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# Investigating Confidence Judgments using Reviews in Human and Monkeys

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**Author Contributions:** FMS and EP designed research; FMS performed research and analysed data; FMS and EP wrote the paper.

**Abbreviated title:** Confidence judgments in Human and monkeys

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38                   **Abstract**

39                   Confidence judgments are self-assessments of the quality of one's own performance,  
40 and are a crucial aspect of metacognitive abilities. The underlying neurobiological mechanisms  
41 are poorly understood. One approach to understanding these mechanisms would be to take  
42 advantage of putative metacognitive abilities in non-human models. However, many  
43 discrepancies exist between human and non-human studies on metacognition due to the mode  
44 of reporting judgements. We here present an attempt to directly compare human and non-  
45 human primates' metacognitive abilities using a protocol assessing confidence judgments. After  
46 performing a categorization test, subjects could either validate their choice or review the test.  
47 We could assess whether subjects detected their errors and how they corrected them according  
48 to their confidence, and importantly did so in both human and non-human primates. 14 humans  
49 and 2 macaque monkeys were tested. Humans showed a well-adapted use of the review option  
50 by reviewing more after incorrect choices or difficult stimuli. Non-human primates did not  
51 demonstrate a convincing use of the review or validate opportunity. In both species, reviewing  
52 did not improve performance. This study shows that decisions to review under uncertainty are  
53 not naturally beneficial to performance and is rather perturbed by biases and alternative low-  
54 cognitive cost strategies.

55

56                   **Introduction**

57                   After a decision, and before receiving any feedback, we may feel more or less confident  
58 that it was the correct one. For example, being confident you locked your car you will continue  
59 shopping, but if you are unsure, you will probably go back and check. Subjective confidence is  
60 one core aspect of metacognitive abilities, which represent higher order mental processes by  
61 which we monitor and control our own cognition<sup>1</sup>. In Humans, subjective confidence has  
62 generally been studied using prospective or retrospective questionnaires, requiring explicit  
63 verbal reports (e.g. confidence ratings<sup>2,3</sup>). Subjects are fairly good at judging their accuracy in  
64 both perceptual or mnemonic tasks<sup>4</sup>. Both prospective and retrospective confidence ratings  
65 appear to be highly correlated with one's own performance, even if humans appear generally  
66 overconfident that their choice was/will be correct. Many theories have been proposed to  
67 explain how confidence judgments predict accuracy, but they do not account for the wide range  
68 of behavioural observations<sup>5</sup>. Nevertheless, an influential proposition is that people rely on  
69 inference to judge their performance, by accessing important features such as familiarity or  
70 difficulty with the test<sup>6,7</sup>.

71 To study confidence in non-human animals, researchers have adopted a broader view  
72 than for human studies, and explored a wider range of behaviour that might elicit metacognitive  
73 processes. Initial demonstration of animal metacognitive abilities involved “uncertain response”  
74 protocols, in which difficult tests could be avoided by the use of an alternative non-directed  
75 option. This option can be seen as a “choice to not choose”, and in theory it should be elicited  
76 by higher uncertainty about the outcome of the main choice<sup>8,9</sup>. Species including monkeys or  
77 dolphins efficiently used this option, although doubts have been raised concerning the  
78 involvement of metacognition in making such decisions<sup>10</sup>. Other studies attempted to  
79 approximate human protocols by assessing confidence judgment using a betting procedure<sup>11</sup>. In  
80 these tasks, monkeys were primarily asked to perform a perceptual test. After each trial they  
81 were then required to rate their confidence by ‘betting on their success’ (validating their choice)  
82 or alternatively by using a safe option. Monkeys correctly took the opportunity to bet, by betting  
83 more when correct<sup>11,12</sup>. Finally, a large body of work has focused on information-seeking  
84 behaviour as a mean of understanding metacognitive abilities in non-human animals<sup>13,14</sup>. This  
85 approach appeared more justified from an ecological point of view, as metacognition might  
86 enable animals to search for or verify information to improve their decisions. Such behaviour is  
87 thought to reflect higher cognitive processing. This is supported by studies highlighting that an  
88 animal will search for information when ignorant or uncertain about what to do<sup>12–16</sup>. Taken  
89 together, these studies show that information-seeking is targeted, ordered and optional,  
90 suggesting that such a search derives from metacognitive processes.

91 However, although information-seeking protocols have provided meaningful behavioural  
92 insight concerning putative non-human metacognitive abilities, they often appear inappropriate  
93 from a psychophysical or neurophysiological perspective, and are frequently criticised for poor  
94 control over experimental conditions. Notably, it has been suggested that simpler heuristics  
95 could be used to solve these tasks, questioning the need to rely on metacognition in such  
96 information-seeking paradigms<sup>17</sup>. Also, available paradigms did not assess an important feature  
97 of metacognition, which goes beyond simply validating or not a response based on uncertainty,  
98 to explicitly test the use of this decision to further seek information for improving performance.  
99 The objective of our current study was to test a new protocol adapted to human and non-human  
100 primates and devoted to study information-seeking and metacognition, possibly in the context of  
101 neurophysiological studies.

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## Results

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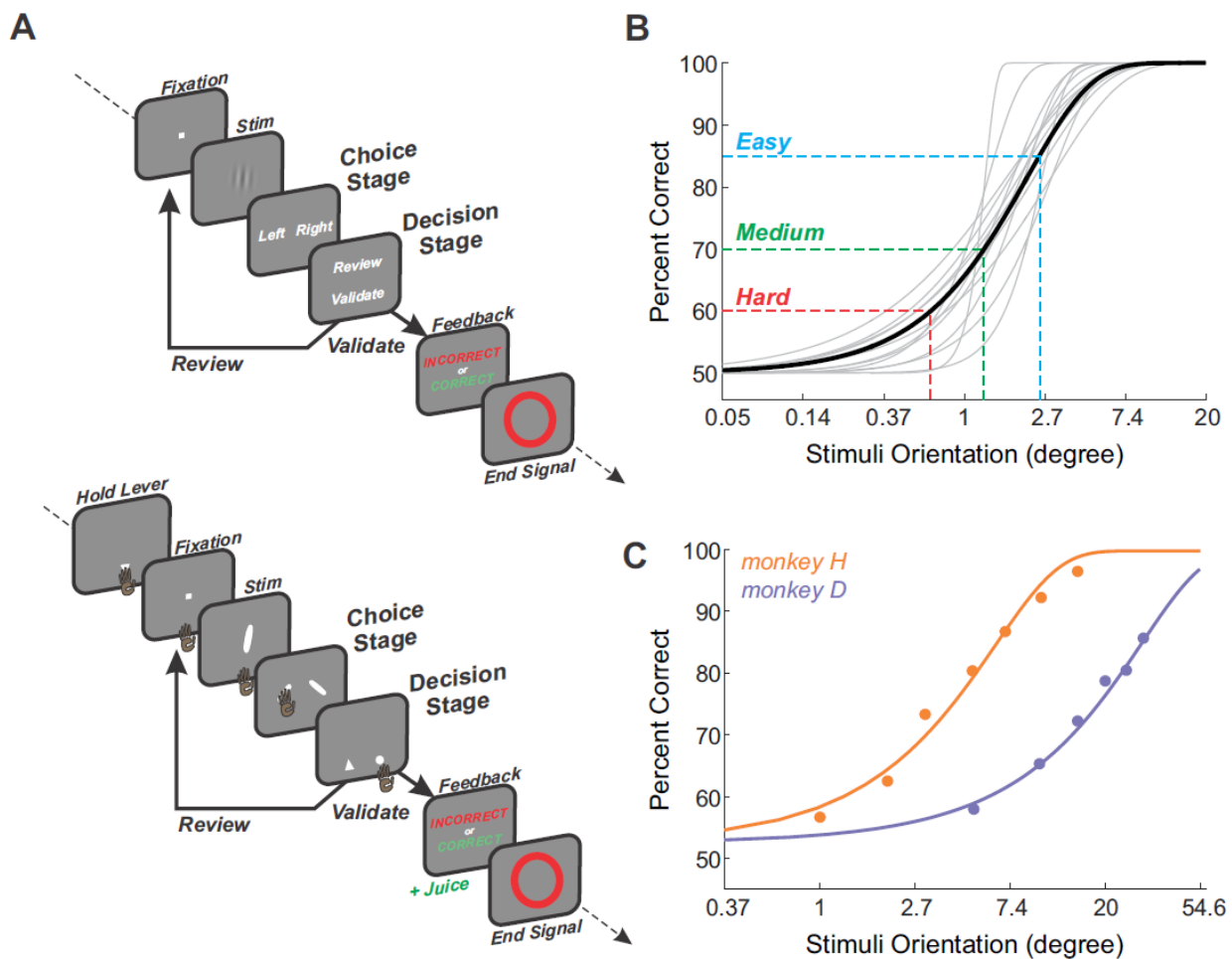
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We designed a new behavioural task that allowed subjects to freely choose whether or not to review a test before validating their decisions (**Figure 1A**). In each trial, subjects were first (1) asked to report the angle (right or left) of an oriented grating and then (2) proposed to review or validate their choice. If subjects decided to review, they were able to go through the categorization and decision stages again. The aim of this task was to promote review depending on one's own perceived uncertainty, as well as allowing subjects to use their uncertainty to guide further decisions. We first tested 14 human subjects in this new task. Subjects' performances in the categorization were standardized using a staircase procedure prior to the experiment, defining the 3 levels of difficulty used thereafter (see Methods and **Figure 1B**).



