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# Task goals shape the relationship between decision and movement speed

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## 30 **Abstract**

31 The speed at which we move is linked to the speed at which we decide to make these  
32 movements. Yet, the principles guiding such relationship remain unclear: while some  
33 studies point towards a shared invigoration process boosting decision and movement  
34 speed jointly, others rather indicate a tradeoff between both levels of control, with  
35 slower movements accompanying faster decisions. Here, we aimed (1) at further  
36 investigating the existence of a shared invigoration process linking decision and  
37 movement and (2) at testing the hypothesis that such a link is masked when  
38 detrimental to the reward rate. To this aim, we tested 62 subjects who performed the  
39 tokens task in two experiments (separate sessions): Experiment 1 evaluated how  
40 changing decision speed affects movement speed while Experiment 2 assessed how  
41 changing movement speed affects decision speed. In the latter experiment, subjects  
42 were either encouraged to favor decision speed (fast decision group) or decision  
43 accuracy (slow decision group). Various mixed model analyses revealed a  
44 coregulation of decision (urgency) and movement speed in Experiment 1 and in the  
45 fast decision group of Experiment 2, but not in the slow decision group despite the fact  
46 that these same subjects displayed a coregulation effect in Experiment 1. Altogether,  
47 our findings support the idea that coregulation occurs as a default mode but that this  
48 form of control is diminished or supplanted by a tradeoff relationship, contingent on  
49 reward rate maximization. Drawing from these behavioral observations, we propose  
50 that multiple processes contribute to shaping the speed of decisions and movements.

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57 **New & NoteWorhty**

58 The principles guiding the relationship between decision and movement speed are  
59 unclear. In the present behavioral study involving two experiments conducted on 62  
60 human subjects, we report findings indicating a relationship that varies as a function of  
61 the task goals. Coregulation emerges as a default mode of control that fades when  
62 detrimental to the reward rate, possibly due to the influence of other processes that  
63 can selectively shape the speed of our decisions and movements.

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65 **5 key words:** Decision making, Urgency, Vigor, Reward Rate, Human

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## 77 Introduction

78           Every day of our life, we make decisions to interact with our environment in a  
79 goal-directed manner. Several models have been developed to explain how we select  
80 actions by describing decision making as a process of noisy accumulation of evidence:  
81 during deliberation, sensory evidence is accumulated until the total evidence in favor  
82 of one of the potential actions reaches a certain threshold, at which point the decision  
83 is made and an action is initiated (Gold & Shadlen, 2007; Hanks et al., 2014; Ratcliff  
84 et al., 2016). In the context of motor behavior, such accumulation directly converts into  
85 an increase of neural activity in the motor cortex, from a starting point to a consistent  
86 decision threshold (Cisek & Thura, 2022; Kelly et al., 2021; Ratcliff & Smith, 2004). In  
87 these models, the time taken to select a motor act is a direct function of the speed with  
88 which motor activity grows (based on evidence) and of the amount of activity required  
89 to reach the threshold, which sets the accuracy criterion.

90           Decisions can be made even when evidence is low or absent, suggesting that  
91 the accuracy criterion can be reduced if necessary. For instance, if we unexpectedly  
92 reach a junction when driving a car, we must rapidly decide whether to turn left or right,  
93 regardless of readiness and evidence, increasing the risk of an inappropriate choice.  
94 Past studies have suggested that this decrease in accuracy criterion can be  
95 implemented by an evidence-independent rising “urgency signal” pushing motor  
96 activity close to decision threshold, which is mathematically equivalent to a lowering of  
97 the latter (Churchland et al., 2008; Cisek et al., 2009; Ditterich, 2006; Murphy et al.,  
98 2016; O’Connell et al., 2018; Thura, 2020). Computationally, this urgency signal is  
99 typically modelled as increasing linearly over time (Cisek et al., 2009; Derosiere et al.,  
100 2019, 2021, 2022; Kelly et al., 2021) it includes an intercept, which reflects the degree  
101 to which motor activity is upregulated already at the onset of the decision process (i.e.,

102 context-sensitive effect), and a slope, which reflects how fast motor activity will be  
103 pushed towards the decision threshold as time elapses (i.e., time-sensitive effect).

104         Reward plays an important role in animal behavior and “reward rate”  
105 maximization is a prominent principle in the field of decision making (Lemon, 1991;  
106 Shadmehr et al., 2019). More precisely, the reward rate is the sum of all rewards  
107 acquired through our actions, minus the costs implied over the total time spent (Carland  
108 et al., 2019; Yoon et al., 2018). Critically, the urgency signal described in models of  
109 decision making is typically considered as useful for maximizing the reward rate  
110 (Carland et al., 2019; Charnov, 1976; Thura et al., 2012). That is, by its context-  
111 sensitive effect, the urgency signal can shorten the time invested to obtain the reward.  
112 In addition, by its time-sensitive effect, it allows to make decisions without waiting  
113 indefinitely, even when there is only little or no evidence.

