings were unchanged, although the interaction between Direction of Image

365   Head Rotation x Side of Pain approached significance ($F_{1,150}$= 3.66, p=0.058, partial η^2 =0.024;

366   see Figure 4B and Supplemental File for full analysis).

367

368   **Sensitivity analyses:** The results of analyses evaluating the left/right judgement performance

369   effects of neck pain evoked by side-specific movement (e.g., pain evoked with head/neck

370   movement to the left, head/neck movement to the right, both, or neither) were consistent with

371   the typical location of neck pain results reported above. See Supplementary File for full analysis

372 results. Supplementary Figures 1A (accuracy), 1B (response time) show results considering full

373 sample (no pain with neck rotation, neck pain with left head rotation, neck pain with right head

374 rotation, neck pain with head rotation in both directions) and Supplementary Figures 2A

375 (accuracy), 2B (response time) show results limited to those with neck pain induced by right or

376 left head rotation.

377

378 ***Interim summary:*** Taken together, people were faster and more accurate in identifying a right-

379 turning neck image than a left-turning neck image, regardless of whether or not they

380 experienced neck pain. People with bilateral pain were most impaired – they were less accurate

381 and slower at making neck left/right judgements than those with no pain (and less accurate than

382 those with right-sided pain). People with left-sided pain were slower at identifying neck images

383 than those with no pain, but no less accurate. Last, people with unilateral pain had varying

384 accuracy based on the location of neck pain side: those with right-sided neck pain were more

385 accurate at identifying right-turning neck images than those with left-sided neck pain (but did not

386 differ for left-turning neck images nor for any comparison of reaction time).

387

388 **Discussion**

389 We hypothesised that people with chronic neck pain would have impaired performance on a

390 left/right *neck* rotation judgement task (versus those without neck pain and those with acute

391 neck pain), but not on a left/right *hand* judgement task (Aim 1). Our hypothesis was partially

392 supported. As hypothesised, people with chronic neck pain were less accurate than people

393 without neck pain on a left/right *neck* rotation judgement task, but not on a left/right *hand*

394 judgement task. However, people with chronic neck pain were no less accurate than those with

395 acute neck pain and response time was unaffected by the presence or duration of neck pain.

396 Our second hypothesis, that the location of neck pain would impair performance on images

397 showing neck rotation towards the painful side (Aim 2), was not supported. We found only group

398   differences based on pain location (those with bilateral pain were less accurate and slower than

399   'no pain' controls, left-sided pain were slower than 'no pain' controls). A significant interaction

400   between side of pain and image (left/right neck rotation) found the opposite of what we

401   predicted: people with right-sided neck pain were more accurate at identifying an image of a

402   right-turning head than those with left-sided neck pain.

403

404   Taken together, the current findings support the possibility of impaired neural proprioceptive

405   representation of the neck in people with chronic neck pain, but also show that overall, the

406   impairment is not specific to the painful side of the neck. The distribution or spread of pain may

407   be important, given that those with bilateral pain had consistently worse performance. These

408   results have important theoretical and clinical implications.

409

410   Effect of Pain Duration on Task Performance:

411   There is accumulating evidence that people with chronic pain are less accurate at left/right

412   judgement tasks that use images that correspond to the painful body-part (Breckenridge, Ginn

413   et al. 2018), indicating disruptions to neural proprioceptive representations that are associated

414   with movement. Our findings are consistent with this body of literature and specifically support

415   previous work in people with recurrent, idiopathic neck pain that showed lower accuracy at a

416   left/right neck judgement task, than that observed in people without neck pain (Elsig, Luomajoki

417   et al. 2014). That similar impairments in accuracy were not detected in one small study in

418   people with chronic whiplash associated disorder (WAD) (Pedler, Motlagh et al. 2013), might

419   suggest differences exist within people with neck pain, between those with and without WAD.

420   However, there are two issues that suggest otherwise. First, the study by Pedler et al. (2013)

421   involved a different task - judging whether an image showed the left or right side of the neck, in

422   contrast to our task – judging whether an image showed the neck and head rotated to the left or

423   the right. It seems probable that the tasks interrogate different processes. Further, it was not

424   powered to detect a difference (only 24 participants in the control group), but instead powered to

425   detect a correlation between performance in left/right judgments and factors that are thought to

426   be predictive of non-recovery (Pedler, Motlagh et al. 2013). Second, it is highly likely that our

427   sample included a large number of people with WAD, but our online design meant we could not

428   assess them, nor definitively classify people as having WAD or not.

429

430   Reduced accuracy in the neck left/right judgement task, but not in the hand task, supports the

431   somatotopically specific nature of impairments in proprioceptive representation. This specificity

432   of impairment is largely consistent with past research in several chronic pain conditions,

433   including back pain (Bowering, Butler et al. 2014) and arm pain (Schwoebel, Friedman et al.

