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Correlated individual differences suggest a common mechanism underlying metacognition

in visual perception and visual short-term memory

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39   **Abstract**

40   Adaptive behavior depends on the ability to accurately introspect about one's own performance.

41   Whether this metacognitive ability is supported by the same mechanisms across different tasks

42   has thus far been investigated with a focus on correlating metacognitive accuracy between

43   perception and long-term memory paradigms. Here, we investigated the relationship between

44   metacognition of visual perception and metacognition of visual short-term memory (VSTM), a

45   cognitive function thought to be more intimately related to visual processing. Experiments 1 and

46   2 required subjects to estimate the perceived or remembered orientation of a grating stimulus and

47   rate their confidence. We observed strong positive correlations between individual differences in

48   metacognitive accuracy between the two tasks. This relationship was not accounted for by

49   individual differences in task performance or average confidence, and was present across two

50   different metrics of metacognition and in both experiments. A model-based analysis of data from

51   a third experiment showed that a cross-domain correlation only emerged when both tasks shared

52   the same task-relevant stimulus feature. That is, metacognition for perception and VSTM were

53   correlated when both tasks required orientation judgments, but not when the perceptual task was

54   switched to require contrast judgments. In contrast to previous results comparing perception and

55   long-term memory, which have largely provided evidence for domain-specific metacognitive

56   processes, the current findings suggest that metacognition of visual perception and VSTM is

57   supported by a domain-general metacognitive architecture, but only when both domains share

58   the same task-relevant stimulus feature.

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Introduction

When humans make decisions they are capable of estimating the likelihood that their decision

was accurate. This introspective ability falls under a class of cognitive processes known as

metacognition because it entails cognizing about the quality of a decision-making process (1).

Intuitively, an individual has high metacognitive accuracy if their estimate of the accuracy of

their decision (e.g., as expressed by a confidence rating) corresponds well with the actual

accuracy of their decision (2). Because decisions can be made on the basis of information from a

plethora of sources—for example, deciding on the basis of current sensory input versus deciding

on the basis of information culled from long-term memory—an outstanding question is whether

metacognitive processes are domain-general or domain-specific (3). A domain-general

metacognitive monitoring process would be expected to evaluate the accuracy of decisions made

from both perceptual inputs as well as those based on memory. In contrast, a domain-specific

metacognitive system would use independent neural resources or computations to estimate the

quality of memory- versus perception-based judgments, for example.

Recent work on this topic has focused on correlating individual differences in metacognition

during perception and long-term memory and has resulted in mixed findings. Several studies

have reported non-significant relationships between individual's metacognitive ability in a

perceptual task and their metacognitive ability in a long-term memory task (4–6), suggesting

domain-specific metacognition. However, an experiment using similar tasks did find a reliable

positive correlation between metacognitive abilities in both domains (7), and other work has

shown correlated metacognitive performance across different perceptual tasks (8), suggesting

some shared underlying resources. A number of the above-mentioned studies, however, have

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85   also reported that structural and function brain imaging data from distinct regions correlated with

86   metacognitive abilities for the distinct tasks, reinforcing domain-specificity at the neural level

87   (4,5,7). Additional evidence for domain-specificity between perception and long-term memory

88   has come from a recent study of patients with lesions to anterior portions of prefrontal cortex.

89   These patients showed a selective deficit in visual perceptual metacognition, but not memory

90   metacognition for a recently studied word list (9).

91

92   A lack of cross-task correlation in metacognition may sometimes be difficult to interpret because

93   this could result from procedural differences between tasks not necessarily related to the

94   cognitive construct under investigation (e.g., the use of different stimuli in the perception versus

95   memory task). Furthermore, perception and long-term memory are themselves quite distinct

96   cognitive functions (although they can certainly interact in some situations, e.g., (10)), and an

97   underexplored question is whether perceptual metacognition relates to metacognition for other

98   cognitive functions more closely related to perception. Across three experiments, we examined

99   whether metacognition in visual perceptual judgments is related to metacognition for visual

100   short-term memory (VSTM) judgments using tasks with the same stimuli that differ only in the

101   requirement for memory storage over a short delay (Experiments 1 and 2), or tasks that differ

102   also in the relevant stimulus feature (Experiment 3). Because perception of and VSTM for a

103   given stimulus feature are hypothesized to rely on shared neural representations (11−14), we

104   might anticipate that metacognition in these domains is also based on some shared resource,

105   leading to positively correlated individual differences in metacognition across tasks, but only

106   when the task-relevant stimulus feature is shared.

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110 **Materials and Methods**

111 **Data availability.** In accordance with the practices of open science and reproducibility, all raw

112 data and code used in the present analyses are freely available through the Open Science

113 Framework (https://osf.io/py38c/).

114

115 **Experiments 1 and 2.** Because of their similarities, the methods pertaining to Experiment 1 and

116 2 are described together in this section, followed by the methods for Experiment 3.

117

118 **Participants**. Forty subjects (twenty in Experiment 1: mean age = 21 years, SD = 1.67, 10

119 female, and twenty in Experiment 2: mean age = 20.6 years, SD = 2.01, 14 female) from the

120 University of Wisconsin-Madison community participated in these experiments and received

121 monetary compensation. All subjects provided written consent, reported normal or corrected-to-

122 normal visual acuity and color vision, and were naive to the hypothesis of the experiment. The

123 University of Wisconsin-Madison Institutional Review Board approved all experiments reported

124 here.

125

126 **Stimuli.** Target stimuli were identical for both experiments and consisted of sinusoidal

127 luminance gratings embedded in white noise presented within a central circular aperture (see

128 Figure 1A). Gratings subtended 2 degrees of visual angle (DVA), had a spatial frequency of 1.5

129 cycles/DVA and a phase of zero. Fixation (a light gray point, 0.08 DVA) was centered on the

130 screen and was dimmed slightly to indicate trial start (see Figure 1A). Noise consisted of white

131   noise luminance values generated randomly on each trial for each pixel in the noise patch. The

132   contrast of the grating was determined for each subject by an adaptive staircase procedure prior

133   to the main tasks. On a random half of the trials the contrast of both the signal and the noise was

134   halved. This was not expected to impact orientation estimation performance because the signal-

135   to-noise ratio of the stimulus was unchanged (15), however it led to a relatively small but reliable

136   performance difference in Experiment 1 (difference in error = 1.7^o, p<0.001), but not in

137   Experiment 2 (difference = 0.15^o, p = 0.79). This manipulation was not further explored here.

138   Stimuli were presented on an iMac computer screen (52 cm wide × 32.5 cm tall; 1920 × 1200

139   resolution; 60 Hz refresh rate). Subjects viewed the screen from a chin rest at a distance of 62

140   cm. Stimuli were generated and presented using the MGL toolbox (http://gru.stanford.edu)

141   running in MATLAB 2015b (MathWorks, Natick, MA, USA).