114         Several observations in both human and non-human primates indicate that the  
115 time one takes to decide impacts the speed of the movement implementing the  
116 decision (Churchland et al., 2008; Thura et al., 2014; Drugowitsch et al., 2012). That  
117 is, faster decisions are typically followed by quicker movements. Interestingly, the  
118 reverse relationship has been observed too: one study in our lab has revealed that  
119 when the context requires movements to be performed in a shorter time period, the  
120 decisions leading to them arise faster, compared to contexts in which subjects have  
121 more time to perform the same movement (Carsten et al., 2023). Altogether, these  
122 findings suggest that the urgency signal implemented in decision making models may  
123 not solely operate at this restricted level but may shape behavior in a global manner,  
124 coregulating the speed of both decisions and movements (Carsten et al., 2023; Thura,  
125 2020). This “coregulation hypothesis” is consistent with the view that the urgency signal  
126 serves to maximize reward rate, as in most situations a speeding up of both decision

127 and movement will shorten the time required to obtain a reward (Shadmehr et al.,  
128 2019). Also consistent with this hypothesis is the fact that some studies have reported  
129 a time-sensitive effect of decision urgency on movement speed: that is, within a given  
130 context, movements that are initiated following a longer deliberation are typically faster  
131 than movements associated with earlier decisions, reflecting well the linear increase in  
132 urgency over time (Thura et al., 2014; Thura, 2020).

133 The “coregulation hypothesis” has received systematic support from studies  
134 investigating the impact of decision urgency on movement speed (Carsten et al.,  
135 2023;Thura et al., 2014; Thura, 2020). By contrast, studies that have addressed this  
136 relationship inversely, by looking at the impact of movement speed on the pattern of  
137 decision speed, have reported mixed findings (Carsten et al., 2023; Kita et al.,2023;  
138 Reynaud et al., 2020; Saleri Lunazzi et al., 2021). As mentioned above, we recently  
139 observed changes in decision speed in relation to context-dependent adjustments in  
140 movement speed that are consistent with the coregulation hypothesis (Carsten et al.,  
141 2023). It is interesting to note that in the latter study, the increase in decision speed  
142 when subjects had to perform faster movements occurred even when there was no  
143 possibility of saving time by doing so; that is, making faster decisions did not allow to  
144 shorten the trial/block duration. This led us to think that coregulation of decision and  
145 movement may be a ubiquitous feature of human behavior, one that occurs by default  
146 even when not required, arising from a neural organization that has developed  
147 because most real-life (urgent) situations require rapid actions (i.e., including fast  
148 decisions and fast movements). Yet, in their recent work, Thura and his team have  
149 reported a slowdown of decision speed (rather than a speedup) in contexts requiring  
150 subjects to perform faster movements (Reynaud et al., 2020; Saleri Lunazzi et al.,  
151 2021), reminiscent of a tradeoff rather than a coregulation effect. Yet importantly, this

152 bunch of work used an experimental design in which subjects knew that a block would  
153 only end after a fixed number of correct decisions. Hence, here speeding up decisions  
154 was detrimental to the reward rate, as the gain of time on a trial basis would have led  
155 to lengthening the experiment, given the decline in accuracy that typically accompanies  
156 faster decisions.

157 Based on these collective findings, it appears that if an urgency mechanism exists in  
158 the brain, it must interact with other processes that provide human beings with a flexible  
159 control of decision and movement for adaptive behavior according to the task goals,  
160 as previously suggested (Saleri Lunazzi et al., 2021) but never tested directly. Here,  
161 we addressed this idea in two behavioral experiments on healthy young human  
162 participants who performed a variant of the Tokens task in different contexts.  
163 Specifically, we tested the prediction that decision and movement durations would be  
164 linked by default in this task but that this coregulation would disappear in the same  
165 subjects when detrimental in terms of reward rate, as a function of the context in which  
166 they perform the task.