434   2001, Moseley 2004) (see also systematic review findings: (Breckenridge, Ginn et al. 2018)),

435   and also in experimentally induced pain (Moseley, Sim et al. 2005) and even the expectation of

436   experimentally induced pain (Hudson, McCormick et al. 2006). It is important to consider the

437   wider body of evidence when interpreting the current results because different problems might

438   underpin impairment of accuracy as distinct from response time. Full review is beyond the

439   scope of this paper, but deficits in accuracy are more consistent with disrupted proprioceptive

440   representation and deficits in RT are more consistent with unequal weighting between

441   representations of either hand, or movement (see (Moseley, Butler et al. 2012, Wallwork, Bellan

442   et al. 2016, Wallwork, Bellan et al. 2017) for extensive reviews, although see Pelletier,

443   Bourbonnais et al. (2018) for other possible contributors to performance).

444

445   Recent findings by Pelletier and colleagues have shown that left/right judgement performance is

446   related to sensorimotor and cognitive function in people with pain (Pelletier, Bourbonnais et al.

447   2018). That is, performance on tasks including tactile acuity and motor function were related to

448   left/right judgement accuracy of the affected body part, as was taking pain medication.

449   Additionally, poor performance in a cognitive stroop task was associated with general impaired

450 left/right judgement performance. Thus, it is possible that the differences observed between the

451 chronic pain and no pain groups in our study (Aim 1) could, in part, be attributable to other

452 factors (such as those reported by Pelletier and colleagues) than to impairments to the

453 proprioceptive neural representation. However, these relationships between sensorimotor

454 function and left/right judgement performance are not straightforward: in people with chronic

455 painful knee osteoarthritis, impairments in tactile acuity were not related to left/right judgement

456 performance (Stanton, Lin et al. 2013). Also, if impaired cognitive function in the chronic neck

457 pain group influenced their task performance (as per Pelletier et al), we would expect impaired

458 performance on both hand and neck image left right judgement tasks, which we did not see.

459 Further work is clearly required to understand the nuanced and complex mechanisms

460 contributing to performance in this task.

461

462 That people with neck pain have impaired accuracy on left/right judgements for neck images

463 has particular clinical relevance, because it raises the possibility that treatments aiming to

464 reverse that deficit might help to reduce pain in those with chronic neck pain. Certainly, in other

465 pain populations (i.e., complex regional pain syndrome and phantom limb pain), motor imagery

466 training, which includes left/right body part judgements, has been shown to be effective at

467 reducing pain (Moseley 2004, Moseley 2006). There are three important caveats here that urge

468 caution before adding motor imagery training to a clinical toolbox. First, it is not known whether

469 an accuracy deficit of ~6% is clinically meaningful. Second, whether deficits vary according to

470 diagnosis or mechanism of injury remains to be determined. Third, any recommendations for

471 new treatments should only be made once the treatment is known to be safe and effective, as

472 determined in clinical trials.

473

474 That we found no difference in accuracy between the acute pain group and the healthy control

475 group (without neck pain) supports the idea that these impaiments do not occur in the acute

476   stages. Such findings are largely consistent with previous work in a back pain sample showing

477   that impairments are minimal in people with current back pain (but no history of back pain)

478   (Bowering, Butler et al. 2014). However, we also found that the acute pain group did not differ in

479   accuracy to the chronic pain group either which raises the possibility that small changes in

480   performance may occur in the acute phase, but they are not large enough to be detected even

481   in a large cohort such as this, which implies any difference would be very small and likely to be

482   unimportant. Investigating longitudinal change in proprioceptive representation as pain persists

483   appears warranted because perhaps early deficit is a risk factor for poor recovery.

484

485   While left/right judgement accuracy was impaired, *response time* was not. This may be

486   explained by the different processes underpinning the two outcomes. That is, RT deficits in limb

487   pain are currently interpreted as reflecting unequal weighting of space-based or side-based

488   representations (see above). There is increasing evidence showing space-based deficits in

489   processing in association with limb pain, with a range of effects including thermoregulation,

490   motor control and tactile processing (Moseley, Gallace et al. 2009, Stanton, Lin et al. 2012,

491   Reid, Wallwork et al. 2016, Reid, Braithwaite et al. 2018)(see Moseley, Gallace et al. (2012) for

492   a review). However, in limb pain, the spatial representations seem to involve the area of

493   peripersonal space in which the limb is used. This clearly is not applicable to spinal pain, so it is

494   perhaps unsurprising that we did not observe RT deficits here.

495

496   Effect of Location/Side Specific Pain on Performance

497   Our finding that location specific neck pain (Aim 2) or movement-evoked neck pain (see

498   Supplementary material) did not affect performance to images showing neck rotation to their

499   affected side would not be predicted on the presumed relationship between proprioceptive

500   representation and motor imagery performance (Bray and Moseley 2011, Schmid and

501   Coppieters 2012, Wallwork, Bellan et al. 2016). That is, we predicted that performance on a task

502   that requires access to the representations for a body part or movement that is normally

503   associated as being painful would be worse than for a task that requires access to the

504   representations for a body part or movement that is not normally associated as being painful.