142

143   **Perceptual task**. To probe each individual's perceptual metacognitive abilities, we employed an

144   orientation estimation task with confidence ratings (16). On each trial, a target grating was

145   presented centrally for 33 ms with a randomly determined orientation between 1-180°, followed

146   shortly (600 ms) by a highly visible probe grating without noise, whose orientation could be

147   rotated via mouse movement. This short interval between the target and probe was necessary to

148   ensure that the probe had no visual masking effect. Subjects were instructed to match the

149   perceived orientation as closely as possible. Subjects pressed the spacebar to input their

150   orientation response and then used number keys 1-4 to provide a confidence rating. Because

151   performance in this task varies continuously (as opposed to a binary correct/incorrect outcome)

152   we instructed subjects to use the confidence scale to indicate how close they think they came to

153   the true orientation using the scale labels 1 = "complete guess" and 4 = "very close". These

154   perceptual task parameters were the same for both experiments. See Figure 1A for complete trial

155   timings.

156

157   **VSTM task**. To probe metacognitive abilities for VSTM, we introduced a delay period between

158   the target and the response probe. In Experiment 1, the delay period was fixed at 7 seconds and

159   in Experiment 2 it was randomly sampled from the set: 3.45, 6.30, 9.15, or 12.00 seconds. The

160   stimuli and all other task events were identical to the perceptual task in order to minimize any

161   differences between tasks that are unrelated to the cognitive manipulation of interest

162

163   **Staircase**. To minimize performance differences across subjects, both experiments began with

164   100 trials of a 1-up, 3-down adaptive staircase procedure, which classified responses as correct

165   or incorrect depending on whether they were within 25° of a trial's true orientation. This

166   procedure aimed to produce ~80% of trials with less than 25° error. The staircase began with the

167   grating component of the stimulus having a Michelson contrast of 50%, which was then

168   averaged with a 100% contrast white noise patch. The step size in grating contrast was adapted

169   according to the PEST algorithm (17), with an initial starting step size of 20% contrast.

170   Procedurally, the staircase task was identical to the perceptual task (described above). The

171   resulting mean (SEM) contrast of the grating (prior to averaging with noise) was 7.8% (0.47) for

172   Experiment 1 and 8.5% (0.61) for Experiment 2, and was held constant throughout the rest of

173   both experiments.

174

175   **Procedure**. For Experiment 1, perceptual and working memory tasks were performed in separate

176   blocks. Following the staircase, each subject completed one block of 120 trials of the perceptual

177   task, followed by three blocks of 60 trials each of the VSTM task, followed by another block of

178   the perceptual task. This resulted in a total of 240 perceptual trials and 180 VSTM trials per

179   subject, completed in a single 1.5 hour session. Experiment 2 differed in that perceptual and

180   VSTM trials were intermixed within blocks and randomly determined with equal probability to

181   be either a perceptual trial or one of the four delay periods (between 3.45 - 12 seconds) of the

182   VSTM task. Intermixing perception and VSTM trials further minimized procedural differences

183   between tasks by eliminating any task-related expecations (since subjects did not know which

184   type of trial would come next) and by removing temporal delays between task performance.

185   Each subject completed 300 trials, seperated into 5 blocks, resulting in an average (± SD) of 55.5

186   (6.4) perceptual trials and 59 (8.0) trials of each delay period of the VSTM task, after removal of

187   trials based on response times (see below). Total task time was ~1.5 hours.
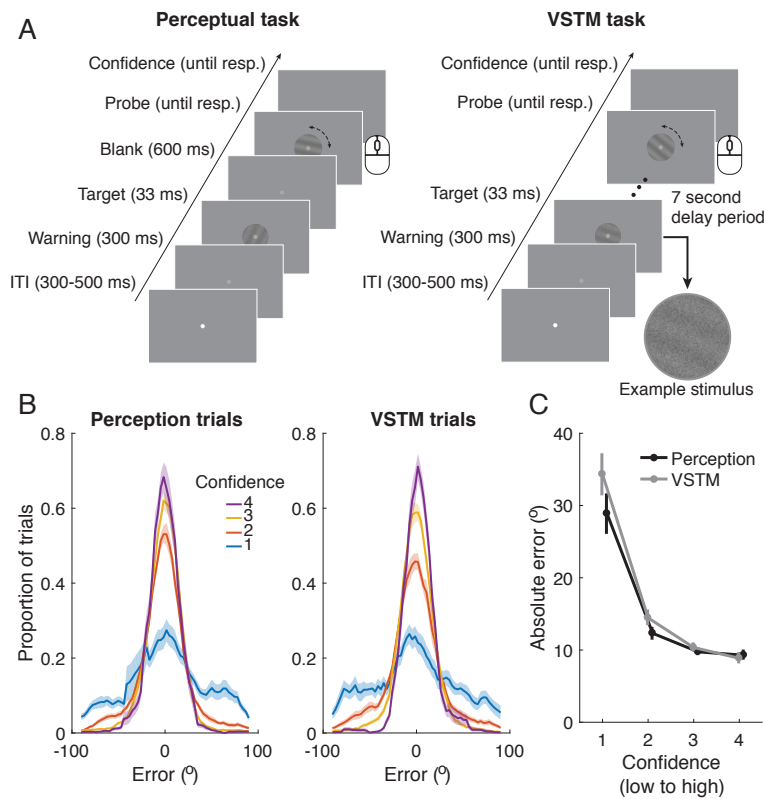
188

189   ***Figure 1.*** *Orientation estimation tasks and confidence-error relationships for Experiment 1. (A)*
190   *On each trial of the perception and VSTM task, subjects moved a computer mouse to match the*

191 *perceived or remembered orientation and then provided a confidence rating on a 1-4 scale to*

192 *indicate how close they thought they came to the true orientation where 1 = "complete guess"*

193 *and 4 = "very close". The tasks differed only by the addition of a 7 second delay period for the*

194 *VSTM task. (B) Distributions of responses relative to the true orientation (i.e., error) show a*

195 *clear scaling with confidence ratings, suggesting that subjective ratings track objective*

196 *performance at the group level. (C) Median absolute error scales with confidence and VSTM*

197 *trials produced overall greater error, indicating that representations became noisier when held*

198 *in VSTM. ITI: inter-trial interval. Shaded bands and error bars denote ± 1 SEM.*

199

200 **Quantifying metacognition**. Task performance is measured as error (in degrees) between the

201 subject's response and the true orientation on each trial (see Figure 1B). To relate this

202 continuously varying performance metric to subjective confidence ratings, we computed rank