## 167 **Methods**

### 168 **Participants and ethical statement**

169 A total of 62 healthy human volunteers were recruited for this study, but due to  
170 technical issues the data were processed on 56 subjects (30 women,  $24.6 \pm 3.4$  years  
171 old). All participants were right-handed according to the Edinburgh Questionnaire  
172 (Oldfield, 1971) and had normal or corrected-to-normal vision. None of them had any  
173 neurological disorder or history of psychiatric illness or drug or alcohol abuse; and no  
174 one was following any clinical treatment that could have influenced performance. The  
175 protocol was approved by the Ethics Committee of the Université catholique de  
176 Louvain (UCLouvain), Brussels, Belgium (approval number: 2018/22MAI/219) and

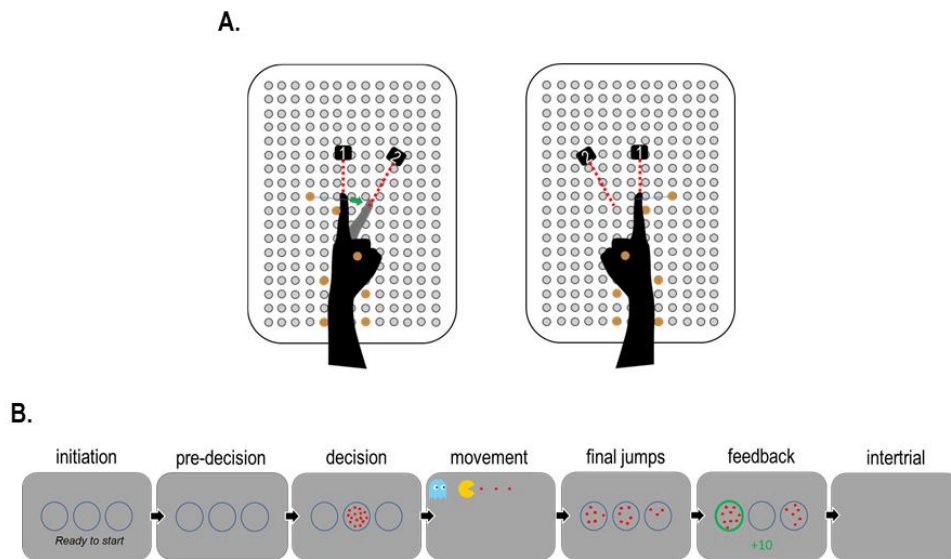


177 adhered to the principles expressed in the Declaration of Helsinki. Participants were  
178 financially compensated for their participation and provided written informed consent.

### 179 **Setup and task**

180 Experiments were conducted in a quiet and dimly lit room. Participants were seated in  
181 front of a 21-inches cathode ray tube computer screen, placed at 60 cm from the  
182 participant's eyes and used to display stimuli during the task. The display was gamma-  
183 corrected, and its refresh rate was set at 75 Hz. Participants' forearms were positioned  
184 in a neutral position (i.e., at 0 degree of pronation and supination) on a Canadian board,  
185 used to standardize and fix the resting position of the index fingers with elastic bands.  
186 Moreover, two lasers (targeting the tip of each index finger) were used to indicate the  
187 resting position (i.e., 0 degree of index flexion) and the minimum amplitude of the left  
188 or right index finger movement required in the task (i.e., 30 degrees of flexion, see Fig.  
189 1.A and below for more details).

190 We used a variant of the Tokens task (Cisek et al., 2009;Thura et al., 2014) which has  
191 already been exploited in various ways in several past studies of our lab (Derosiere et  
192 al., 2019, 2022; Fievez et al., 2022) The current version of the task was implemented  
193 with Matlab 2016 (The Mathworks, Natick, Massachusetts, USA) and the Cogent 2000  
194 toolbox (Functional Imaging Laboratory, Laboratory of Neurobiology and Institute of  
195 Cognitive Neuroscience at the Wellcome Department of Imaging Neuroscience,  
196 London, UK).



197

198 **Figure 1. Experimental material A. Setup.** Participant forearms were positioned in a neutral  
199 position on a Canadian board, with elastic bands maintaining the index fingers in a resting  
200 position. Two lasers (targeting the tip of each index finger) were used to indicate the resting  
201 position (i.e., 0 degree of flexion; laser 1) and the minimum amplitude (i.e., 30 degrees of  
202 flexion; laser 2) of the left or right index finger movement required in the task. **B. Task.** Each  
203 trial starts with an initiation phase during which participants have to perform a bilateral flexion  
204 of index fingers to signal their readiness. When index fingers return to their resting position,  
205 the 3 circles remain empty for a variable pre-decision period (150-300 ms). Then, 15 tokens  
206 appear in the central circle and start jumping one by one every 200 ms. Subjects are required  
207 to determine, as soon as they feel ready, which lateral circle will end up with the largest number  
208 of tokens (left one in this example), and to report their decision with a left or right index finger  
209 movement triggering a pacman animation (more details can be found in the main text). Once  
210 the movement phase is over, the central circle finishes to empty with the final token jumps.  
211 The trial ends with a feedback (fully successful trial in this example; more in the main text)  
212 followed by a blank screen of variable intertrial duration (1800-2000 ms).