505   Such a hypothesis is supported by past work in people with painful osteoarthritis (Stanton, Lin et

506   al. 2012) and also by contemporary theories (i.e., the cortical body matrix theory (Moseley,

507   Gallace et al. 2012)) in this area.

508

509   Contemporary theories of motor processing emphasise the distributed nature of processing and

510   the conceptual construct of neural networks (or 'neurotags' (Butler and Moseley 2003, Moseley

511   and Butler 2015)) that are under a potentially infinite number of other neural networks (see

512   Wallwork, Bellan et al. (2016) for a review). For example, a movement of neck rotation (the

513   'output'), depends on incoming data (including proprioceptive cues, visual cues [head rotation],

514   tactile cues [from skin stretching]), stored data (past experience) and predicted outcomes of a

515   movement. As part of this complex process, motor efferent copies (i.e., a copy of the motor

516   command) are created with multi-sensory feedback from the movement used to determine if the

517   movement occurred as planned. The more often the network is activated, the stronger and more

518   precise it becomes (Pearson, Finkel et al. 1987, Pilz, Veit et al. 2004), which in turn facilitates

519   activation of the 'learned' network. It might be predicted then, that when performing a left/right

520   neck rotation judgement task that uses these disrupted proprioceptive representations,

521   performance would be specifically hindered for an image congruent with painful movement –

522   even when the full movement output has not occurred (i.e., they have not actually moved). That

523   we did not consistently find an interaction effect in this study indicates that perhaps these

524   proprioceptive representations have general alterations for the affected body part, and are not

525   specific to the location of pain, or movement-evoked side of pain. Alternatively, it may be that

526   the precision with which neck proprioceptive input is represented for side-specific movements is

527   less than we would expect in lateralised body parts (e.g., left and right hand).

528

529

530   We found that people were generally more accurate at identifying images of right neck rotation

531   than left neck rotation, regardless of neck pain status. Previous studies have identified side-

532   specific effects as a function of hand dominance: right-handers are more accurate at identifying

533   right hand images than left-handers (Braithwaite et al. In Preparation)(Wallwork, Butler et al.

534   2013) and perhaps these findings transfer to our results too. In our sample, 1192 of 1404 were

535   right-handed so there was a much stronger right-handed presence in our sample group which

536   would be consistent with this idea. However, it seems unlikely that the same effect of

537   dominance extends to the neck like it does the hand. Of relevance, people are faster and more

538   accurate at a left/right judgement task when images are rotated 90° clockwise (medial) than

539   when they are rotated 90° anti-clockwise (lateral) for images of the neck (Wallwork, Butler et al.

540   2013) and for images of the back (n=1189 participants) (Bowering, Butler et al. 2014). Given

541   that past work has also shown that such differences based on image orientation may reflect a

542   switch from implicit motor imagery to more proprioceptive-visual matching strategies (as seen in

543   hand left/right judgements) (De Simone, Tomasino et al. 2013), these hypotheses clearly

544   require further investigation.

545

546   An interaction between side of the body and side of pain was seen only for analyses considering

547   the location of neck pain (left versus right-sided), but it was opposite to the direction

548   hypothesised. People with right-sided neck pain were *more accurate* at identifying an image of a

549   right-turning head than people with left-sided neck pain. While previous work by Stanton, Lin et

550   al. (2012) found that people with right-sided knee osteoarthritic pain or upper limb pain were

551   generally more accurate than those with left-sided pain at identifying images of hands or feet,

552   enhanced performance for right-sided pain x right sided images was not seen. Specifically,

553   those with right-sided knee or upper limb pain were no more accurate at identifying a right

554   hand/foot than a left hand/foot, where as in participants with left-sided pain, performance was

555   most impaired for left hand or foot images versus right images (side of pain matched side of

556   impairment) (Stanton, Lin et al. 2012). Together with generalised reduction in performance for

557   left versus right-sided neck images seen here, such findings raise the possibility that there might

558   be a lateralised performance effect whereby spatial lateralisation of processing during the task

559   (i.e., in the right posterior parietal cortex) results in an interference effect with left-sided (right

560   processed) proprioceptive representations (i.e, left images), which can be further affected by

561   left-sided (right processed) pain, but is relatively spared by right-sided (left processed) pain.

562   However, why performance for right images in people with right-sided neck pain is seemingly

563   enhanced remains unclear. To our knowledge, this line of enquiry remains to be tested.

564

565   Last, we found that people with bilateral neck pain (typical and movement-evoked) were slower

566   and less accurate than people with no neck pain. Such findings raise the possibility that the

567   disruptions to proprioceptive representation are greater when pain is more widespread in area

568   (i.e., bilateral). Finally, people with right-sided neck pain were more accurate than people with

569   bilateral neck pain, but no faster than people with left-sided pain, and people with no pain were

570   also faster than people with left-sided pain. This pattern of findings requires validation, but

571   generally supports the largest impairments seen in those with bilateral pain, followed by left-

572   sided pain, and the least impairment in those with right-sided pain.

573

574   *Study limitations*

575   While this is one of the largest left/right judgement studies undertaken to date, interpretation of

576   our results should consider several limitations. First, the online nature of the study means that

577   computer malfunctions, screen size, screen resolution, and refresh rate could increase variance

578   and reduce our power, although it is unlikely to systematically bias the results. Furthermore,

579 being an online study, we cannot exclude that participants took part more than once or provided

580 inaccurate information when answering the online questionnaire. To combat limitations imposed

581 by this increase in variability of the data, we purposefully aimed to collect a large sample. There

582 is also the possibility that participants' responses to the fifth block (hand images) may have

583 been affected by fatigue when compared to responses to the second block (neck images).