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**Figure 1. Confidence Judgment Task and categorization performance.** **A**, The events of an individual trial of the task used for human subjects (top) and monkeys (bottom). Frames represent main successive events during a trial. Subjects had to choose whether the stimulus was oriented to the right or to the left. After the right/left choice (*Choice Stage*), subjects could decide whether to validate or review the stimulus to retry the test (*Decision Stage*). Visual feedback was given only after subjects' decision to validate. In the monkey version of the task (bottom panel), they were required to hold a lever to initiate a trial and stimuli were oriented

124 bars. Also, choice targets were represented by rightward and leftward oriented bars, randomly  
125 positioned. Decision targets were represented by a triangle (review option) or a circle (validate  
126 option), also randomly positioned. Additionally, correct trials were rewarded by juice, incorrect  
127 were penalized by a timeout. **B and C**, Individuals and average psychometric curve (binomial  
128 GLM using a logistic regression) showing performance across stimuli orientations (absolute  
129 value by pooling rightward and leftward stimuli) tested during the staircase procedure in human  
130 subjects (B) or across different sessions in both monkeys (C). Three absolute stimuli  
131 orientations were chosen from individual psychometric curves to elicit 60, 70 and 85% of correct  
132 choices (Hard, Medium and Easy conditions respectively).

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### 134 **An adapted use of the review option in Humans**

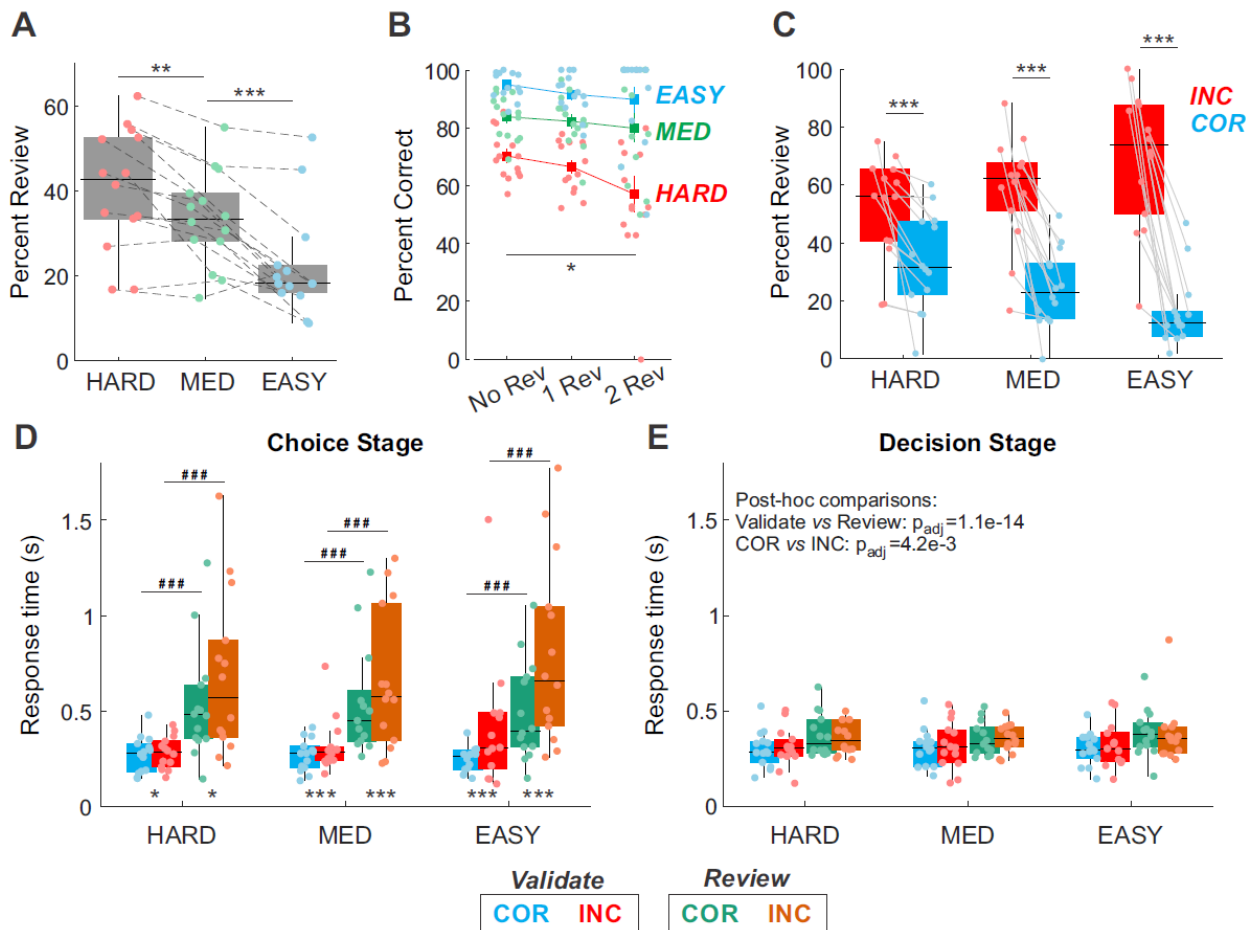
135 As expected, human subjects used the review option depending on categorization  
136 difficulty (**Figure 2A**). They reviewed significantly more often for harder stimuli than easier ones  
137 (mixed-effect *glm*, factor difficulty,  $F=33.6$ ,  $p=3.3e-9$ ). Contrary to our predictions, however, we  
138 observed no gain in performance after reviews (**Figure 2B**). In fact, the number of successive  
139 reviews a subject performed had a significantly detrimental effect on performance, notably after  
140 2 successive reviews (mixed-effect *glm*; factor difficulty,  $F=61.7$ ,  $p=4.0e-19$ ; factor nbReview,  
141  $F=4.24$ ,  $p=0.016$ ; the interaction did not survive model selection) (post hoc comparison of  
142 performance after 0 vs. 2 reviews, Wald test  $p=0.013$ ; other conditions,  $p>0.12$ ). Thus subjects  
143 took the opportunity to review when it made sense to do so, but gained no benefits on  
144 performance. This suggests that the probability to review depended on confidence level but that  
145 reviewing could not be leveraged to increase performance.

146 A more detailed analysis revealed that subjects not only reviewed more often for difficult  
147 trials than for easy ones, but also that decisions were related to categorization accuracy (**Figure**  
148 **2C**). Reviews were significantly more frequent after an incorrect response on the first choice  
149 than after a correct one (mixed-effect *glm*, interaction feedback x difficulty,  $F=13.3$ ,  $p=1.04e-5$ ).  
150 The percent of reviews after a correct choice decreased with easier conditions, but  
151 concomitantly increased after incorrect choices. The difference incorrect versus correct  
152 decreased with increased difficulty. Thus, subjects were able to detect their own errors and  
153 reviewed appropriately, and this ability was greater when confronted with simple  
154 categorizations. This indicates that uncertainty about one's own performance was higher in the  
155 most difficult condition, inducing more decisions to review.