213

### 214 ***Sequence of events in a trial***

215 The overall sequence of events for each trial of our task is depicted in Figure 1.B. Each  
216 trial starts with the appearance of 3 empty blue circles (4 cm diameter each), placed  
217 on a horizontal axis, with the sentence “Ready to start” displayed below them. During  
218 this initiation phase, subjects are required to perform a bilateral flexion of index fingers  
219 to indicate that they are ready to start the trial. When index fingers return to their resting  
220 position, the 3 circles remain empty for a short pre-decision phase of random duration

221 (150-300 ms). The decision phase then starts with the appearance of 15 randomly  
222 arranged tokens (0.3 cm diameter) in the central circle that start to jump one by one  
223 from the center to one of the 2 lateral circles, every 200 ms. The task of the subjects  
224 is to determine which of the two lateral circles will end up with the largest number of  
225 tokens and to report their decision with a left or right index finger movement. The  
226 movement phase involves a pacman animation that will be described below in more  
227 details. Once this phase is over, the final tokens continue to jump until the central circle  
228 is empty (i.e., until the 15<sup>th</sup> token jump; Jump<sub>-15</sub>). Note that subjects are told that they  
229 are expected to respond before Jump<sub>-15</sub>, as soon as they feel sufficiently confident.  
230 The trial always ends with a feedback (see below for more details) which is followed  
231 by a blank screen during a variable intertrial interval (1800-2000 ms).

### 232 ***Trial types and success probability***

233 The difficulty of the decision in each trial of the task depends on the dispersion of  
234 tokens along the jumps, which could point more or less obviously to one of the lateral  
235 circles. This pattern of token distribution and the degree to which it affects success of  
236 the subjects can be formalized with what is called the “success probability”. That is, for  
237 each trial  $i$ , and at each moment in time, we can define the success probability  $p_i(t)$   
238 associated with choosing a response (left or right). If at a moment, the left (L) circle  
239 contains  $N_L$  tokens, the right (R) once contains  $N_R$  tokens, and  $N_C$  tokens remain in  
240 the central (C) circle, then the probability that the left response is ultimately the correct  
241 one (i.e., the success probability of guessing left) is described as follows:

$$242 \quad p(L|N_L, N_R, N_C) = \frac{N_C!}{2^{N_C}} \sum_{k=0}^{\min(N_C, 7-N_R)} \frac{1}{k! (N_C - k)!} \quad (1)$$

243 Calculating this quantity for the 15 token jumps allowed us to characterize the temporal  
244 profile of success probability  $p_i(t)$  for each trial. As such, as far as the participants knew,  
245 the individual token jumps and the correct choice were completely random. However,  
246 we interspersed distinct trial types within the full sequence of trials. First, in 60% of  
247 trials, the  $p_i(t)$  remained between 0.33 and 0.66 up to Jump-8, that is, the initial token  
248 jumps were balanced between the lateral circles, keeping the  $p_i(t)$  close to 0.5 until late  
249 in these “ambiguous” trials. As such, in ambiguous trials, the tokens jumped  
250 alternatively to the correct and incorrect lateral circles until Jump-8, such that the  
251 number of tokens was equal in both lateral circles after each even jump (i.e., after 2,  
252 4, 6 and 8 jumps) and a difference of one token was present after each odd jump (i.e.,  
253 after 1,3,5 and 7 jumps). Second, in 20% of trials, the  $p_i(t)$  was above 0.7 after Jump-3  
254 and above 0.8 after Jump-5, that is, the initial jumps consistently favored the correct  
255 choice in these “obvious” trials. In the remaining 20% of trials, the  $p_i(t)$  was below 0.4  
256 after Jump-3, that is, the initial jumps favored the incorrect choice and the following  
257 ones favored the correct choice in these “misleading” trials.

### 258 ***Sensory evidence and SumLogLR***

259 As in previous studies (Cisek et al., 2009; David Thura et al., 2014; Derosiere et al.,  
260 2022), we assumed that participants would estimate the level of evidence based on  
261 the number of tokens that have already jumped into the two side circles rather than by  
262 calculating the probability of success. This estimation can be computed as a first-order  
263 approximation of the real probability function after each jump (see Eq. 1), called the  
264 sum of log-likelihood ratios (SumLogLR):

$$265 \quad \text{SumLogLR}(n) = \sum_{j=1}^n \log \frac{p(e_j|C)}{p(e_j|U)} \quad (2)$$

266 In this equation,  $p(e_j / C)$  is the likelihood of a token event  $e_j$  (a token favoring either the  
267 chosen or the unchosen response) during trials in which the chosen response C is  
268 correct, and  $p(e_j / U)$  is the likelihood of  $e_j$  during trials in which the unchosen response  
269 U is correct. The SumLogLR is proportional to the difference between the number of  
270 tokens that favored each of the 2 possible choices (i.e., that moved toward each lateral  
271 circle) at any given time.