584 Although possible, we think this is unlikely as fatigue is primarily seen when an identical task is

585 repeated. Because the hand task in the fifth block was new, we anticipate that fatigue is less of

586 a concern. If fatigue were a factor, we would expect that people with neck pain would perform

587 worse at the hand task than pain-free people (Dailey, Keffala et al. 2015), which was not

588 observed. Additionally, we were unable to explore image orientation specific performance

589 results for neck and hand images; these data were not retrievable. Given that evaluating image

590 orientation can help to interpret what might underlie accuracy impairments (e.g., impairments in

591 motor imagery or alterations in visual processing (Edwards, Causby et al. 2019)), future

592 research that purposefully explores the influence of neck image orientation on performance is

593 clearly needed.

594 Given an online study, there are also inherent limitations in participant self-report for 'acute' and

595 'chronic' neck pain, because people might have different interpretations. For example, despite

596 providing clear descriptors about duration, it is possible that someone with an ongoing chronic

597 problem might report 'acute' pain because they are suffering a recent flare-up. Such challenges

598 may also be a potential factor in the lack of performance difference seen between acute and

599 chronic neck pain. Furthermore, while it would have been of interest to consider pain intensity

600 as a covariate in the analyses, limitations in the online questionnaire meant that pain intensity

601 values were not collected for those who reported having acute or chronic pain but who only

602 reported pain with neck movement. That is, pain intensity scores only captured current neck

603 pain. Unfortunately then, including pain as a covariate would have excluded numerous

604   participants from the analysis. Additionally, given that past studies have shown an inconsistent

605   relationship between pain intensity and left/right judgement performance (Bray and Moseley

606   2011, Linder, Michaelson et al. 2016, Pelletier, Bourbonnais et al. 2018, Stanton, Gilpin et al.

607   2018), this makes the relevance of including pain intensity as a covariate less certain. For these

608   reasons pain intensity was not included covariate in our analyses. Last, as reported in a

609   previous study using this data (Wallwork, Butler et al. 2013), using the 'a' and 'd' keys on the

610   keyboard as a response apparatus has limitations in that both keys are located on the left of the

611   keyboard (i.e.,in the left side of space). We now understand that a bias in the allocation of

612   attention to a spatially-defined location could influence responding (Moseley, Gallace et al.

613   2012, Reid, Wallwork et al. 2016); however such influences are less likely to impact our main

614   findings, given that the neck is not like the limbs which are normally situated in one spatial field

615   (right or left of body midline) Regardless, future work in this area should aim to use keys that

616   result in the response hands being positioned on either side of the body midline. Finally, that we

617   did not lodge and lock our experimental protocol prior to conducting this experiment reflects that

618   we began the study before we fully understood the importance of doing so. This practice

619   enhances the transparency of research and is now recommended for observational and clinical

620   designs in many fields including pain (Lee, E Lamb et al. 2018).

621

622   *Conclusions*

623   In our large online cohort (n=1404), including 266 people with neck pain, we found evidence of

624   disruptions to proprioceptive representations that were specific to the neck in people with

625   chronic neck pain. In particular, people with chronic neck pain were less accurate at a left/right

626   neck rotation judgement task, but not a left/right hand judgement task, than people with no neck

627   pain. Contrary to our expectations, we found that the location of neck pain generally did not

628   influence responses to images associated with movement towards their painful side. Overall

629   these findings indicate that investigation of a graded motor imagery program to reduce pain in

630   people with neck pain may be warranted. However, further investigations in neck pain

631   subgroups, such as whiplash associated disorder, need to be addressed.

632

633   **Conflicts of interest:**

634   In the last 5 years, G. Lorimer Moseley has received support from: ConnectHealth UK, Seqirus,

635   Kaiser Permanente, Workers' Compensation Boards in Australia, Europe and North America,

636   AIA Australia, the International Olympic Committee, Port Adelaide Football Club and Arsenal

637   Football Club. Professional and scientific bodies have reimbursed him for travel costs related to

638   presentation of research on pain at scientific conferences/symposia. He has received speaker

639   fees for lectures on pain and rehabilitation. He receives book royalties from NOIgroup

640   publications, Dancing Giraffe Press & OPTP. G. Lorimer Moseley is an Academic Editor for