156 Response times can reflect the process by which confidence contribute to the decision to  
157 review. Indeed, subjects were significantly slower to choose when they subsequently reviewed  
158 than when they subsequently validated (**Figure 2D**, mixed-effect *glm*, factor decision,  $F=684.9$ ,  
159  $p=7.4e-143$ ). Subjects were slower when making an incorrect choice compared to a correct one,  
160 independently of the subsequent decision (validate or review) and more strongly for difficult

161 trials (interaction feedback x difficulty,  $F=9.37$ ,  $p=8.6e-5$ ; Wald test,  $p<0.03$  for all  
 162 incorrect/correct comparisons. No other interactions survived model selection). At decision time  
 163 (review or confirm), subjects were also slower following incorrect choices compared to correct  
 164 ones, and slower when reviewing compared to confirming their choice (**Figure 2E**, mixed-effect  
 165 *glm*, factor decision,  $F=63.4$ ,  $p=2e-15$ ; factor feedback,  $F=8.51$ ,  $p=3.5e-3$ ). Difficulty as well as  
 166 interactions did not survive in that case. Even though similar effects were observed for both  
 167 response times, differences appeared substantially greater at the choice stage (right/left target  
 168 selection) than the decision stage. Such observations revealed that subjects' confidence  
 169 continuously impacted behaviour at all stages and even before the appearance of decision  
 170 targets.

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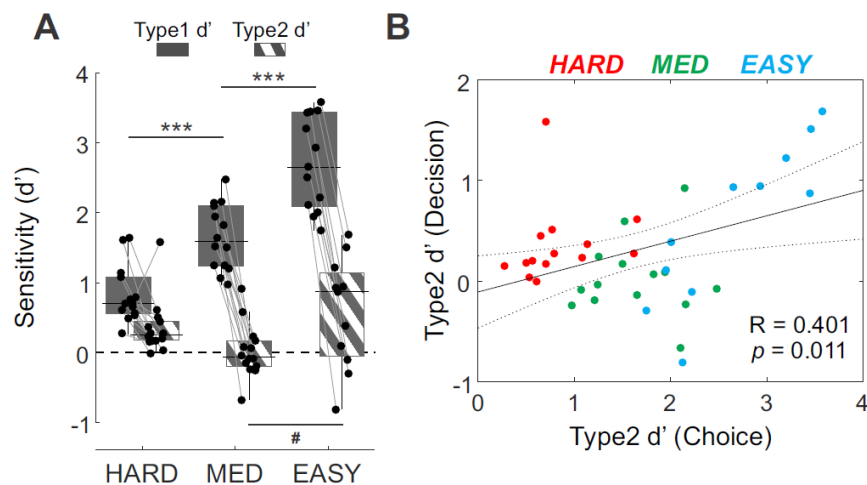
173 **Figure 2. Behavioural performance of humans.** **A**, Average percent of review choices for the  
 174 three difficulty levels. **B**, Average final performance for no review (validate at the first decision),  
 175 and after 1 or 2 successive reviews. **C**, Percent of reviews for each difficulty level separated by  
 176 performance at the 1<sup>st</sup> choice stage (either correct or incorrect). **D & E**, Median response times  
 177 at the choice (**A**) and decision (**B**) stages depending on performance (correct or incorrect  
 178 choice, blue/green and red/orange respectively) and difficulties. Blue/red colours represent  
 179 validated trials, while green/orange colours reviewed ones. Significant post-hoc comparisons



180 (Wald test with FDR correction) are reported as follow: \* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ . In **D**,  
181 stars and sharp symbols stand respectively for a significant difference between incorrect/correct  
182 or validate/review. In **E**, no symbols were reported given that the best final model did not include  
183 the factor condition. Instead, FDR-corrected p-values were provided. In **A-E**, dots represent  
184 individual subjects' performance.  
185

## 186 Lack of behavioural adaptation following a review in Humans

187 The above results mostly show that subjects use the review option in an adapted  
188 manner. However, the main goal of metacognitive abilities is not only to estimate how uncertain  
189 subjects are in a given situation, but also to promote information seeking to improve  
190 performance. To investigate such process, we calculated the categorization sensitivity (type1)  
191 and metacognitive sensitivity (type2) for each subject and for the three different conditions (see  
192 Methods for details). As expected, type1 sensitivities decreased with difficulty (mixed-effect *glm*,  
193  $F = 87.9$ ,  $p = 5.5e-15$ ) (**Figure 3A**). However, type2 sensitivities revealed an unexpected result.  
194 Even though type2 sensitivities varied significantly with difficulty (mixed-effect *glm*,  $F = 3.96$ ,  
195  $p = 0.028$ ), subjects showed relatively low metacognitive abilities, with type2 sensitivities close to  
196 0 in the most difficult conditions. Also, type1 and type2 sensitivities were significantly correlated  
197 (Spearman linear correlation,  $R = 0.401$ ,  $p = 0.011$ , **Figure 3B**). This suggests that subjects'  
198 metacognitive performance depended partially on sources of variation that affected their  
199 categorization performances. This might have been the case if for instance subjects used the  
200 review option to discriminate difficult vs. easy trials instead of interring the correctness of their  
201 choice independently of the categorization's difficulty.



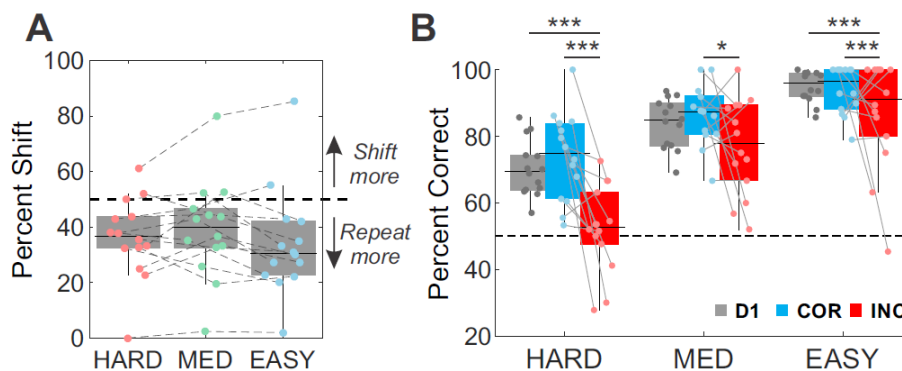
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203 **Figure 3. Choice and Decision sensitivities.** **A**, Average sensitivity measures ( $d'$ ) for Type1  
204 (Choice, plain grey) and Type2 (Decision, grey stripes) ROC depending on difficulties.  
205 Significant post-hoc comparisons (Wald test with FDR correction) are reported as follow:  
206 \*\*\* $p < 0.001$  for type1 comparisons; # $p < 0.05$  for type2 comparisons. **B**, Individual  $d'$  for type2  
207 plotted against type1, for each difficulty level (Hard in red, Medium in green, Easy in blue). The  
208 dotted line represents the Pearson's linear correlation ( $\pm 95\%$  CI), independent of difficulty.



209

210 Even if subjects showed markers of their ability to detect errors, they were relatively  
211 unable to correct them (as suggested in **Figure 2B**). Consistent with the overall low level of  
212 metacognitive sensitivity, further analysis revealed unexpected consequences of the review  
213 process. First, subjects showed on average a significant bias toward repeating the same  
214 right/left choice after a review (i.e. percent of shift across difficulties was below 50%, Wilcoxon  
215 sign rank test,  $z=-2.54$ ,  $p=0.011$ ) (**Figure 4A**), and this bias toward confirmation was not  
216 modulated between conditions (mixed-effect *glm*, factor difficulty:  $F=1.97$ ,  $p=0.152$ ). **Figure 4B**  
217 presents performance of subjects at different levels of review and depending on performance: in  
218 grey the performance for first validated choices (D1, no review); in red, final performance  
219 following an incorrect first choice (whatever the number of reviews, one or more), and in blue,  
220 the final performance following a correct first choice. Note that in the HARD condition, the final  
221 performance was particularly low when subjects initially made a mistake (i.e. red bar for HARD,  
222 Wald test  $p<0.001$ ) (mixed-effect *glm*, interaction difficulty x Trial type,  $F=2.74$ ,  $p=0.03$ ). Similar  
223 decreases in performance following incorrect trials compared to correct ones was also observed  
224 for MED and EASY conditions, albeit to a lesser extent (post-hoc comparison,  $p<0.018$ ).  
225 Alternatively, no differences were observed between the immediately validated performance  
226 (D1) compared to the final performance following a correct choice in the first selection (COR)  
227 (Wald test, all conditions at  $p>0.39$ ). Thus, the review process worsened performance only  
228 when the trial started with a mistake. In other word, confusion and/or confirmation biases arose  
229 after errors during the successive reviews.

230



231 **Figure 4. Performance changes following a review.** **A**, Average percent of shift in response  
232 compared to the previous choice following a review. **B**, Average performance before (grey, first  
233 Choice response) and after reviews (blue and red, final Choice response). Final performance  
234 was separated depending on the first choice (correct first choice in blue and incorrect first  
235 choice in red). Significant post-hoc comparisons (Wald test with FDR correction) are reported as  
236 follow: \* $p<0.05$ , \*\* $p<0.01$ , \*\*\* $p<0.001$ .