203 correlations between each trials' absolute error and confidence rating to capture how well

204 confidence tracks performance. Error should decrease with increasing confidence so a subject

205 with good metacognition would have a stronger negative correlation between confidence and

206 error than a subject with poor metacognition. Although intuitive, and used elsewhere (18,19),

207 this metric is potentially influenced by factors not necessarily related to metacognitive accuracy

208 per se, such as task difficulty and biases in confidence scale use (e.g., under or overconfidence;

209 (2)). Although we used a staircase procedure to match difficulty, there was still considerable

210 variability across subjects in median absolute error in both Experiment 1 (range: 8 - 16.5$^{\text{o}}$) and

211 Experiment 2 (range: 6.9 – 23.3$^{\text{o}}$). A recently introduced measure called meta-d'/d' can correct

212 for these influences (20), however, meta-d'/d' has been developed only for tasks with discreet

213 outcomes amenable to signal detection theory analysis (e.g., hits, misses) and cannot be applied

214 to the continuous estimations tasks we employed in Experiments 1 and 2 (but see Experiment 3).

215 In order to control for these influences when testing our primary hypothesis about the

216 relationship between perceptual and VSTM metacognition, we ran two additional multiple

217 regression models that included covariates for average and task-specific error and confidence

218   (see *Statistics* below). In the case of models with multiple predictors, the relationship between

219   perceptual and memory metacognition was visualized (Figure 2 and 4) using added variable plots

220   (MATLAB function *plotAdded.m*), which use the Frisch–Waugh–Lovell theorem to partial out

221   the effects of other predictors in the model, revealing the effect of a single predictor while all

222   other predictors are held constant. Predictor R^2 for these models was computed as the sum of

223   squares for the perceptual metacognition predictor divided by the total sum of squares for all

224   other predictors and error.

225

226   Additionally, we verified that the results of this analysis were robust to our particular metric of

227   metacognition by repeating all analyses using the non-parametric area under the type 2 receiver

228   operating characteristics curve (A_{ROC}; (21–23) as our measure of metacognitive accuracy. This

229   measure is obtained by taking the area under the curve formed by plotting the type 2 false alarm

230   rate by the type 2 hit rate at different type 2 criteria. A type 2 false alarm is an incorrect but high

231   confidence trial and type 2 hit is a correct and high confidence trial and the number of

232   confidence criteria is the number of ratings on the scale minus 1. At values of 0.5, this metric

233   indicates that confidence ratings do not discriminate between correct and incorrect trials and

234   values of 1 indicate perfect discriminability. A_{ROC} was computed using the method outlined in

235   (21). Because this metric requires binarizing the data into correct and incorrect responses, we

236   defined thresholds for each subject based on the 75th percentile of their response error

237   distributions such that a trial with error larger than this threshold was considered incorrect. This

238   analytically set performance at 75% for each subject, equating accuracy for this analysis. Using a

239   common threshold of 25° for each subject did not change the statistical significance of any

240   analyses reported with this metric. Prior to any analysis, trials with response times below 200

10

241   milliseconds or above the 95th percentile of the distribution of response times across all subjects

242   were excluded. The same trial exclusion procedure was applied to both experiments.

243

244   **Statistics**. We used linear regression to predict individual differences in VSTM metacognition

245   from variation in perceptual metacognition scores (Figures 2 and 4). In a first, "basic model", we

246   considered only these two variables. Then, to control for individual differences in task

247   performance and confidence ratings, we ran two additional regression models. One included each

248   subject's mean error and mean confidence as covariates (3 predictors in total) and the other

249   included task-specific confidence and error as covariates (i.e., mean perceptual error and

250   confidence and mean VSTM error and confidence; 5 predictors in total). These three models

251   were run for each metric of metacognition (r values and A_{ROC}; see above) and for both

252   experiments. To test for linear effects of confidence on error (Figures 1C and 3D) we regressed

253   single-trial confidence ratings on absolute error for each subject and task and tested the resulting

254   slopes against zero at the group level using a t-test. To test for performance differences between

255   tasks we compared median absolute error between the perception and VSTM task with a paired

256   t-test. We additionally tested for a linear effect of delay period duration in Experiment 2 (Figure

257   3B) by fitting slopes to each subject's single-trial absolute error by delay period data and testing

258   these slopes against zero at the group level with a t-test. All tests were two-tailed.

259

260   **Experiment 3**. This experiment was conducted to test whether the correlation between

261   perceptual and VSTM metacognition depended on both tasks sharing the same task-relevant

262   stimulus feature (e.g. orientation). To this end, we compared metacognition in an orientation

263   perception task and a contrast perception task (Figure 5A) to metacognition in an orientation

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264   VSTM task. If the perception of and short-term memory for orientation depend on overlapping

265   representations (13,14), then individual differences in metacognition may be correlated between

266   orientation perception and orientation VSTM, but not between contrast perception and

267   orientation VSTM. Furthermore, we used 2-choice discrimination tasks in Experiment 3 which

268   are amenable to a recently developed Bayesian hierarchical model-based analysis of

269   metacognition that controls for individual differences in task performance and confidence biases

270   while appropriately accounting for variability in individual-subject parameter estimates at the

271   group level (24).

272

273   **Participants.** Twenty subjects (mean age = 21.8 years, *SD* = 3.18, 13 female) from the

274   University of Wisconsin-Madison community participated in these experiments in exchange for

275   monetary compensation.

276

277   **Stimuli.** Sinusoidal luminance gratings subtending 2 DVA were centered 1.5 DVA to the right

278   and/or left of fixation (Figure 5A). As in Experiments 1 and 2, the gratings were averaged with

279   white noise. The contrast of the grating and the noise components were adjusted for each subject

280   using a staircase procedure (see below). Stimuli were presented on an iMac computer screen (52

281   cm wide × 32.5 cm tall; 1920 × 1200 resolution; 60 Hz refresh rate) and viewed by subjects from

282   a chin rest 62 cm away. Stimuli were generated and presented using the MGL toolbox

283   (http://gru.stanford.edu) running in MATLAB 2015b (MathWorks, Natick, MA, USA).

284

285   **Contrast perception task.** Subjects were instructed to indicate whether the left or right stimulus

286   contained a higher contrast grating using the left and right arrow keys, respectively. Subjects

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287   then indicated their confidence using number keys 1-4, where 1 denotes a "complete guess" and

288   4 denotes "very confident". Subjects were encouraged to use the full range of the scale and were

289   instructed to understand a number 4 rating as indicating the highest confidence they would feel

290   in this task, given the difficult nature of the task. This confidence rating procedure was the same

291   for all three tasks in this experiment. A target and a standard stimulus were presented

292   simultaneously to the left and right of fixation for 50 ms. The location containing the target was

293   randomly determined on each trial. Each stimulus also had a randomly and independently

294   determined orientation that was task irrelevant. Responses could be made as soon as the stimuli

295   were presented and there was no time limit for responding. The standard stimulus was created by

296   averaging a 10% Michelson contrast grating with an 80% contrast noise patch and the contrast of

297   the target grating was adapted for each subject with a staircase procedure (see below).