641   PeerJ. TRS has received support from Eli Lilly Ltd for travel and accommodation costs.

642

643 **References**

644 Alazmi, L., G. E. Gadsby, N. R. Heneghan and T. D. Punt (2018). "Do trunk-based left/right judgment tasks
645 elicit motor imagery?" Musculoskelet Sci Pract **35**: 55-60.
646 Bland, J. M. and D. G. Altman (1996). "Statistics Notes: The use of transformation when comparing two
647 means." BMJ **312**(7039): 1153.
648 Boonstra, A. M., S. J. de Vries, E. Veenstra, M. Tepper, W. Feenstra and E. Otten (2012). "Using the Hand
649 Laterality Judgement Task to assess motor imagery: a study of practice effects in repeated
650 measurements." Int J Rehabil Res **35**(3): 278-280.
651 Bowering, K. J., D. S. Butler, I. J. Fulton and G. L. Moseley (2014). "Motor imagery in people with a
652 history of back pain, current pain, both, or neither." The Clinical Journal of Pain **30**(12): 1070-1075.
653 Bray, H. and G. L. Moseley (2011). "Disrupted working body schema of the trunk in people with back
654 pain." British Journal of Sports Medicine **45**(3): 168-173.
655 Breckenridge, J. D., K. A. Ginn, S. B. Wallwork and J. H. McAuley (2018). "Do people with chronic
656 musculoskeletal pain have impaired motor imagery? A meta-analytical systematic review of the
657 left/right judgement task." The Journal of Pain.
658 Butler, D. and G. L. Moseley (2003). Explain pain. Adelaide, NOI Group Publishing.
659 Coslett, H. B., J. Medina, D. Kliot and A. Burkey (2010). "Mental motor imagery and chronic pain: The
660 foot laterality task." Journal of the International Neuropsychological Society: 1-10.
661 Dailey, D. L., V. J. Keffala and K. A. Sluka (2015). "Do cognitive and physical fatigue tasks enhance pain,
662 cognitive fatigue, and physical fatigue in people with fibromyalgia?" Arthritis care & research **67**(2): 288-
663 296.
664 De Simone, L., B. Tomasino, N. Marusic, R. Eleopra and R. I. Rumiati (2013). "The effects of healthy aging
665 on mental imagery as revealed by egocentric and allocentric mental spatial transformations." Acta
666 Psychol (Amst) **143**(1): 146-156.
667 Dey, A., N. Barnsley, R. Mohan, M. McCormick, J. H. McAuley and G. L. Moseley (2012). "Are children
668 who play a sport or a musical instrument better at motor imagery than children who do not?" British
669 Journal of Sports Medicine.
670 Edwards, L. M., R. S. Causby, H. Stewart and T. R. Stanton (2019). "Differential influence of habitual
671 third-person vision of a body part on mental rotation of images of hands and feet." Experimental Brain
672 Research.
673 Elgueta-Cancino, E., S. Schabrun and P. Hodges (2018). "Is the Organization of the Primary Motor Cortex
674 in Low Back Pain Related to Pain, Movement, and/or Sensation?" Clin J Pain **34**(3): 207-216.
675 Elsig, S., H. Luomajoki, M. Sattelmayer, J. Taeymans, A. Tal-Akabi and R. Hilfiker (2014). "Sensorimotor
676 tests, such as movement control and laterality judgment accuracy, in persons with recurrent neck pain
677 and controls. A case-control study." Manual Therapy **19**(16): 555-561.
678 Holm, S. (1979). "A Simple Sequentially Rejective Multiple Test Procedure." Scandinavian Journal of
679 Statistics **6**(2): 65-70.
680 Hoy, D. G., M. Protani, R. De and R. Buchbinder (2010). "The epidemiology of neck pain." Best Pract Res
681 Clin Rheumatol **24**(6): 783-792.
682 Hudson, M. L., K. McCormick, N. Zalucki and G. L. Moseley (2006). "Expectation of pain replicates the
683 effect of pain in a hand laterality recognition task: Bias in information processing toward the painful
684 side?" European Journal of Pain **10**(3): 219-224.
685 Kunde, W. (2001). "Response-Effect Compatibility in Manual Choice Reaction Tasks." Journal of
686 Experimental Psychology: Human Perception and Performance **27**(2): 287-394.
687 Lee, H., S. E Lamb, M. Bagg, E. Toomey, A. Cashin and L. Moseley (2018). Reproducible and Replicable
688 Pain Research: A Critical Review.

689 Linder, M., P. Michaelson and U. Roijezon (2016). "Laterality judgments in people with low back pain--A
690 cross-sectional observational and test-retest reliability study." Man Ther **21**: 128-133.
691 Lotze, M., P. Montoya, M. Erb, E. Hulsmann, H. Flor, U. Klose, N. Birbaumer and W. Grodd (1999).
692 "Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an
693 fMRI study." J Cogn Neurosci **11**(5): 491-501.
694 Michelon, P., J. M. Vettel and J. M. Zacks (2006). "Lateral somatotopic organization during imagined and
695 prepared movements." J Neurophysiol **95**(2): 811-822.
696 Moseley, G. and P. Brugger (2009). "Interdependence of movement and anatomy persists when
697 amputees learn a physiologically impossible movement of their phantom limb." Proceedings of the
698 National Academy of Sciences of the United States of America **106**(44): 18798-18802.
699 Moseley, G., D. Butler, T. Beames and T. Giles (2012). The graded motor imagery handbook. Adelaide,
700 NOIgroup publishing.
701 Moseley, G., A. Gallace and G. D. Iannetti (2012). "Neglect-like tactile dysfunction in chronic back pain."
702 Neurology **79**: 327-332.
703 Moseley, G., A. Gallace and C. Spence (2009). "Space-based, but not arm-based, shift in tactile
704 processing in complex regional pain syndrome and its relationship to cooling of the affected limb."
705 BRAIN **132**: 3142-3151.
706 Moseley, G. L. (2004). "Graded motor imagery is effective for long-standing complex regional pain
707 syndrome: a randomised controlled trial." Pain **108**: 192-198.
708 Moseley, G. L. (2004). "Why do people with complex regional pain syndrome take longer to recognize
709 their affected hand?" Neurology **62**(12): 2182-2186.
710 Moseley, G. L. (2006). "Graded motor imagery for pathologic pain: A randomized controlled trial."
711 Neurology **67**(12): 2129-2134.
712 Moseley, G. L. and D. S. Butler (2015). "15 years of Explainig Pain - the past, present and future." The
713 Journal of Pain **In Press**.
714 Moseley, G. L., A. Gallace and C. Spence (2012). "Bodily illusions in health and disease: Physiological and
715 clinical perspectives and the concept of a cortical 'body matrix'." Neuroscience and biobehavioral
716 reviews **36**: 34-46.
717 Moseley, G. L., D. F. Sim, M. L. Henry and T. Souvlis (2005). "Experimental hand pain delays recognition
718 of the contralateral hand--Evidence that acute and chronic pain have opposite effects on information
719 processing?" Cognitive Brain Research **25**(1): 188-194.
720 Parsons, L. M. (2001). "Integrating cognitive psychology, neurology and neuroimaging." Acta
721 Psychologica **107**(1-3): 155-181.
722 Parsons, L. M., P. T. Fox, J. H. Downs, T. Glass, T. B. Hirsch, C. C. Martin, P. A. Jerabek and J. L. Lancaster
723 (1995). "Use of implicit motor imagery for visual shape discrimination as revealed by PET." Nature **375**:
724 54.
725 Pearson, J. C., L. H. Finkel and G. M. Edelman (1987). "Plasticity in the organization of adult cerebral
726 cortical maps: a computer simulation based on neuronal group selection." J Neurosci **7**(12): 4209-4223.
727 Pedler, A., H. Motlagh and M. Sterling (2013). "Laterality judgments are not impaired in patients with
728 chronic whiplash associated disorders." Man Ther **18**(1): 72-76.
729 Pelletier, R., D. Bourbonnais, J. Higgins, M. Mireault, M. A. Danino and P. G. Harris (2018). "Left Right
730 Judgement Task and Sensory, Motor, and Cognitive Assessment in Participants with Wrist/Hand Pain."
731 Rehabilitation research and practice **2018**: 1530245-1530245.
732 Pilz, K., R. Veit, C. Braun and B. Godde (2004). "Effects of co-activation on cortical organization and
733 discrimination performance." NeuroReport **15**(17): 2669-2672.
734 Reid, E., S. B. Wallwork, D. Harvie, K. J. Chalmers, A. Gallace, C. Spence and G. L. Moseley (2016). "A New
735 Kind of Spatial Inattention Associated With Chronic Limb Pain?" Ann Neurol **79**(4): 701-704.