237

238

## 239 **Categorization performance in monkeys**

240 Two male rhesus monkeys were tested in a task similar to the one used for human  
241 subjects (**Figure 1A, bottom panel**). Monkeys behaved correctly in the categorization test, by  
242 showing appropriate psychometric performance. The discrimination thresholds differed between  
243 monkeys, with monkey H being more accurate with lower angles than monkey D (**Figure 1C**).  
244 To elicit 60, 70 and 85% of correct responses, monkey H was tested with bar orientations of 1°,  
245 2° and 5° relative to the vertical (5°, 10° and 20° for monkey D). Both monkeys had slightly  
246 better performance for rightward stimuli compared to leftward (0.15° and 3.8° of performance  
247 difference between right and left orientations for monkey H and D respectively).

248 To assess whether reaction and movement times varied between conditions, we used a  
249 mixed-effect *glm* for each individual monkey and measure (choice RT, choice MT, decision RT,  
250 decision MT), with a random-effect of sessions on the intercept. All initial models included the 3  
251 following factors: feedback, difficulty and decision, as well as all possible interactions. The  
252 results for the best models are reported below (see also Methods for model selection  
253 procedure). Choice RT were slower when monkeys made an incorrect choice compared to a  
254 correct one (mixed-effect *glm*, factor feedback, monkey D:  $F=40.1$ ,  $p=2.9e-10$ ; monkey H:  
255  $F=14.6$ ,  $p=1.3e-4$ ; factor difficulty and decision, as well as interactions did not survive model  
256 selection). Decision RT also increased following incorrect choices for both monkeys, with an  
257 additional interaction with difficulty (mixed-effect *glm*, interaction feedback x difficulty, monkey  
258 D:  $F=4.5$ ,  $p=0.011$ ; monkey H:  $F=7.3$ ,  $p=6.8e-4$ ) (Wald test, all difficulty  $p<0.04$ , except for  
259 monkey H in the hard condition,  $p=0.33$ ). In only one monkey (monkey D) choice MTs were  
260 slower following incorrect compared to correct trials, especially in Hard and Easy conditions  
261 (mixed-effect *glm*, interaction feedback x difficulty,  $F=3.13$ ,  $p=0.04$ ) (Wald test,  $p<0.024$ , but not  
262 in Med condition,  $p=0.08$ ). Decision MT in monkey D did not depend on feedback or difficulty,  
263 but significantly change with the subsequent decision to review or validate, as reported in the  
264 next section. Overall, monkeys tended to be slower to plan their choice when incorrect, but this  
265 was mostly independent of the difficulty of the categorization.

266

## 267 **A sub-optimal use of the review option in monkeys**

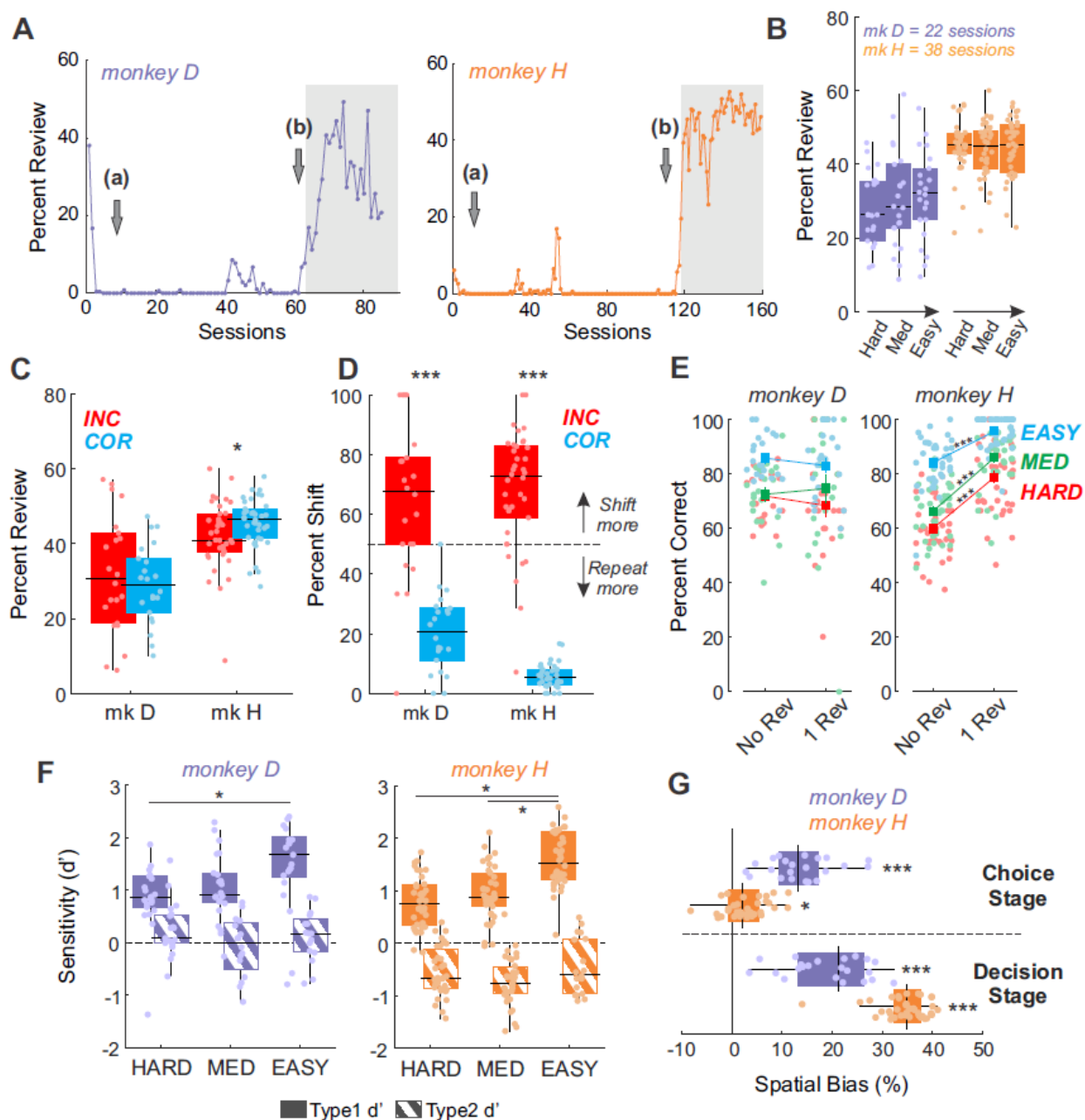
268 After an initial use of the review option during the first sessions, both monkeys stopped  
269 doing so for a long period of time (**Figure 5A**). Such behaviour forced us to slightly change the  
270 task to familiarize them with the review option. Two main changes were tested: forced review  
271 trials were included (i.e. in which the validate option was not available) and correct/incorrect  
272 feedback was also adjusted to increase review benefits (i.e. more juice reward when correct and  
273 less time penalty when incorrect after a review, these parameters also changed over time) (see

274 also “Notes on training procedure with monkeys” in *Methods*). Contrary to our predictions, these  
275 changes did not elicit voluntary reviews (**Figure 5A**, arrows 'a'). A final change allowed monkeys  
276 only one single review, without requiring the validation of their last choice. This was done at  
277 session number 61 and 112 for monkey D and H respectively (arrows 'b' in **Figure 5A**). This  
278 modification was efficient in the sense that both monkeys freely selected the review option again  
279 after a few sessions, without resorting to a heavier training approach. Thereafter, their  
280 behaviour remained stable. For the purpose of this study, we focused our analysis on sessions  
281 where monkeys used the review option in a stable way, from session number 64 and 120 until  
282 the end for monkey D and H respectively ( $n = 22$  &  $38$  sessions for monkey D and H) (**Figure**  
283 **5A**, highlighted in grey).

284 Contrary to what was observed with human subjects, monkeys did not use the review  
285 option differently with different levels of difficulty (**Figure 5B**) (mixed-effect *glm*, factor difficulty;  
286 monkey D:  $F=2.05$ ,  $p=0.13$ ; monkey H:  $F=0.41$ ,  $p=0.66$ ). Moreover, if monkeys were using the  
287 review option based on their own uncertainty, one would expect a greater proportion of reviews  
288 following incorrect choices compared to correct ones, as observed in human subjects. This was  
289 not the case (**Figure 5C**). In fact, an opposite effect was observed for monkey H (mixed-effect  
290 *glm*, factor feedback; monkey D:  $F=1.25$ ,  $p=0.27$ ; monkey H:  $F=5.86$ ,  $p=0.017$ ). However, both  
291 monkeys repeated more their choices following correct choices compared to incorrect ones, a  
292 situation where they usually shifted (mixed-effect *glm*, factor feedback; monkey D:  $F=57.1$ ,  
293  $p=2.3e-9$ ; monkey H:  $F=372$ ,  $p=1.3e-30$ , **Figure 5D**). Such observation suggests a potential  
294 benefit of the review process.