298

299   **Orientation perception task.** This task required subjects to indicate whether the two gratings

300   had the same or different orientation. Both stimuli appeared simultaneously for 50 ms and then

301   subjects indicated their choice followed by their confidence. On "same" trials, both stimuli had

302   an identical orientation, which was randomly determined on each trial (between 1 and 180°),

303   whereas on "different" trials one stimulus was offset by 25° clockwise or counter-clockwise

304   (randomly determined). Whether a trial was same or different was randomly determined.

305   Difficulty was controlled by a staircase procedure that adapted the contrast of both stimuli.

306

307   **Orientation VSTM task.** This task also required that subjects indicate whether two gratings

308   were the same or different, but here there was a temporal delay of 3 seconds between the first

309   and second stimulus. Thus, the orientation of the first stimulus must be maintained over the delay

310   in order to perform the task. Each grating was presented for 50 ms and subjects provided their

311   choice and confidence, with no time pressure, following the second "probe" stimulus. As in the

312   orientation perception task, both stimuli had an identical randomly determined orientation on

313   same trials, and a difference in orientation of 25° (clockwise or counter-clockwise) on different

314   trials. Trial type was randomly determined as was the location (left or right of fixation) of both

315   stimuli, although the location of both stimuli was always the same for any given trial.

316

317   **Staircase.** Each task began with 60 trials of a 1-up, 3-down staircase procedure, aimed to

318   converge on ~80% accuracy. During these 60 trials, stimulus contrast was adjusted according to

319   the PEST algorithm (17), with a starting step size of 8% contrast for all task. For the contrast

320   perception task, the staircase adapted the contrast of the grating component of the target and

321   modulated the contrast of the noise component of the target in the opposite direction so that the

322   overall stimulus contrast always matched the standard (see Figure 5A *left*). For example, if the

323   contrast of the grating component of the target was +12% relative to the grating component of

324   the standard then the noise component of the target was reduced by 12%, thereby matching total

325   stimulus contrast between the target and standard, but producing higher contrast in just the

326   grating component of the target. Starting contrast of the target grating was +20% relative to the

327   standard. For the orientation perception and VSTM tasks the starting contrast of the grating

328   component of each stimulus was 30%, which was averaged with 80% contrast noise. After these

329   initial PEST trials, a threshold was computed as the mean contrast from the last 4 staircase

330   reversals. The staircase continued throughout the duration of each task but with a fixed step size

331   of 0.5% for the contrast task and 0.25% for the orientation tasks, with the starting threshold

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332   determined from the initial PEST staircase in the case of the first block of each task, or from the

333   mean of the last 4 reversals from the most recent block.

334

335   **Procedure**. Each subject completed 3 blocks of 100 trials each for each of the three tasks,

336   resulting in 300 trials per task (with the exception of one subject who only completed 100 trials

337   of the contrast perception task). Blocks of the same task were completed sequentially and task

338   order was randomized. Prior to the start of each new task, subjects completed 60 trials of the

339   initial PEST staircase corresponding to that task. These 60 trials were not included in any

340   analysis. Total task time was ~1.5 hours.

341

342   **Model-based analysis of metacognition**. Because Experiment 3 employed 2-choice

343   discrimination tasks we quantified metacognition in a bias-free signal detection theory model

344   (20,24). We used an estimate of metacognitive efficiency (M-ratio) that quantifies the extent to

345   which confidence ratings discriminate between correct and incorrect decisions (i.e., type 2

346   performance), given the underlying difficulty of the discrimination itself (i.e., type 1

347   performance), thereby optimally controlling for task difficulty and confidence biases (2). M-ratio

348   is the ratio between the d' estimated from the confidence data according to a metacognitively

349   ideal observer and the actual d' computed from task performance. Because both metrics are in

350   the same units, M-ratio will approach 1 if all the information used for the type 1 decision was

351   also available to the type 2 decision, indicating optimal metacognition. Values below 1 reflect

352   suboptimal metacognition.

353

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354   We used a recently introduced hierarchical modeling approach to estimate the cross-task

355   correlation between individual differences in M-ratio, as is implemented in the freely available

356   toolbox HMeta-d (24, https://github.com/smfleming/HMM) for MATLAB. This toolbox is a

357   hierarchical Bayesian extension of Maniscalco and Lau's (20) meta-d' model. The advantage of

358   a Bayesian model in this context is that the estimation of group-level parameters of interest (i.e.,

359   M-ratio correlation coefficient across tasks) takes into account parameter uncertainty at the

360   single subject level. This means that a subject whose M-ratio is estimated with high uncertainty

361   will contribute less to the group-level parameter estimate than a subject whose M-ratio is

362   estimated more precisely. In typical maximum likelihood or sum of squares fitting (20), this

363   knowledge of parameter uncertainly is discarded. Simulations suggest this approach produces

364   more accurate parameter recovery and lower false positive rates than non-Bayesian alternatives

365   (24). Cross-task M-ratio correlations were estimated using the HMeta-d function

366   *fit_meta_d_mcmc_groupCorr.m.*

367

368   Posterior distributions of parameters were sampled using Markov-Chain Monte-Carlo methods

369   (MCMC) implemented in JAGS (http://mcmc-jags.sourceforge.net). We ran 3 chains of 20,000

370   samples each with 5,000 burn-in samples. Each subject's log(M-ratio) for each domain are

371   specified as draws from a bivariate Gaussian. We used a weakly informative normal prior on

372   log(M-Ratio) which encompasses estimates from 167 previous subjects (24), and a uniform prior

373   between -1 and 1 for the correlation coefficient. To assess convergence we ensured that all

374   MCMC chains were well mixed and that the Gelman and Rubins $\hat{R}$ convergence statistics were

375   between 1 and 1.1. Statistical significance for each correlation was assessed by computing the

376   proportion of MCMC samples that fell below zero, multiplied by 2 (akin to a two-tailed non-

377   parametric frequentist test) and by computing 95% high-density intervals (HDI) on the

378   correlation posterior distributions.

379

380   **Results**

381   **Experiment 1.** Distributions of response error as a function of confidence are shown in Figure

382   1B. Absolute error significantly decreased with increasing confidence for both the perceptual

383   task (t(19) = -13.48, p < 0.0001) and the VSTM task (t(19) = -14.88, p < 0.0001), indicating that

384   subject's confidence reasonably reflected their task performance at the group level (Figure 1C).