### 272 ***Index finger movement and pacman animation***

273 As explained in more detail below in the “Experimental design” section, testing our  
274 predictions required us to characterize and/or to manipulate the movement features of  
275 index finger responses. To allow us to do so, we asked the subjects to provide their  
276 response, not with a single finger movement as we usually do, but with a tapping  
277 movement involving a repetition of 4 index finger flexions, with the left or right hand  
278 depending on their decision in the Tokens task. Moreover, this tapping movement was  
279 associated with a pacman animation. That is, as soon as the first tap was completed  
280 (i.e., flexion of at least 30 degrees, as indicated by the laser device), a pacman  
281 appeared together with 3 additional tokens in front of it, on a horizontal axis, as shown  
282 on Figure 1.B. Subjects knew that each further tap would allow the pacman to “eat”  
283 one of these supplementary tokens. The pacman was presented together with a ghost  
284 which will be described in the “Experimental Design” section, as its features depended  
285 on the experimental condition the subjects were in. Notably, the pacman animation  
286 often ended with a blank screen to cover the minimum 3000 ms period of the  
287 movement phase: as such, completing the tapping movement faster never allowed to  
288 shorten the trial duration, as in Carsten et al, 2023. Finally, note also that trials in which  
289 subjects did not provide a response before Jump-15 did not involve any pacman

290 animation; in this case participants had instead to remain still in front of a blank screen  
291 for a period corresponding to the movement phase duration.

### 292 ***Trial feedback and score calculation***

293 As a feedback at the end of the trial, the chosen circle turned either green or red,  
294 depending on whether the choice was correct or incorrect, respectively. The feedback  
295 also included a numerical score presented below the central circle, which depended  
296 on both the decision and movement requirements of the task. Subjects got +5 points  
297 for a correct decision and another +5 points for a correct tapping movement (see below  
298 for specific movement requirements). Hence, fully successful trials were worth +10  
299 points (i.e., +5+5), as illustrated on Figure 1.B. Then, any failure, whether at the level  
300 of the decision or the movement, was penalized by -2 points. Hence, a partially  
301 successful trial was worth +3 points (i.e., +5-2 or -2+5), while a fully failed trial led to -  
302 4 points (i.e., -2-2). Finally, in the absence of response before Jump-15 (i.e., a no-  
303 response trial), the displayed score corresponded to 0 point and came along with a  
304 ‘Time Out’ message at the bottom of the screen. All trial scores were summed up and  
305 displayed at the end of each block, providing a global feedback on the block to maintain  
306 motivation of participants.