736 Reid, E. J., F. A. Braithwaite, S. B. Wallwork, D. Harvie, K. J. Chalmers, C. Spence, A. Gallace and G. L.
737 Moseley (2018). "Spatially-defined motor deficits in people with unilateral complex regional pain
738 syndrome." Cortex **104**: 154-162.
739 Schmid, A. B. and M. W. Coppieters (2012). "Left/right judgment of body parts is selectively impaired in
740 patients with unilateral carpal tunnel syndrome." Clinical Journal of Pain **28**(7): 615-622.
741 Schwoebel, J., H. B. Coslett, J. Bradt, R. Friedman and C. Dileo (2002). "Pain and the body schema: Effects
742 of pain severity on mental representations of movement." Neurology **59**(5).
743 Schwoebel, J., R. Friedman, N. Duda and H. B. Coslett (2001). "Pain and the body schema: Evidence for
744 peripheral effects on mental representations of movement." Brain **124**(10): 2098-2104.
745 Silva, S., I. Loubinoux, M. Olivier, B. Bataille, O. Fourcade, K. Samii, M. Jeannerod and J. F. Demonet
746 (2011). "Impaired visual hand recognition in preoperative patients during brachial plexus anesthesia:
747 importance of peripheral neural input for mental representation of the hand." Anesthesiology **114**(1):
748 126-134.
749 Stanton, T., C. Lin, R. Smeets, D. Taylor, R. Law and G. Moseley (2012). "Spatially-defined disruption of
750 motor imagery performance in people with osteoarthritis." Rheumatology **51**: 1455-1464.
751 Stanton, T. R., H. R. Gilpin, L. Edwards, G. L. Moseley and R. Newport (2018). "Illusory resizing of the
752 painful knee is analgesic in symptomatic knee osteoarthritis." PeerJ **6**: e5206-e5206.
753 Stanton, T. R., H. B. Leake, K. J. Chalmers and G. L. Moseley (2016). "Evidence of Impaired Proprioception
754 in Chronic, Idiopathic Neck Pain: Systematic Review and Meta-Analysis." Physical therapy **96**(6): 876-
755 887.
756 Stanton, T. R., C. W. Lin, H. Bray, R. J. Smeets, D. Taylor, R. Y. Law and G. L. Moseley (2013). "Tactile
757 acuity is disrupted in osteoarthritis but is unrelated to disruptions in motor imagery performance."
758 Rheumatology **52**(8): 1509-1519.
759 Wallwork, S. B., V. Bellan, M. J. Catley and G. L. Moseley (2016). "Neural representations and the cortical
760 body matrix: implications for sports medicine and future directions." Br J Sports Med **50**(16): 990-996.
761 Wallwork, S. B., V. Bellan and G. L. Moseley (2017). "Applying Current Concepts in Pain-Related Brain
762 Science to Dance Rehabilitation." J Dance Med Sci **21**(1): 13-23.
763 Wallwork, S. B., D. S. Butler, I. Fulton, H. Stewart, I. Darmawan and G. L. Moseley (2013). "Left/right neck
764 rotation judgments are affected by age, gender, handedness and image rotation." Man Ther **18**(3): 225-
765 230.
766 Wallwork, S. B., D. S. Butler, D. J. Wilson and G. L. Moseley (2015). "Are people who do yoga any better
767 at a motor imagery task than those who do not?" Br J Sports Med **49**(2): 123-127.