385   Error was also significantly greater in the VSTM task as compared to the perceptual task (t(19) =

386   -2.10, p = 0.049), reflecting an expected degradation of orientation information when the task

387   required short-term memory maintenance. Confidence ratings were distributed similarly for

388   perception and VSTM tasks (Supplementary Figure 1), and average confidence ratings did not

389   significantly differ between tasks (p = 0.15). See Supplementary Figure 2 for a breakdown of

390   accuracy and response time by block.

391

392   Central to our hypothesis, we found a positive relationship across individuals between perceptual

393   metacognition and VSTM metacognition (Figure 2). This relationship was observed when using

394   confidence-error correlations as the measure of metacognition (slope = 0.51, t = 2.63, predictor

395   R^2 = 0.28, p = 0.016; Figure 2A) and, importantly, was still present after controlling for average

396   confidence and error (slope = 0.54, t = 2.55, predictor R^2 = 0.28, p = 0.021) and in the model

397   controlling for task-specific confidence and error (slope = 0.62, t = 2.66, predictor R^2 = 0.29, p =

398   0.018). All covariate predictors in both control models were not statistically significant (ps >

399   0.30). These results indicate that, although the confidence-error correlation may be influenced by

400   task performance and confidence biases, these factors did not account for the across-subjects

401   correlation between perceptual and VSTM metacognition.
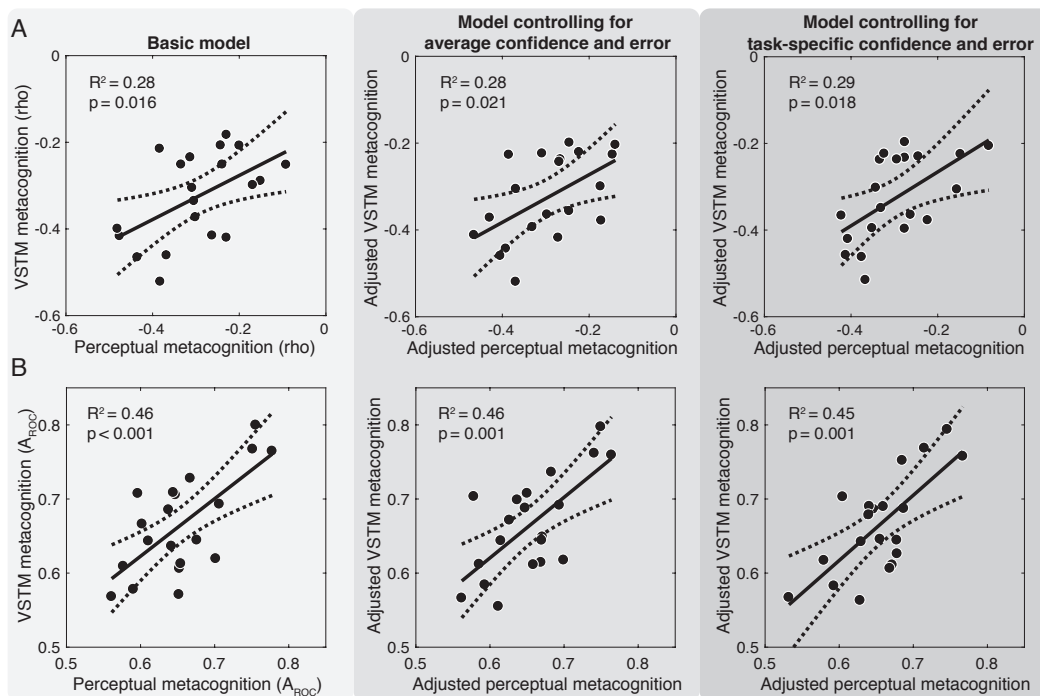
Figure 2. *Positive relationship between perceptual and VSTM metacognition in Experiment 1.*
(A) Cross-task regression using confidence-error correlations as the metric of metacognition.
Increasingly complex regression models controlling for task performance and confidence shown
from left to right (see Methods). (B) Same models as in A, but using the area under the type 2
ROC curve (A_{ROC}) as a measure of metacognitive performance. Dashed lines denoted 95%
confidence intervals on the linear fit. Black points are individual subjects.

410   The same relationship was observed when using A_{ROC} as the metric of metacognition (Figure

411   2B). With the basic model, perceptual metacognition significantly predicted VSTM

412   metacognition (slope = 0.77, t = 3.96, predictor R^2 = 0.46, p = 0.0009). This relationship held

413   when controlling for average confidence and error (slope = 0.82, t = 3.78, predictor R^2 = 0.46, p

414   = 0.0016) and when controlling for task-specific confidence and error (slope = 0.88, t = 3.85,

415   predictor R^2 = 0.45, p = 0.0017). As before, all other covariate predictors across both control

416   models were non-significant (ps > 0.26). We examined the correlation between all predictor

417 variables in all of our models (Table 1) and found that there was collinearity between several,

418 quite expected, covariate predictors (e.g., average confidence predicted average error, perceptual

419 confidence predicted VSTM confidence). Importantly, however, there were no significant

420 correlations between our predictors of interest (both perceptual metacognitive scores, A_{ROC} or

421 rho) and any other covariate predictors, indicating that task performance and confidence are

422 unlikely to be driving the cross-task correlation in metacognition. These results indicate that the

423 relationship observed between perceptual and VSTM metacognition was independent of the

424 particular metric used and was not accounted for by correlated individual differences in task

425 performance or average confidence.

Predictor – Exp. 1, *Exp. 2*	1	2	3	4	5	6	7	8
1. Perceptual metacognition (rho)	-	-0.13	-0.03	-0.16	-0.04	-0.10	-0.01	X
2. Average confidence	0.33	-	-0.41	X	X	X	X	0.15
3. Average error	0.01	**-0.54***	-	X	X	X	X	0.01
4. VSTM confidence (average)	0.33	X	X	-	-0.42	**0.95***	-0.38	0.17
5. VSTM error (average)	0.08	X	X	**-0.54***	-	-0.42	**0.91***	-0.01
6. Perceptual confidence (average)	0.32	X	X	**0.94***	**-0.44***	-	-0.38	0.13
7. Perceptual error (average)	-0.05	X	X	**-0.53***	**0.83***	**-0.53***	-	0.03
8. Perceptual metacognition (A_{ROC})	X	-0.29	0.07	-0.28	0.01	-0.14	-0.29	-

426

427 **Table 1.** *Correlation matrix for every predictor in each model in Experiment 1 and Experiment 2*
428 *(gray regions). X's denote predictor combinations that were not used in any model. Significant*
429 *correlations (p<0.05) are noted in bold and with asterisks.*
430