### 307 **Experimental Design**

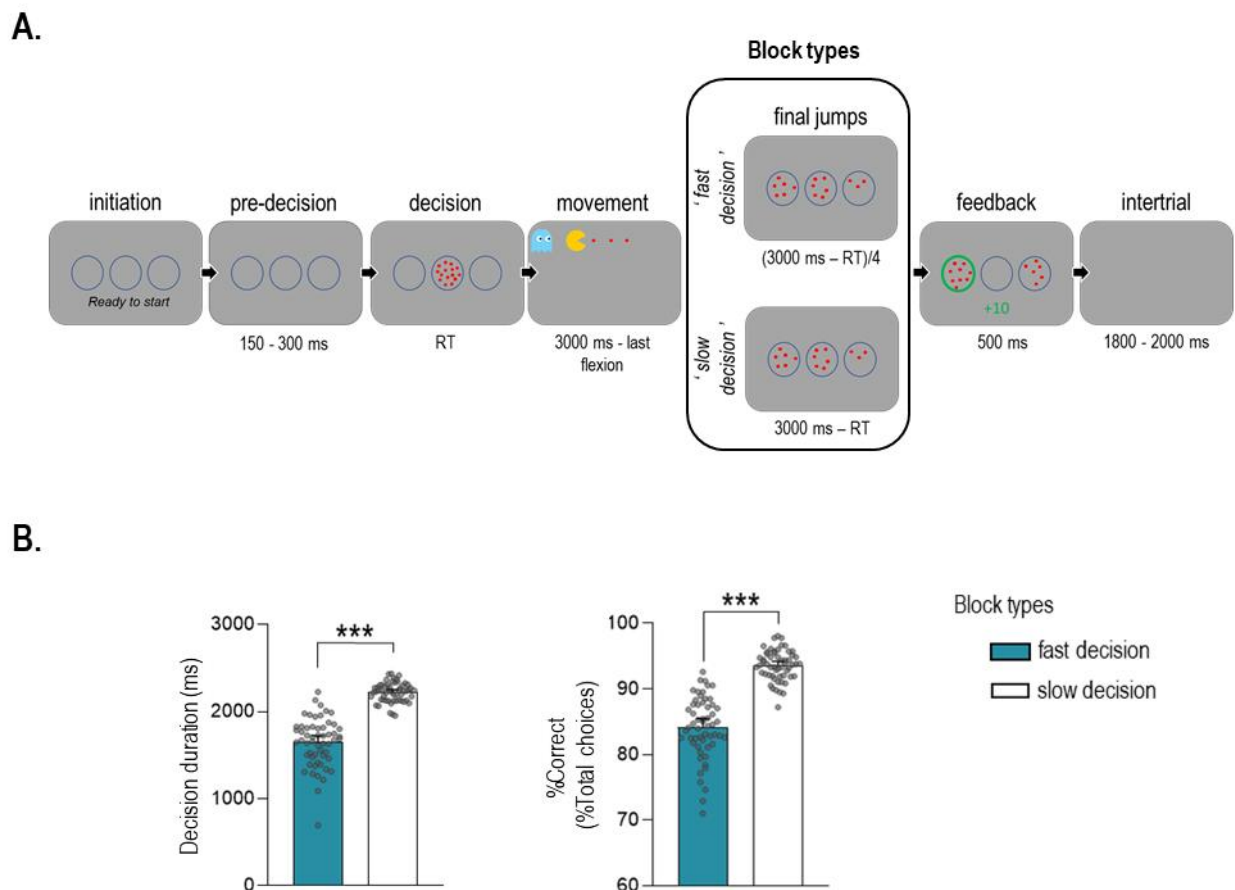
308 Participants performed two experiments as part of the current study. These  
309 experiments occurred on separate days (average interval of  $9 \pm 8$  days) and in a  
310 counterbalanced order. In Experiment 1, we designed the task such that, in separate  
311 blocks, subjects were either encouraged to make slow or fast decisions. The purpose  
312 here was to further investigate the existence of a shared invigoration process linking  
313 decision and movement by looking at how contextual changes in decision speed would  
314 influence movement speed. Inversely, in Experiment 2, we aimed at testing the reverse

315 relationship, thus how contextual changes to movement speed (slow or fast) influence  
316 decision speed. In addition, to test the hypothesis that such a link is masked when  
317 detrimental to the reward rate, we separated subjects in two groups who performed  
318 the slow and fast movement blocks in a context that either favored fast (fast decision  
319 group) or slow decisions (slow decision group). As such, we predicted that fast  
320 movement blocks would involve faster decisions (as compared to slow movement  
321 blocks) in the fast decision group (where coregulation is beneficial) but not in the slow  
322 decision group (where coregulation is detrimental). The specific features of these two  
323 experiments are described in the sections below.

### 324 ***Experiment 1***

325 All subjects (n=56) took part in Experiment 1. This experiment required participants to  
326 perform the Tokens task in two different block types, where a small adjustment to one  
327 trial event (the final jumps phase) allowed us to promote either slow (accurate) or fast  
328 decisions (see Fig. 2.A). That is, in the “slow decision” blocks, tokens kept on jumping  
329 every 200 ms during the final jump phase, as in the decision phase, until the central  
330 circle was empty. In contrast, in the “fast decision” blocks, final tokens jumped much  
331 faster (i.e., every 50 ms), such that deciding faster allowed subjects to finish the trial  
332 earlier. Because blocks had a fixed duration of 265 sec, deciding earlier in fast decision  
333 blocks allowed subjects to perform more trials and thus to accumulate more points.  
334 This was not the case in the slow decision blocks, where it was a better strategy to  
335 decide later and reach a higher accuracy, given the fixed number of trials (26) that they  
336 would be able to do over the same block duration (always about 265 sec). All of this  
337 was made explicit to the subjects to enhance the change in decision policy between  
338 the two block types. Finally, as mentioned above, the pacman animation during the  
339 movement phase also involved a ghost which, in this experiment, always chased the

340 pacman at a fixed speed established during pilot tests. Subjects knew that they had to  
341 avoid the ghost and would get a negative feedback (-2 points, as explained in the  
342 feedback section above) if they tapped so slowly that they got caught, in which case  
343 the pacman turned into a skull. Yet this happened very rarely because the imposed  
344 speed was easy to attain, as it was just there to exhort subjects to do their tapping  
345 movement in a row, as opposed to encourage them to go as fast as possible. That is,  
346 subjects were able to escape the ghost on most trials, regardless of the block type (see  
347 Fig. S1 in supplementary materials).