768

Demographic information of included participants

All numbers represent count data unless otherwise specified.

Demographic variables	All participants	Duration of pain			Location of pain				Movement-evoked neck pain			
		No pain	Acute neck pain	Chronic Neck pain	No pain	Left	Right	Bilateral	No pain	Left	Right	Bilateral
TOTAL	1404	1138	105	161	1104	79	73	96	1075	43	42	118
Male	422	364	20	38	352	12	17	22	338	9	7	24
Female	912	720	82	110	701	63	50	68	692	33	32	86
Gender not reported	70	54	3	13	51	4	6	6	45	1	3	8
Left-handed	141	119	9	13	120	9	5	6	112	3	4	11
Right-handed	1192	962	92	138	927	66	63	87	913	38	34	101
Ambidextrous	41	33	3	5	33	3	3	1	31	2	2	2
Handedness not reported	30	24	1	5	24	1	2	2	19	0	2	4
Age (mean ± SD)	39 ± 12.9	37 ±12.8	37 ±12.5	45 ±12.7	37 ±12.7	42 ±11.8	41 ±13.2	42 ±14.0	37 ±12.7	42 ±11.6	43 ±11.6	43 ±13.6

1   All numbers represent count data unless otherwise specified.

Figure 1

Sample images used in the left/right judgement tasks

(A-D) Head-turning images at various orientations and in various postures. (E-F) Hand images depicting various postures. Photo credit: Juliet Gore; received from Noigroup archived images (www.noigroup.com)
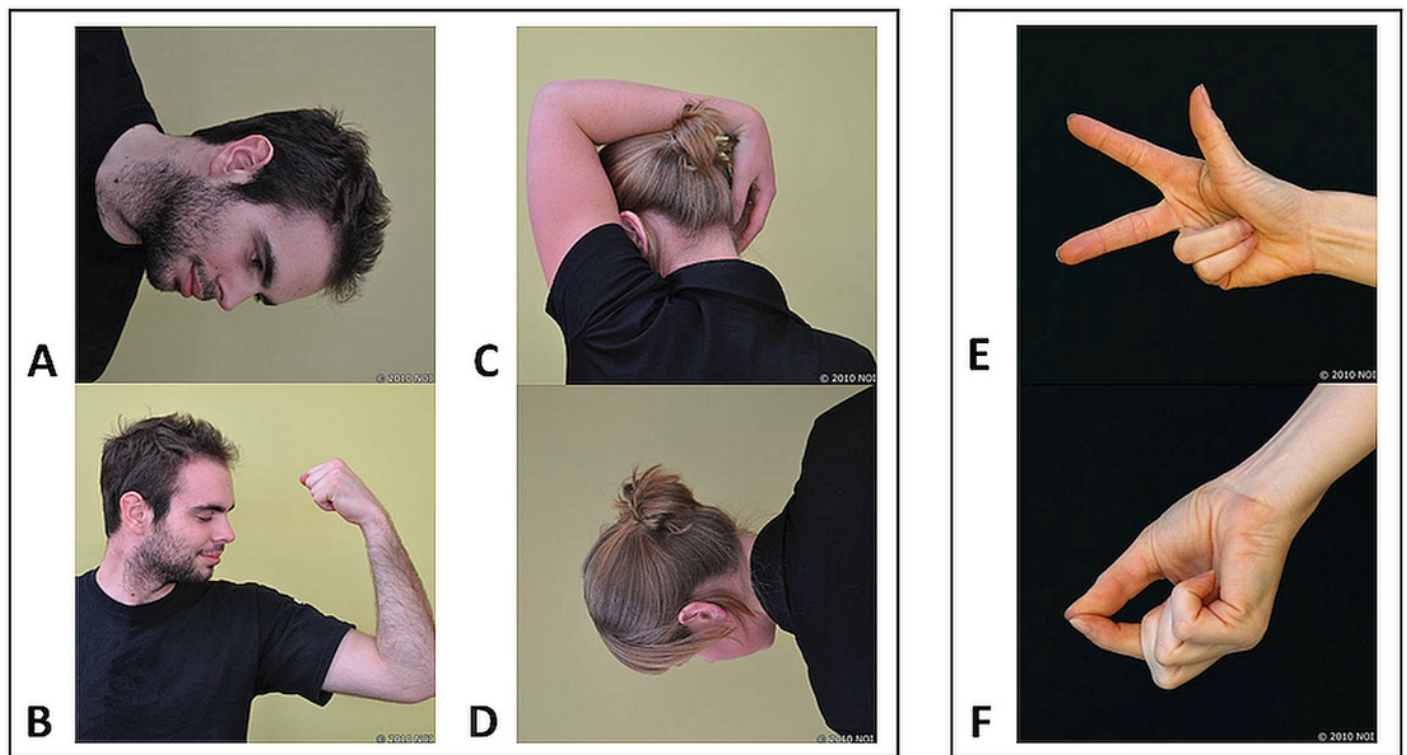
Figure 2