295 As described in the previous section, we did not observe clear modulations in RT and  
296 MT depending on the subsequent decision to review or validate. Only decision MT in monkey D  
297 were slower for confirmed choice compared to reviewed ones (mixed-effect *glm*, factor decision,  
298  $F=19.8$ ,  $p=8.7e-6$ ). In all other cases, the factor ‘decision’ did not survive model selections. The  
299 absence of RT/MT modulations suggests both monkeys might not have use the review option  
300 as an expression of their uncertainty.

301



302

303 **Figure 5. Behavioural performance of monkeys.** **A.** Percent of reviews over sessions for  
 304 monkey D (left panel) and H (right panel). Grey arrows indicate major changes in task design:  
 305 (a) forced reviews were introduced; (b) the first session where monkeys were proposed to  
 306 review only once, without the need to validate the second choice. Grey highlight represents the  
 307 sessions included in the following analyses. **B & C,** Percent of reviews depending on conditions  
 308 (**B**) and previous performance (**C**; correct in blue; incorrect in red). **D,** Percent of shifts  
 309 depending on previous performance. **E,** Final performance when monkeys validated  
 310 immediately (No review) or after 1 review depending on conditions (Hard in red; Medium in  
 311 green; Easy in blue) and for both monkeys. **F,** Average sensitivity measures ( $d'$ ) for Type1  
 312 (Choice, plain) and Type2 (Decision, stripes) ROC depending on difficulties. **G,** Spatial bias  
 313 (tendency to choose a particular side rather than a particular target) for Choice (Right or Left)  
 314 and Decision (Review or Validate) stages for both monkeys. Significant post-hoc comparisons

315 (Wald test with FDR correction) are reported as follow: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Dots in  
316 **B-G** represent individual sessions' performance.

317  
318 The behavioural benefits of the review process in terms of performance were different in  
319 the two monkeys (**Figure 5E**). Specifically, for monkey D reviewing was neither advantageous  
320 nor deleterious, the performance being modulated only by the difficulty (mixed-effect *glm*,  
321 monkey D, factor difficulty:  $F=12.3$ ,  $p=1.3e-5$ ; no other factor or interaction survived model  
322 selection). However, monkey H showed a significant increase in performance on reviewed trials,  
323 modulated by the difficulty (mixed-effect *glm*, monkey H, interaction difficulty x nbReview,  
324  $F=4.77$ ,  $p=9.3e-3$ ; post-hoc comparison for each difficulty, Wald test  $p < 4.5e-17$ ). The  
325 discrepancy between monkeys might be explained by differences in experimental conditions.  
326 Monkey D was allowed to see the stimulus longer during the review (+400ms, representing a  
327 duration gain of 80% on average), whereas monkey H was proposed a slightly simpler stimulus  
328 after session number 94 (+3°, representing an ideal performance gain of 16.25% on average).  
329 Such differences tends to suggest that reviewing the same stimulus (as in monkey D) did not  
330 increase performance at all, even when displayed longer.

331  
332 Similar to what we found in human subjects, monkeys' type1 sensitivities decreased with  
333 difficulty (**Figure 5F**) (mixed-effect *glm*, factor difficulty, monkey D:  $F=4.05$ ,  $p=0.022$ ; monkey H:  
334  $F=18.2$ ,  $p=1.4e-7$ ; post-hoc comparisons, Wald test, monkey D: Hard vs Easy,  $p=0.027$ ; other  
335 comparisons,  $p > 0.051$ ; monkey H: all comparisons at  $p < 1.4e-5$ , except Hard vs Med at  $p=0.31$ ).  
336 This was not the case for type2 sensitivities, where low values were observed as well as no  
337 modulation (mixed-effect *glm*, factor difficulty, monkey D:  $F=1.98$ ,  $p=0.15$ ; monkey H:  $F=2.58$ ,  
338  $p=0.08$ ).

339  
340 In order to avoid spatial biases, but also to limit preparatory responses, we randomized  
341 both Right/Left targets and Review/Validate levers locations between trials (on the right or left of  
342 the screen). Yet we observed that both monkeys developed a strong spatial bias toward one  
343 side, especially at the decision stage (**Figure 5G**) (Wilcoxon sign-rank test, choice stage;  
344 monkey D:  $z=4.1$ ,  $p=4e-5$ ; monkey H:  $z=2.24$ ,  $p=0.025$ ; decision stage; monkey D:  $z=4.1$ ,  $p=4e-$   
345  $5$ ; monkey H:  $z=5.37$ ,  $p=7.7e-8$ ). The use of this low cognitively demanding strategy (spatial)  
346 strongly suggests that monkeys poorly discriminated between review or validate options.

347 Taken together, our findings reveal that monkeys were unable to develop and use the  
348 opportunity to review or validate the test in an optimal manner. Despite a long and careful  
349 training, no clear evidence supported a metacognitive evaluation at the decision stage in  
350 monkeys. It is important to acknowledge the possibility that a heavier training approach might

351 have been able to elicit such behaviour. This was however not the objective as we were trying  
352 to obtain a natural development of a review strategy.

353

## 354 ***Discussion***

355 In this study, we designed a protocol to assess confidence judgments under uncertainty,  
356 but also the resulting behavioural adaptations. Inspired by information-seeking tasks, this novel  
357 metacognitive task used reviews as a means to reveal confidence and was intended to test both  
358 human and non-human primates. Observations in human subjects performing this task was in  
359 accordance with previously reported results, showing that subject might be able to report  
360 confidence with the opportunity to review or validate. However, in monkeys, the behavioural  
361 study did not reveal expected review vs. validate behaviour. The main issue might be that, in  
362 both species, reviewing did not improve performance and rather competed with, or was  
363 perturbed, by alternative low-cognitive cost strategies. In this context, the design might have  
364 hinder monkeys to use the review option appropriately.

365

366 The behavioural task induced a review process triggered by difficulty and estimated  
367 performance. Subjects' uncertainty on choice was reflected in the use of this option. They  
368 showed behavioural markers of error detection, even before any feedback was delivered. This  
369 confirmed previous observations that human subjects can adequately report retrospectively their  
370 confidence in a perceptual choice<sup>3</sup>, although our protocol reveals subjects' confidence through  
371 the measure of review behaviour and does not require explicit report. In this sense, this protocol  
372 might be useful from a clinical perspective, especially when trying to understand why obsessive  
373 compulsive disorder (OCD) patients showed excessive checking behaviour and impairments in  
374 self-performance monitoring<sup>18,19</sup>. Moreover, from a neurophysiological perspective, studies of  
375 performance monitoring generally investigate adaptive processes after subjects receive  
376 feedback on performance<sup>20-22</sup> (but see <sup>23</sup>). Our protocol allows us to study markers of  
377 performance monitoring in the absence of external feedback.

378 Metacognitive processes might also serve to promote correction of putative mistakes, in  
379 order to improve decisions<sup>1,17</sup>. Apparently, the current task design did not allow subjects to  
380 improve their performance after the review process. Rather, subjects developed a bias toward  
381 repeating the same choice even if they mostly reviewed after incorrect choices. Such  
382 confirmation bias, often reported in the literature<sup>24</sup>, might contribute to the absence of  
383 improvement. But it might also reveal that subjects used reviews as a form of verification, with  
384 the objective of reducing their uncertainty about their first decision. This is in contrast to the use



385 of review to simply revise their first choice (as it would be the case for changes of mind). In that  
386 sense, our task design might well capture the use of metacognitive evaluation for adaptive  
387 change in control in order to acquire more information. Nevertheless, given that both underlying  
388 reasons might contribute to subjects' use of reviews, further experiments are needed to reveal  
389 subject's actual strategies at the trial level, for example by varying and controlling the *quantity* of  
390 information given at any moment. Using appropriate modelling tools and experimental changes,  
391 it might be possible to dissociate between subjects' overall bias (i.e. reviewing only for  
392 confirmation about an uncertain first choice) and decisions that depend on recently collected  
393 information.