348

349 **Figure 2. Protocol of Experiment 1. A. Task.** In this experiment, participants performed two  
350 block types that differed according to the speed at which the final tokens jumped in the lateral  
351 circles at the end of the trial (after the finger tapping movement). That is, fast final jumps (every  
352 50 ms) led participants to prioritize decision speed (fast decision blocks) while slow jumps  
353 (every 200 ms) led subjects to rather prioritize decision accuracy (slow decision blocks). **B.**  
354 **Manipulation check.** Participants adjusted their decision policy depending on the type of block



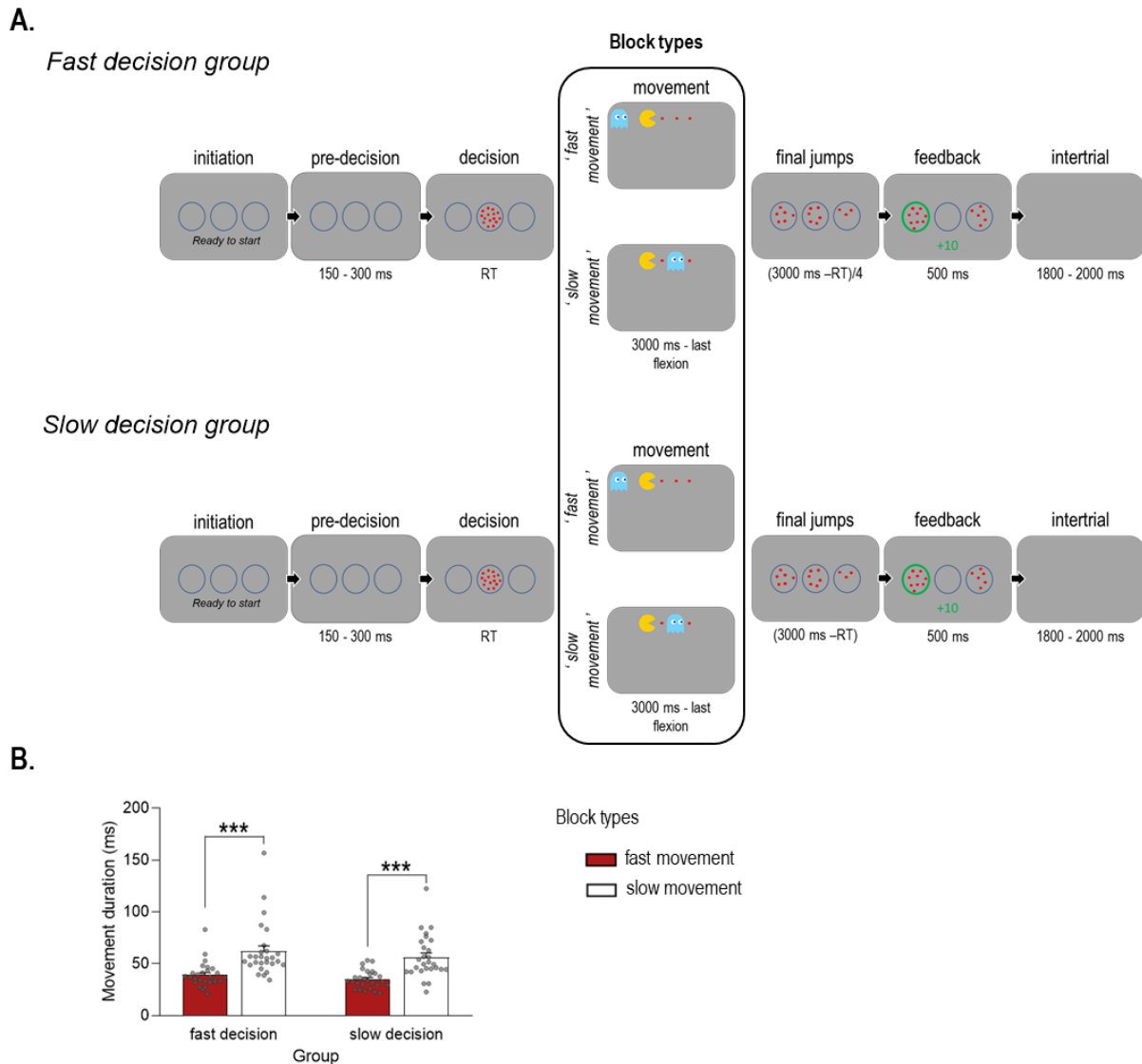
355 by making faster (shorter decision duration) and less accurate (lower %Correct) decisions in  
356 fast (blue bars) relative to slow (white bars) decision blocks. Error bars represent SE. \*\*\* $p <$   
357 0.001.