Effect of pain duration on left/right judgement performance

(A) Accuracy results for neck images. (B) Accuracy results for hand images. (C) Response time for neck images. (D) Response time for hand images. The red line indicates the significant post-hoc independent t-test findings for this comparison performed following an overall main effect of pain duration. Photo credit: Juliet Gore.
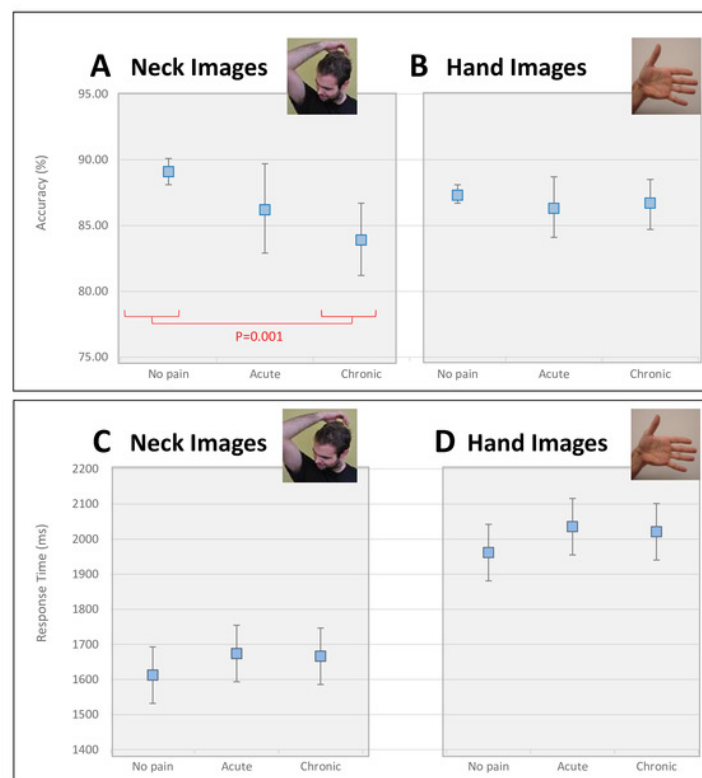
Figure 3

The effect of neck pain location (none, left-sided, right-sided, bilateral) on left/right neck judgement performance.

(A) Accuracy. (B) Response time. The blue line shows a main within subject effect of image type (direction of image head rotation). The red lines show significant posthoc independent t-test comparisons, following a main significant effect of pain location. Photo credit: Juliet Gore.
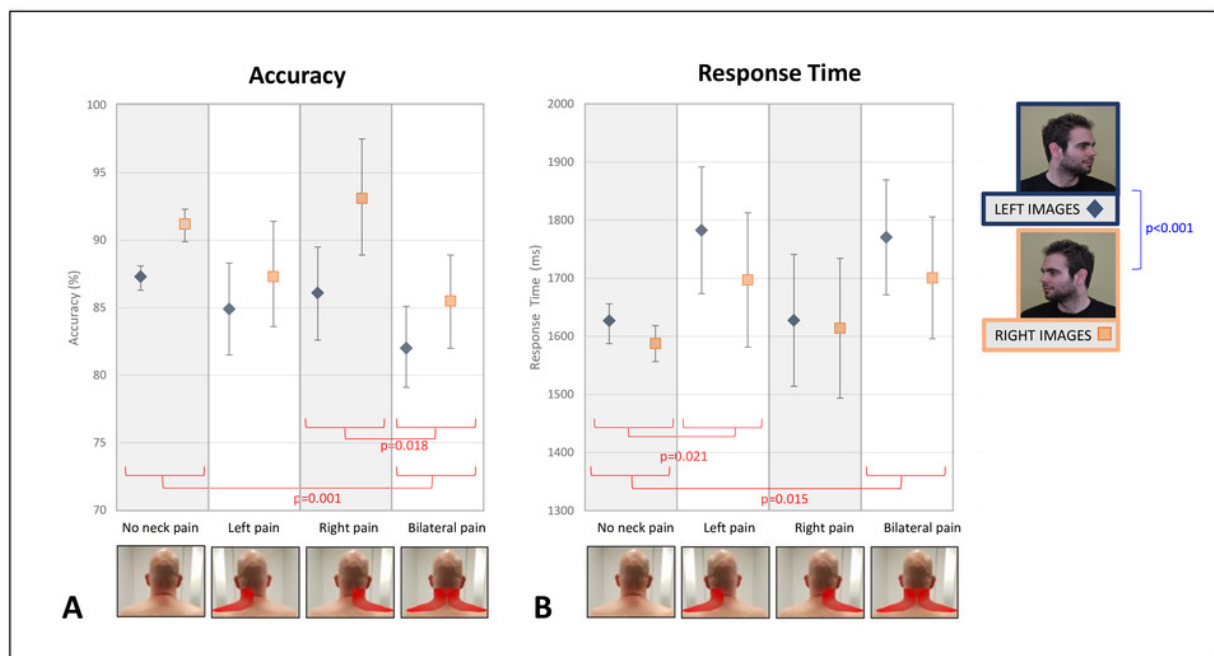
Figure 4

Effect of unilateral pain location (left- versus right-sided neck pain) on left/right neck judgement performance

(A) Accuracy. (B) Response time. The red lines indicate main between group effects of image type (left versus right head turning images). The dotted red line shows the posthoc independent t-test results showing significant performance differences between left- and right-sided pain *only* for right-sided neck images, following a significant interaction between image type and side of pain. Photo credit: Juliet Gore.