394 The absence of improvement following a review might also explain why the signal  
395 detection approach indicated poor metacognitive abilities. In the procedure, type2 measures  
396 reflect the ability to detect and correct wrong decisions<sup>25</sup>, and scores of this measure were very  
397 low. This should not be taken as the sole measure of metacognition. Subjects could not  
398 adequately adapt their behaviour under high uncertainty (i.e. following a review), but had  
399 chosen to review in a way that indicates some metacognitive process. This dissociation  
400 therefore underlines the difficulty of finding a single measure of metacognition, and the fact that  
401 several factors impinge on this ability. One interpretation is that, in the present context, the  
402 review process counterintuitively generates interference or doubts that prevent the addition of  
403 information across the successive reviews and hence the increase in performance. After the first  
404 choice, during review, the perceptive information that is offered again to the subjects appeared  
405 not to be integrated and cumulated. Rather, subjects might have based their decisions on purely  
406 internal information related to performance (the perception of an initial error) or memory of the  
407 first perceived stimulus. In this context reviews are detrimental. A study with OCD patients  
408 similarly observed that patients seemed to use mnemonic cues to respond to a discrimination  
409 test after numerous reviews and did not use the available perceptual information anymore<sup>26</sup>.  
410 More recently, other experiments report similar detrimental effect of reviews in healthy  
411 subjects<sup>27-29</sup>. We argue here that subjects did so especially when uncertainty was maximal (in  
412 the more difficult condition), by making a choice depending only on a poor memory of the  
413 stimulus and a pure guess on the current correct response. If this appears to be true, we might  
414 expect changes in neurophysiological markers that are incongruent with the information  
415 provided by the stimulus.

416 Finally, the existence of a correlation between perceptual and metacognitive abilities  
417 suggests that both rely on the same underlying estimation (i.e. perceptual in this case). The  
418 difference in choice response times between reviewed trials and validated ones also support  
419 such interpretation. Nevertheless, relationships between perceptual and metacognitive



420 measures have been often reported in the literature (for example <sup>4,30,31</sup> but see <sup>2</sup>), and have  
421 been considered as an argument toward a metacognitive explanation of human and non-human  
422 strategies<sup>5,7</sup>. In our case, subjects might decide whether to review or validate a choice  
423 depending on the speed of their responses, by assuming that a long deliberation might be  
424 related to greater uncertainty<sup>6</sup>. Even if not metacognitive in the sense defined by Nelson &  
425 Narens<sup>1</sup>, this gives rise to a widely accepted proposition that metacognitive abilities are based  
426 on an *indirect* access to one's own cognition, by making inferences from observable cognitive  
427 processing results<sup>6,7</sup>. Specifically, ease of processing, retrieval fluency or cue familiarity might  
428 be used to report confidence and have been argued to reflect metacognitive processes<sup>4,5,32</sup>. The  
429 present data are in favour of such theories.

430 Taken together, our observations highlight that the task might be appropriate to study  
431 metacognition from an information-seeking point of view. Review behaviour allowed us to  
432 address two metacognitive mechanisms: the monitoring of decisions and the related adaptation  
433 that might occur. However, subjects' behaviour suggests that the review option was mostly for  
434 self-confirmation rather than a way to modify a choice. Post-decision adaptation was sub-  
435 optimal in our subjects, possibly due to task design issues as discussed next.

436  
437 Recent studies have shown the possibility to test some forms of checking behaviours in  
438 monkeys<sup>33,34</sup>. In the present study, we were not able to elicit reviews in monkeys that would be  
439 based on their perceived uncertainty. Despite weak evidence of their ability to adequately use  
440 the review option, monkeys quickly fell into a non-optimal and cognitively less-demanding  
441 strategy to perform the task. Such failure might be explained by different factors as discussed  
442 below.

443 First, the difficulty to elicit reviews in monkeys might depend on the learning procedure  
444 we adopted, or a related issue concerning the task design itself. Assessing metacognitive  
445 abilities in monkeys requires avoidance of the development of alternative strategies<sup>35</sup>. In  
446 particular, reward-induced biases or external cue associations need to be tightly controlled so  
447 as to avoid confounds with the intended effect of metacognitive process. In the literature, many  
448 studies were debated due to the possible use of alternative non-metacognitive processes<sup>8,9,13,35</sup>.  
449 We tested whether a protocol with an adaptive review process would be efficient. However, as  
450 observed by Son & Kornell<sup>11</sup>, even simpler protocols by comparison to the one we developed,  
451 using high and low-bets following a perceptual response, are tricky to use in monkeys. In their  
452 study, authors reported their failure to elicit an efficient use of the decision stage, due to the  
453 expression of a bias toward a specific option (selecting only the high-bet option). However, after

454 a long training and many modifications in the task design, they were able to elicit what they  
455 consider to be an optimal use of bet options<sup>11,12</sup>.

456 In our task, the credit assignment problem, i.e. figuring out the link between a specific  
457 choice (right or left) and a delayed reward (after the decision stage), was arguably the most  
458 challenging element. Credit assignment is a complex issue especially in sequentially structured  
459 tasks or in multiple choice situations<sup>36</sup>. For monkeys, one way to bypass such an issue might be  
460 to always validate a choice and not take into account the decision stage. This was our monkeys'  
461 first strategy. Importantly, when we introduced the single review option, monkeys soon used the  
462 opportunity to review. In this case, the association between choice and feedback was  
463 sometimes present (after a review, the feedback was given immediately after the second  
464 right/left choice), and monkeys changed their strategies accordingly. However, both monkeys  
465 also adopted a simpler spatial strategy. Reviewing might have been perceived as effortful, and  
466 as similar as cancelling a previous choice. Even if a visual cue indicated trial transitions, adding  
467 contextual information to clarify the structure of a trial might have helped (e.g. changing the  
468 background colour from one trial to another).

469 Another possible explanation was that monkeys never perceived the benefits associated  
470 with the review option, even if analyses revealed an advantage for one individual. Reviewing a  
471 choice underlies a greater cost than validating, in terms of physical and cognitive effort at least.  
472 Delay and effort are two separate features that both depreciate human and non-human  
473 decisions when experienced<sup>37,38</sup>. Even if the review vs. validate options were equalized in  
474 duration, our results might suggest that our monkeys were more sensitive to effort than delay,  
475 and so were less willing to review a choice than to wait during the time penalty after an error.

476 Finally, one might question the ability of monkeys to use their own confidence. The  
477 failure to induce reviews in our experiment is certainly not only explained by a natural inability to  
478 express metacognition. Nevertheless, this question is hotly debated in the literature<sup>32,39,40</sup>.  
479 Information-seeking protocols appear to be highly relevant to study metacognitive processes in  
480 animals as one-trial tests have revealed abilities of self-knowledge based adaptive behaviour in  
481 macaques<sup>16</sup>. Importantly, macaques showed appropriate patterns of responses in uncertainty  
482 test whereas new world monkeys (capuchin) did not<sup>41</sup>. Yet, few studies reported the relative  
483 volatility of metacognitive responses or even the absence of such response in many individuals  
484 and different species tested with or without extensive training<sup>11,14,42</sup>. Concomitantly, two main  
485 criticisms have been proposed against the existence of metacognition in non-human animals.  
486 The first is that simple heuristics like reward associations, and not metacognition, guide  
487 behaviour in information-seeking or uncertainty response paradigms<sup>10,17,35,40</sup>. The second  
488 questions the relevance of metacognition to address problems to which animals are

489 confronted<sup>39</sup>. Even if animal research tried to answer these issues<sup>43</sup>, more investigations and  
490 new protocols are required to confirm whether and how non-human animals have access to  
491 metacognition<sup>32,44</sup>.

492

493 Few improvements are required to adapt our protocol to the study of metacognitive  
494 evaluation and control in animals for behavioural and neurophysiological studies. One possibility  
495 to explain the failure to induce reviews in monkeys is that, like in humans, the transfer of  
496 information from one trial to the next during the review process was not optimal. Hence the  
497 review was not beneficial. If this is the case, adding contextual information to link decisions and  
498 outcomes across actions and events might help. Similarly, information transfer might not have  
499 been facilitated by using fixed stimuli like oriented gratings. Dynamic stimuli (random dot motion  
500 for example) could contribute to enhance the gain of perceptual information after a review, and  
501 so might be beneficial.

502

## 503 **Methods**

### 504 **Participants and Apparatus**

505 **Humans.** Fourteen subjects (7 males and 7 females, aged 20-34 years, mean = 24.15  
506 years) participated in this study after giving informed consent. The study was carried out in  
507 accordance with the recommendations of the Code de la Santé Publique and performed in a  
508 laboratory approved by the “Agence Nationale de Sécurité des Médicaments et des produits de  
509 santé (ANSM)”. All subjects had normal or corrected-to-normal vision and all were right-handed.  
510 Testing was performed on an Apple computer (Apple Inc., USA) using Matlab (MathWorks Inc.,  
511 USA) and the Psychtoolbox<sup>45</sup>. Subjects were comfortably seated 19.6 inches (50cm) away from  
512 a 23-inch screen, on which visual stimuli were displayed. Responses were made by using  
513 arrows on a computer keyboard with their right (dominant) hand. Experiments were done in a  
514 low-luminosity room.