431 **Experiment 2.** This experiment served to replicate the cross-task correlation observed in

432 Experiment 1 while further minimizing procedural differences between tasks by intermixing

433 perceptual and VSTM trials of differing delays (Figure 3A). Error increased monotonically with

434 delay duration ($t(19) = 2.85$, p = 0.010. Figure 3B), and perception trials had lower error than

435 VSTM trials, collapsing across delays ($t(19) = 3.33$, p = 0.003), indicating the expected loss of

436 information in VSTM relative to perception. As in Experiment 1, error decreased with increasing

437 confidence during both perception ($t(19) = -7.56$, p < 0.0001) and VSTM trials ($t(19) = -8.99$, p

19

438   < 0.0001), indicating that confidence reliably tracked performance at the group level (Figure 3C

439   & 3D). Average confidence was lower on VSTM (mean = 2.59, SEM = 0.133) than on

440   perception trials (mean = 2.71, SEM = 0.132; $t(19) = 2.97$, p = 0.0077; Supplementary Figure 1).

441

442
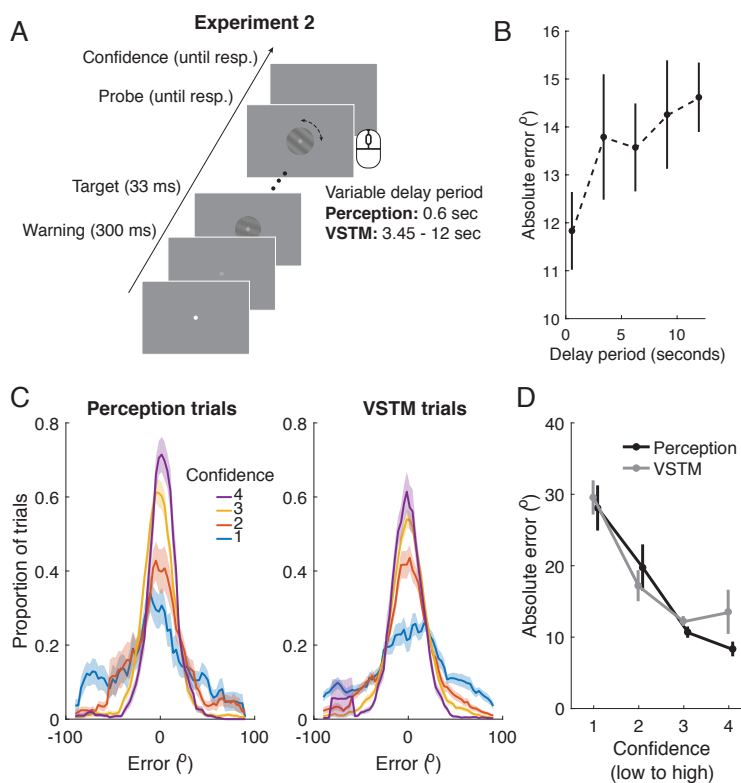
Figure 3. *Task and behavior for Experiment 2. (A) Perceptual trials (delay 0.6 seconds) and VSTM trials (delay between 3.45 and 12 seconds) were intermixed within blocks. (B) Error increased with increasing delay length, indicating a loss of information when the orientation needed to be maintained in VSTM. (C) Response error distributions show a clear scaling with confidence. (D) Error decreased as confidence increased in both perceptual and VSTM trials. Shaded bands and error bars indicate ± 1 SEM.*

449
450   Importantly, we replicated the positive relationship between perceptual and VSTM

451   metacognition with quantitatively better model fits in a new set of subjects. Using confidence-

452   error correlations (Figure 4A) perceptual metacognition robustly predicted VSTM metacognition

453   in the one-predictor basic model (slope = 0.60, t = 5.21 predictor R^2 = 0.60, p < 0.0001), the

454   three-predictor model controlling for average confidence and error (slope = 0.60, t = 4.91,

20

455   predictor $R^2 = 0.59$, p = 0.0001), and in the five-predictor model controlling for task-specific

456   confidence and error (slope = 0.59, t = 4.44, predictor $R^2 = 0.58$, p = 0.0005. All covariate

457   predictors in both control models were non-significant (ps > 0.64). As in Experiment 1, some

458   covariate predictors were significantly correlated (Table 1; gray region), but no covariates were

459   significantly correlated with perceptual metacognition, the predictor of interest. This effect was

460   also observed when using A_{ROC} as the metric of metacognition for the basic model (slope = 0.53,

461   t = 3.88, predictor $R^2 = 0.45$, p = 0.0011), the three-predictor model (slope = 0.52, t = 3.58,

462   predictor $R^2 = 0.44$, p = 0.002), and the five-predictor model (slope = 0.54, t = 3.43, predictor R^2

463   = 0.44, p = 0.004). All covariates in both control models were non-significant (ps > 0.52).

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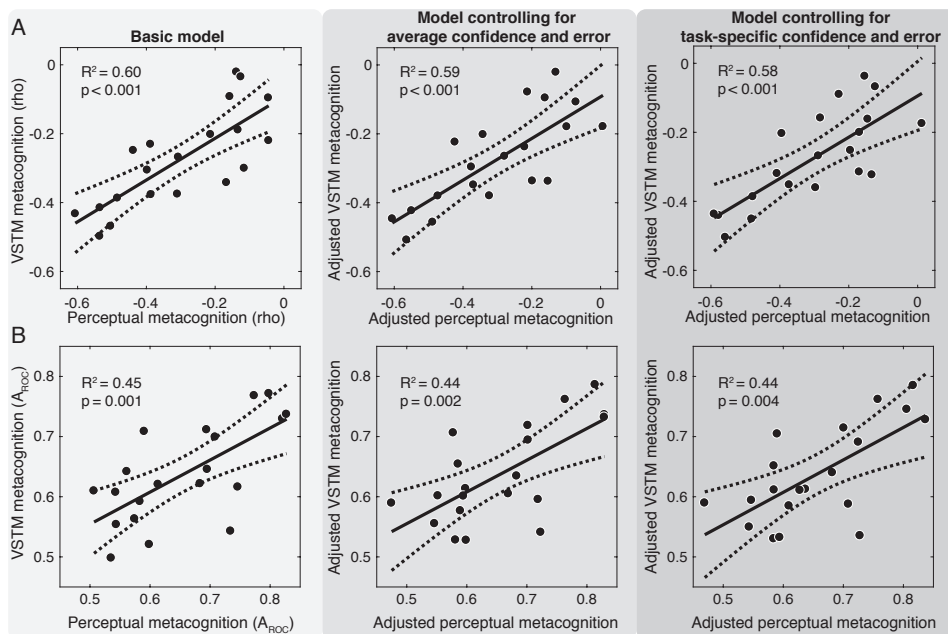
Figure 4. *Replication of the positive relationship between perceptual and VSTM metacognition in Experiment 2. (A) Same regression models as in Figure 2, indicating the cross-task relationship using confidence-error correlations as the metric of metacognition. (B) Same as in A, but with A_{ROC} as the metric of metacognition. Dashed lines denoted 95% confidence intervals on the linear fit.*