515

516 **Monkeys.** Two male rhesus monkeys (*Macaca mulatta*), weighing 8 kg and 12 kg  
517 (monkeys D & H respectively) were used in this study. All procedures followed the European  
518 Community Council Directive (2010) (Ministère de l’Agriculture et de la Forêt, Commission  
519 nationale de l’expérimentation animale) and were approved by the local ethical committee  
520 (CELYNE, C2EA #42, project reference: C2EA42-13-02--0402-10). Monkeys were trained to  
521 perform the task while seated in a primate chair (Crist Instrument Co., USA) in front of a tangent  
522 touch-screen monitor (Microtouch System, Methuen, USA). An open-window in front of the chair

523 allowed them to use their preferred hand to interact with the screen (monkey D, left-handed;  
524 monkey H, right-handed). The position and accuracy of each touch was recorded on a  
525 computer, which also controlled the presentation of visual stimuli via the monitor (CORTEX  
526 software, NIMH Laboratory of Neuropsychology, Bethesda, MD). During experiments, monkeys  
527 were not head-restrained and eye movements were not controlled.

528

## 529 **Behavioural Task**

530 **Humans.** Subjects were first asked to perform a categorization task, based on the  
531 orientation of a stimulus following a staircase procedure to adjust difficulty (**Figure 1A, top**  
532 **panel**). Each trial started with a 1000ms fixation period during which subjects fixated a central  
533 dot. Then, a stimulus, consisting of a low-contrast Gabor patch oriented from vertical reference  
534 either on the left or on the right, was presented centrally on a grey background during 200ms.  
535 After a 500ms delay, subjects reported the orientation of the stimulus by using the right or left  
536 arrow keys of a standard keyboard. After reporting their choice (right or left) and an additional  
537 delay of 1000ms, they were asked to either validate or review (re-execute) the test (with either  
538 the bottom or the top arrow keys respectively). If subjects decided to validate their choice, a  
539 visual feedback was displayed centrally for 800ms, consisting of the word “correct” (shown in  
540 green) or “incorrect” (in red), and a new stimulus was presented on the subsequent trial. A  
541 review was potentially triggered by a subjective lack of confidence. If subjects decided to review,  
542 the same stimulus was presented again and a new choice could be made. Note that following  
543 half of the reviews, subjects were presented with a longer stimulus than on its first presentation,  
544 for a duration of 250ms instead of 200ms. The trial ended only after the subject validated their  
545 choice. Correct trials were not rewarded *per se*, but incorrect trials were penalized by a time  
546 penalty of 15 seconds. A 1000ms delay was introduced between trials.

547 Subjects were required to perform 420 trials, divided into 6 blocks of 70 trials (note that 1  
548 subject performed blocks of 65 trials instead). Between blocks, subjects were able to take rest.  
549 At the start of the experiment, instructions were given to explain the nature of the task as  
550 described above. Emphasis was placed on the general idea that the review option could help  
551 the subject complete the experiment more quickly, i.e. that reviews and consequent  
552 improvement of performance would compensate for the time-out after errors.

553

554 **Monkeys.** Monkeys were trained to perform a task similar to the one use with humans,  
555 where they were required to perform a categorization test based on the orientation of a bar, and  
556 then to either validate or review their choice (**Figure 1A, bottom panel**).

557 To initiate a trial, monkeys had to touch and hold a lever item, represented by a grey  
558 triangle on the bottom of the screen. Once touched, a central dot appeared on the screen for  
559 800ms. Then, the central dot turned off and the stimulus appeared on the screen (a grey  
560 rightward or leftward oriented bar) for a duration between 400 and 900ms (this duration was  
561 fixed during a session but changed across training). After a delay of 200ms, two oriented bars  
562 (one oriented 45° to the left, the other 45° to the right relative to the vertical) were used as  
563 targets. The relative position of targets was randomized from one trial to another (e.g. the  
564 leftward bar might be either positioned on the right part or the left part of the screen, randomly).  
565 Monkeys reported their choice by touching one of the targets. This was followed by an  
566 additional delay of 200ms. The two decision levers were then displayed, allowing monkeys to  
567 review or validate their previous choice. The review option was represented by a grey inverted  
568 triangle lever, and the validate option by a grey disk. The position of each lever on the screen  
569 (bottom right or left) was randomly assigned from one trial to the next.

570 If monkeys touched the validate option they received a feedback corresponding to their  
571 performance: correct choices were rewarded by a squirt of apple juice lasting between 300 and  
572 1000ms, incorrect choices were penalized by a grey screen lasting between 10000 and  
573 15000ms (note that rewards and penalties changed over the course of training, hence the range  
574 of values). To equalize review/validate options duration, the duration of a penalty for incorrect  
575 validation was set to be equal to two review trials. However, it is important to keep in mind that,  
576 by design, review trials are more effortful than validated ones, given the number of touches  
577 required. After the feedback delivery, a visual signal was displayed on the screen, consisting of  
578 a red circle lasting 800ms, and indicating the change of condition.

579 If monkeys touched the review option, the central dot appeared again on the screen for  
580 800ms and the stimulus was displayed. Two particular modifications of the task were used to  
581 stimulate the review process. First, the duration of the stimulus was increased by 400ms after  
582 each review. In some of monkey H's sessions, the duration of the stimulus was not increased,  
583 but instead the stimulus became easier (larger angle) after reviews (this was the case for all the  
584 sessions analysed thereafter, see Results for details). The following events were the same as  
585 described above. Second, feedback duration was modified if monkeys reviewed at least once.  
586 Correct choices were more rewarded after a review than after no review, with duration of reward  
587 between 500 and 1400ms (+91.6% and +77.7% of reward for monkey D and H respectively).  
588 Also, incorrect choices were less penalized after reviews, with a time penalty between 1000 and  
589 3000ms (-82.6% and -79.4% for monkey D and H respectively). These explicit benefits of the  
590 review were introduced to help monkeys during the training procedure (by increasing the review

591 utility), but were not intended to be used after the completion of the training (see below for  
592 details on training).

593

### 594 **Staircase & Psychometric analysis**

595 To maintain different levels of uncertainty during the categorization, three different  
596 stimulus orientations were used randomly across trials (i.e. HARD, MED and EASY).

597 For human subjects, orientations were determined depending on subject's own  
598 performance using a classical staircase procedure prior to the experiment. In this procedure  
599 (which lasted 240 trials), subjects had to choose whether the stimulus was leftward or rightward  
600 oriented, without the possibility to review or validate their choice. Stimulus orientations were  
601 defined depending on subjects' performance, with 3 randomly mixed staircase rules<sup>46</sup> (one-up  
602 one-down, one-up two-down and one-up three-down). The use of the 3 parallel staircases  
603 procedure (80 trials each) allowed us to assess subjects' performance more accurately. Based  
604 on performance during the staircase procedure, we calculated a psychometric curve for each  
605 subject, using a binomial generalized linear model (logistic regression). Three absolute stimuli  
606 orientations were then extracted and used during the main experiment to induce 70%, 75% and  
607 85% of correct responses (HARD, MED and EASY conditions respectively, see **Figure 1B** for  
608 an average psychometric curve and related orientations).

609 Similarly, for monkeys, orientations were not fixed between sessions but varied  
610 depending on their performance in preceding sessions (by considering the 5 to 10 last  
611 sessions). We computed a psychometric curve from past monkeys' performance using a  
612 binomial generalized linear model (logistic regression) (**Figure 1C**). Then, stimuli orientations  
613 were selected to elicit 70, 80 or 90% of correct responses on average. Such procedure allowed  
614 us to maintain uncertainty in categorization trials across sessions independently of other  
615 learning-related processes.

616

### 617 **Notes on training procedures with monkeys**

618 We first trained monkeys on the categorization task alone, which lasted several months.  
619 During this period, performance feedback was given immediately after their choices. Once  
620 performance in the categorization task was stable and sufficiently accurate, monkeys were then  
621 introduced to the decision stage, allowing to review or validate choices. This was done without  
622 any particular shaping. That is, we did not imposed any familiarisation with one of the two  
623 decision stage options prior to this stage, initially to avoid as much as possible biases toward a  
624 specific behaviour (review or validate). Over-training monkeys could lead to non-optimal  
625 strategies and is particularly problematic when it comes to understand natural behaviour such



626 as monkeys' metacognitive ability<sup>16</sup>. However, during the learning phase with the decision  
627 stage, we faced a few issues that led us to modify the task design in several steps. Specifically,  
628 after experiencing the review option both monkeys stopped using it within a few sessions (see  
629 **Figure 5A**). We thus implemented three main changes: 1) a small proportion of forced review  
630 trials (10-25%) were introduced (on these trials, only the review target is presented at the first  
631 decision stage), 2) penalties and rewards were adjusted throughout the training to increase the  
632 utility of the review and 3) monkeys could not review more than one time in a row, without the  
633 need to validate after the review (i.e. no second decision stage were proposed, and importantly,  
634 feedback was delivered immediately after the second choice).

635 Here, we report behavioural data for 22 and 38 sessions (for monkey D and H  
636 respectively). Sessions were selected based on the frequency in choosing the review option. To  
637 accurately assess putative metacognitive performances, we excluded sessions before the  
638 monkeys selected the review option in a stable manner (see Results for details).

639

## 640 **Behavioural Analysis**

641 **Humans.** Classical performance measures were calculated for each subject.  
642 Specifically, choice response times (i.e. time between the appearance of the right/left targets  
643 and the button press) and decision response times (i.e. time between the appearance of the  
644 review/validate targets and the button press) were recorded and analysed. Response times  
645 exceeding 10 seconds were rejected from further analyses (n=3 and 1 trials for choice and  
646 decision times, respectively, across all subjects). To improve the normality of the data  
647 distribution, we used the log transform of response times as dependent variable in the statistical  
648 analyses. Also, we calculated the percentage of review decisions (whatever the number of  
649 successive reviews), depending on conditions or depending on previous performance (correct  
650 or incorrect in the first selection). Initial and final performance was computed for each trial.  
651 Moreover, subjects' strategy following a review was studied by calculating the percent of shift,  
652 which is the proportion of reviewed trials after which the initial choice (before review) was  
653 changed in the decision that was made after reviews. As very few subjects made more than four  
654 successive reviews, these trials were entirely removed from further analyses (n=6/5850 trials).  
655 For similar reasons, we restricted our analyses of the performance against the number of review  
656 (**Figure 2B**) as well as type1/type2 performance (**Figure 3**) to a maximum of two successive  
657 reviews (n=5731/5844 included trials, 2% of trials were rejected).

658 As mentioned previously, the stimulus was displayed for an extra 50ms following half of  
659 subjects' reviews. This manipulation did not elicit any difference in performance, as assessed  
660 using mixed effect models (see Statistical procedure for more details). Specifically, the



661 performance after 1 review was only modulated by difficulty; the factor Stim Length did not  
662 survive model selection. For the performance after 2 successive reviews, we found a significant  
663 interaction (mixed effect *glm*, interaction difficulty x Stim Length,  $F=3.51$ ,  $p=0.035$ ) but post-hoc  
664 comparisons revealed no statistically significant differences between stimulus length levels  
665 (Wald test,  $W<1.48$  and  $p>0.42$  for all comparisons). For this reason, all trials were pooled  
666 together in further analyses, independently of stimulus length.

667

668 **Monkeys.** In addition to the measures used for human subjects, choice reaction times  
669 (choice RT; i.e. time between the appearance of oriented targets and the release of the lever)  
670 and choice movement times (choice MT; i.e. time of arm movements from lever release to the  
671 touch on selected target) were computed on each trial. Decision reaction times (decision RT; i.e.  
672 time between the appearance of the decision levers and the release of the target) and  
673 movement times (decision MT; time between the target release and the touch of a decision  
674 lever) were also recorded. As for human subject analyses, we used the log transform of the  
675 reaction and movement times as dependent variables in statistical analyses. Moreover, a  
676 measure of spatial bias was calculated for both stages (choice and decision) by dividing the  
677 number of touches made ipsilateral to the hand used by the total number of touches (note that  
678 monkey D and H use their left and right hand respectively).

679

### 680 **Signal Detection Theory approach**

681 To assess subjects' performance in the categorization test and their metacognitive  
682 abilities, we used the signal detection theory approach implemented by MacMillan &  
683 Creelman<sup>25</sup>. For this purpose, we computed the receiver operating characteristic (ROC) curve  
684 for both categorization (type1) and metacognitive (type2) performance. In this analysis, all trials  
685 are designated a 'trial type' amongst HIT, Correct Rejection (CR), False Alarm (FA) and MISS.  
686 In a 2-choice task such as ours, a reference for this classification must be chosen. It is the  
687 reference that differentiates type1 and type2 performance.

688 For type1 we sought to measure categorization performance, and the reference was  
689 trials on which the stimulus was oriented to the right. Hence a trial that had a rightward stimulus  
690 and a response 'right' was classified as a HIT, whereas a trial that had a leftward stimulus and a  
691 response 'left' was classified as CR. It follows that rightward stimulus and response 'left' was  
692 Miss, and leftward stimulus and response 'right' was a false alarm. This referencing approach  
693 allowed us to complete a ROC analysis despite the two-choice nature of the task.

694 In the type2 analysis, we sought to measure the metacognitive performance, i.e. whether  
695 the subject correctly self-diagnosed their performance in their choice to review or not. Hence the

696 reference was trials where the response was both correct AND validated. In this case a HIT was  
697 a correct and validated choice, whereas a CR was an incorrect then reviewed response. As  
698 such, FA was a correct reviewed response, whereas a MISS was an incorrect validated  
699 response.

700 Finally, we took into consideration the number of reviews (none, one or two) made within  
701 a trial, because this can be considered as a rating scale of certainty - no review meant that  
702 subjects were sure, 2 reviews that they were really unsure of their response. Hence, for a given  
703 trial, each new choice after a review or 2 reviews was assigned a cumulative probability of HIT  
704 and FA, based not only on the outcome of that choice but also of the previous choices within the  
705 same trial. We then derived ROC curves from cumulative HIT and FA probabilities before  
706 applying a Gaussian z transformation (i.e. zROC). We fitted a linear curve in order to obtain the  
707 slope of the zROC. We further defined  $d'_1$  and  $d'_2$ , the horizontal and vertical intercept of the  
708 zROC curve, respectively:

709

$$710 \quad d'_1 = -z(pFA) \text{ at the point where } z(pHIT)=0$$

$$711 \quad d'_2 = z(pHIT) \text{ at the point where } z(pFA)=0$$

712

713 From there, we then extracted the sensitivity measures (type1 and type2  $d'_a$ ) according to the  
714 formula [1] defined in Chapter 3 of MacMillan & Creelman's guide<sup>25</sup> :

715

$$716 \quad d'_a = \left( \frac{2}{1 + s^2} \right)^{1/2} d'_2 \quad [1]$$

717

718 where  $d'_a$  represents the sensitivity and  $s$  the slope of the linear zROC curve. This  
719 measure of sensitivity, contrary to the classic  $d'$ , is able to characterize a ROC curve using a  
720 single value of distance from each pair of HIT and FA probabilities.

721

## 722 **Statistical procedures**

723 All statistical procedures were performed using Matlab. Behavioural differences between  
724 conditions were assessed using mixed-effect generalized linear models (*glm*). For human  
725 subjects, each model included a random-effect on the intercept of the variable that the model  
726 was fitting (e.g. performance, percent of review, or the log of response times), to account for  
727 baseline differences between subjects (random-effect of subjects). For monkeys, models  
728 included a random-effect on the intercept to account for baseline differences between sessions  
729 (random-effect of sessions). Across models, the following factors (and levels) were considered:

730 Difficulty (Hard, Medium, Easy), Feedback (Incorrect, Correct), Number of Review (0 to 2),  
731 Decision (Review, Validate), Trial Type (Validated choice, Correct choice Reviewed, Incorrect  
732 choice Reviewed), and Stimulus Length (post-review increased or not). For every model used,  
733 we first performed a model selection by repeatedly testing the effect of dropping the least  
734 significant factor (starting with the interactions). The most appropriate models were then  
735 selected using Log Likelihood ratio test (with  $p < 0.05$ ). F-tests for each fixed-effects term in the  
736 selected models were reported in the Results section. Post-hoc comparisons were performed by  
737 computing the estimated marginal means<sup>47</sup> and using Wald test. P-values were corrected with  
738 False Discovery Rate (FDR) to account for multiple comparisons.

739

## 740 Data availability

741 All relevant data and codes are available from the authors upon request.

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