21

472   **Experiment 3.** This experiment was conducted to test whether correlated individual differences

473   in metacognition depended on the perception and VSTM tasks sharing the same task-relevant

474   stimulus feature (i.e., orientation). Task accuracy (% correct) and metacognitive efficiency (M-

475   ratio) for each task and subject are shown in Figure 5B. Accuracy was comparable between the

476   contrast perception task (mean = 78.6%, SEM = 0.012) an the orientation perception task (mean

477   = 80.4 %, SEM = 0.009; p = 0.33), as well as between the contrast perception task and the

478   orientation VSTM task (mean = 76.5%, SEM = 0.018%, p = 0.39), but differed significantly

479   between the orientation perception and the orientation VSTM tasks ($t(19) = 2.68$, p = 0.015).

480   This is party because four subjects reached the maximum contrast allowable by the staircase

481   (25%), so the VSTM task never got easier for them. In general, higher target contrasts were

482   needed in the VSTM task (mean = 15.5%, SEM = 0.012) compared to both the orientation

483   perception task (mean = 8.5%, SEM = 0.005; $t(19) = 6.50$, p < 0.0001), and the contrast

484   perception task (mean = 6.2%, SEM = 0.005; $t(19) = 6.49$, p < 0.0001), indicating that more

485   signal was needed in the VSTM task to achieve threshold performance. Metacognitive

486   efficiency, on the other hand, did not significantly differ between tasks (ps > 0.16; see

487   Supplementary Figure 3 for full posterior distributions of M-ratio for each task, and comparisons

488   between tasks), and was well below the optimal M-ratio of 1 for all tasks (contrast perception:

489   mean M-ratio = 0.4, HDI = [0.27, 0.54], orientation perception: mean = 0.44, HDI = [0.30, 0.59],

490   orientation VSTM: mean = 0.53, HDI = [0.38, 0.68]). Mean confidence (see Supplementary

491   Figure 1) also did not differ between either of the perceptual tasks and the VSTM task (ps >

492   0.08), but was significantly lower in the contrast perception task as compared to the orientation

493   perception task ($t(19) = 3.06$, p = 0.006).

494

495   To our primary question of correlated individual differences in metacognition, we observed a

496   large positive correlation between metacognitive efficiency in the orientation perception task and

497   orientation VSTM task (Figure 5C; rho = 0.90, HDI = [0.58 0.99], p < 0.0001), consistent with

498   the results of Experiments 1 and 2. However, we did not observe a significant correlation

499   between metacognition in the contrast perception task and the orientation VSTM task (rho =

500   0.32, HDI = [-0.32 0.85], p = 0.32), suggesting that the correlation between perception and

501   VSTM metacognition depends on both tasks sharing the same task-relevant stimulus feature.

502   Interestingly, metacognition was also not correlated between the two perceptual tasks (rho =

503   0.24, HDI = [-0.35 0.76], p = 042), again underscoring the importance of the similarity of

504   stimulus feature used. We also computed the difference between these correlation distributions

505   and found that the correlation between orientation perception and orientation VSTM memory

506   was significantly larger than the correlation between contrast perception and orientation

507   perception (HDI = [0.07 1.27], p = 0.027) and trending larger than the correlation between

508   contrast perception and orientation VSTM (HDI = [-0.03 1.24], p = 0.063).

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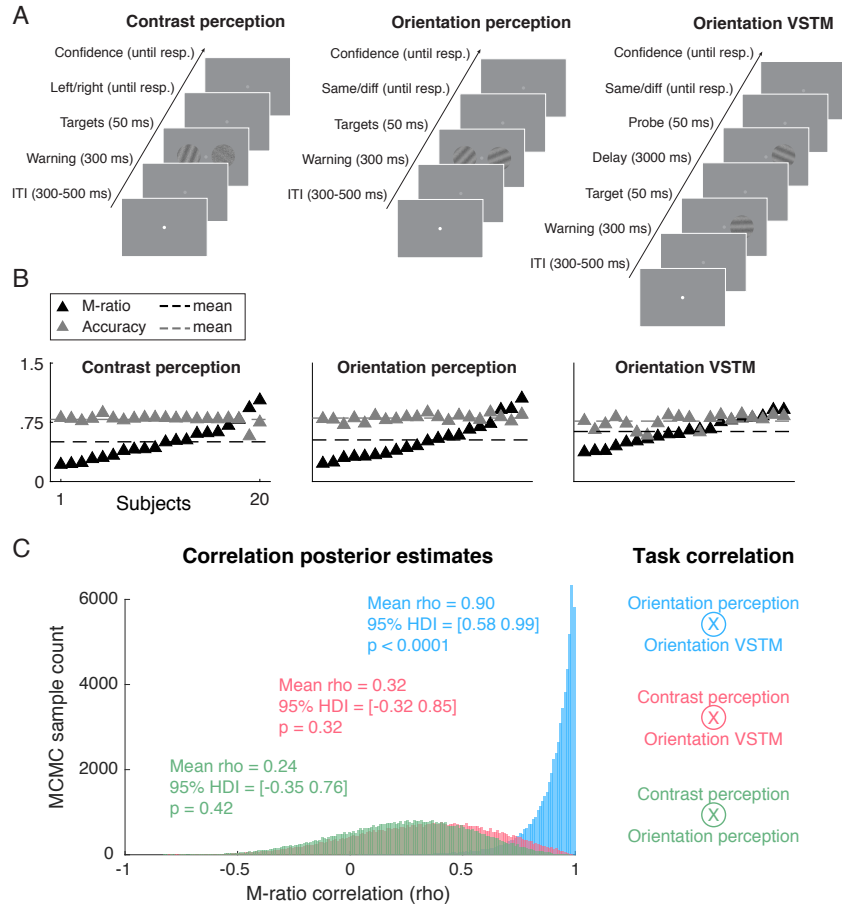
Figure 5. Tasks, behavior, and metacognitive correlations from Experiment 3. (A) To compare metacognition across discrimination tasks while varying task and the task-relevant stimulus feature, subjects performed 1) a contrast perception task, judging which stimulus contained a higher contrast grating, 2) an orientation perception task, judging whether the two stimuli had the same orientation, and 3) an orientation VSTM task, judging whether a memorized target grating had the same orientation as a probe grating that appeared 3 seconds later. (B) Individual subject accuracies (proportion correct) and estimates of metacognitive efficiency (M-ratio) for each task. Note that because M-ratio for each subject is estimated in the same model, estimates are not fully independent (24). (C) Posterior distributions of cross-task correlations in metacognitive efficiency, which reveal a strong positive correlation between orientation perception and orientation VSTM metacognition, but not between other tasks.

Discussion

Metacognition is an important aspect of decision-making (25,26), learning (27), development (28), and perhaps certain aspects of conscious experience (29,30), and can be compromised in psychiatric disorders (31–33). It is currently unclear whether an individual with good

24

526 metacognitive ability in one domain also has good metacognition in other domains. In

527 Experiment 1, we found that individuals with more accurate metacognition in perceptual

528 judgments also showed more accurate metacognition in a VSTM task requiring stimulus

529 maintenance over a 7 second delay period. This relationship was present when using two

530 different measures of metacognitive performance and regression models controlling for task

531 performance and mean confidence revealed that this effect was not driven by correlated

532 individual differences in task performance or confidence biases. We then replicated these

533 findings in Experiment 2 with a new set of subjects using a task that intermixed perceptual and

534 VSTM trial types within blocks. Intermixing trial types in Experiment 2 more than doubled the

535 proportion of variance in VSTM metacognition explained by perceptual metacognition in the

536 models using error-confidence correlations relative to Experiment 1 when trial types were

537 blocked (mean increase in $R^2 = 0.30$, a factor of ~2.2), highlighting the importance of

538 minimizing procedural differences between tasks. A comparable increase across experiments

539 was not seen, however, when using the AUC metric, which already showed a very large effect

540 size in both experiments and across all models (mean $R^2 = 0.45$, Cohen's $d = 1.81$). In

541 Experiment 3 we compared an orientation VSTM task to an orientation perceptual task and a

542 contrast perception task. We again found a large positive correlation ($R^2 = 0.81$) between

543 metacognition in the orientation VSTM and orientation perception task, but not between the

544 orientation VSTM and contrast perception task, nor between contrast perception and orientation

545 perception tasks, highlighting the importance of both tasks sharing the same relevant stimulus

546 feature. Importantly, given known biases in VSTM metacognitive judgments (34), metacognition

547 in Experiment 3 was quantified within a signal detection theory model (20,24) that controls for

548 confidence biases and task performance. Taken together, these results provide the first evidence

25

549   in humans for a medium-to-high positive correlation between an individual's metacognitive

550   abilities in perception and VSTM, when both domains share a common stimulus feature.

551

552   The present results contrast with recent experiments examining the relationship between

553   metacognition of visual perception and long-term memory, which have typically observed no

554   correlation (4–6; but see 7). We reason that, in contrast to long-term memory, VSTM for a given

555   stimulus feature is thought to rely on the same neural representations that support perception of

556   that stimulus feature (11–14), and this may underlie the cross-task correlation in metacognitive

557   performance. This explanation follows naturally from "first-order" models of metacognition

558   according to which confidence and task performance are driven by the same internal

559   representation of stimulus evidence (35–38). For example, in signal detection theoretic models,

560   the absolute distance of the decision variable from the decision criterion is a proxy for

561   confidence (39,40). Thus, if perception and VSTM were supported by the same internal

562   representation of the stimulus, then the computation of confidence across the two tasks would

563   also be based on the same representations, leading to correlated behavior. "Second-order"

564   models of metacognition, in contrast, posit an architecture with a secondary confidence read-out

565   process, which may be influenced by additional sources of noise (41) or other signals not directly

566   related to the stimulus, such as action-related states (42,43), cortical excitability (44), or arousal

567   (45,46).

568

569   The results of Experiments 1 and 2 are also compatible with second-order models of

570   metacognition, although several possible relationships between first- and second-order processes

571   could explain our findings. Shared first-order (sensory) representations across tasks might be

26

572   enough to produce a behavioral correlation despite separate second-order readout mechanisms.

573   Alternatively, both first- and second-order processes may be shared across tasks, or only the

574   second-order process shared, though this latter possibility is unlikely given existing neural

575   evidence for shared representations in visual regions across perception and VSTM (14,47,48).

576   The results of Experiment 3, however, provide support for 1st-order models because they suggest

577   that shared sensory representations underlie the cross-task correlation in metacognition. Because

578   metacognition was not reliably correlated when tasks differed in their relevant stimulus feature,

579   even when both tasks were perceptual, this points towards a first-order model of metacognition.

580   Yet another alternative is that the correlation was dependent on the task structure, for example,

581   because both orientation tasks involved same/different judgments. This account may also explain

582   why a previous report comparing metacognition for contrast and orientation judgments in the

583   context of a visual search paradigm did find correlated individual differences (8), but recent

584   work comparing a variety of perceptual paradigms with different task structures and stimuli did

585   not find a correlation (49).

586

587   Although the present findings are consistent with a domain-general model of metacognition for

588   perception and VSTM, correlations at the behavioral level raise further questions about what

589   specific aspects of metacognitive processing are shared. For example if one's ability to learn

590   stable confidence criteria over time improves metacognitive accuracy (38), then metacognitive

591   abilities may be high across domains for an individual with superior learning abilities, perhaps

592   related to recent work implicating hippocampal myelination in perceptual metacognition (50).

593   However, this need not imply that the underlying neural substrate responsible for computing the

594   appropriate levels of confidence is itself domain-general. Similarly, recent work has highlighted

595   specific factors beyond stimulus evidence that modulate confidence, leading to dissociations of

596   confidence and task performance within an individual (15,51,52). For example, spontaneous

597   trial-to-trial fluctuations in oscillatory neural activity in the alpha-band (8-13 Hz), which are

598   thought to reflect visual cortical excitability (53,54), have been shown to bias confidence ratings,

599   but not objective performance in a visual discrimination task (44). Perhaps a subject who is less

600   susceptible to such influences from sources not directly related to the difficulty of stimulus

601   discrimination would show better metacognition across different domains. Future work

602   examining neural correlates of metacognitive performance across different domains may

603   contribute in a substantive way to this issue. As an example, McCurdy and colleagues (7)

604   observed a positive correlation between metacognition of perception and recollection memory at

605   the behavioral level, but found distinct (as well as overlapping) neural structures whose gray

606   matter volume related to metacognitive performance in the different tasks. This suggests that

607   only a portion of the processing stages or computations involved in generating confidence need

608   be shared across tasks in order to produce a behavioral correlation. Nevertheless, the experiments

609   reported here provide an important first step for future work by demonstrating a clear correlation

610   between metacognitive behavior in perception and VSTM.

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