358

## 359 ***Experiment 2***

360 All subjects also performed Experiment 2 but due to a lack of data after cleaning, 2  
361 subjects had to be excluded from the analysis ( $n=54$ ; 32 Women,  $24.5 \pm 3.3$  years old).  
362 As shown on Figure 3.A, in this experiment again there were two different block types,  
363 which here differed according to the movement speed requirement. That is, subjects  
364 were explicitly asked to report their decision in the Tokens task with a tapping  
365 movement that was either fast, in the “fast movement” blocks, or slow, in the “slow  
366 movement” blocks. The exact speed that subjects had to adopt in both block types  
367 depended on their spontaneous speed. In the fast movement blocks, subjects had to  
368 tap at a speed that was twice the spontaneous speed ( $\pm 20\%$ ), while the speed in the  
369 slow movement blocks had to be equal to the spontaneous speed or to any value below  
370 it. The spontaneous tapping speed was calculated during a calibration phase at the  
371 beginning of the experiment, by asking subjects to perform a block of 15 trials of the  
372 Tokens task in a neutral condition, with no specific instruction regarding decision or  
373 movement speed. Once the average spontaneous speed was determined based on  
374 these trials, the participants were then specifically trained to perform fast tapping  
375 movements at the required speed (i.e., twice the spontaneous speed) during 4 blocks  
376 for each index finger. In these blocks, subjects repetitively tapped their index finger  
377 and each of these movements was followed by a feedback indicating if the tapping was  
378 “ok”, “too fast” ( $>20\%$  above the targeted speed) or “too slow” ( $<20\%$  below the  
379 targeted speed). A block ended as soon as subjects had completed 9 tapping

380 movements at the targeted speed. There was no training for the speed of slow  
 381 movement blocks as this speed was the one obtained spontaneously.



382  
 383 **Figure 3. Protocol of Experiment 2. A. Task.** In this experiment, participants performed two  
 384 block types that differed according to the speed at which they had to perform the finger tapping  
 385 movement; that is, at twice the spontaneous speed (fast movement blocks: pacman chased  
 386 by ghost) or at about the spontaneous speed (slow movement blocks; pacman preceded by  
 387 ghost). Moreover, subjects were split into two experimental groups according to whether they  
 388 performed the version of the task that led them to prioritize decision speed due to fast (every  
 389 50 ms) final jumps (fast decision group, upper panel), or to prioritize decision accuracy due to  
 390 slow (every 200 ms) final jumps (slow decision group, lower panel). **B. Manipulation check.**  
 391 As required by the instruction in this Experiment, participants displayed shorter (faster) tapping  
 392 movements in the fast (red bar) than slow (white bar) movement blocks, regardless of whether  
 393 they belong to the fast or slow decision group. Error bars represent SE. \*\*\* $p < 0.001$ .

394

395 As in Experiment 1, tapping movements in the Tokens task were performed in relation  
396 to a pacman (and ghost) animation, where each tap provided the opportunity to “eat”  
397 an additional token placed on a horizontal axis. Yet, here the animation served the  
398 further purpose to control for the movement speed instruction in each block type. First,  
399 to provide a guide to subjects, the ghost here was either moving behind the pacman,  
400 chasing it, in the fast movement blocks, while it was preceding the pacman, in the slow  
401 movement blocks (see Fig. 3.A). Given the continuous requirement to avoid a collision  
402 with the ghost, this feature reminded the subjects to tap rapidly (to escape the ghost)  
403 in the fast movement blocks and incited them to tap tranquilly (to avoid bumping into  
404 the ghost) in the slow movement blocks.

405 Importantly, a specificity of Experiment 2 is that we separated subjects in two groups  
406 who performed the slow and fast movement blocks in slightly different contexts, due to  
407 a small difference in the Tokens task. That is, the final tokens either jumped every 50  
408 ms or every 200 ms, allowing subjects to shorten the trial duration by deciding faster  
409 in the group performing the task in the former condition (fast decision group) but not in  
410 the group using the latter version (slow decision group). Here, the number of trials was  
411 always fixed such that shortening the trial duration never allowed to do more trials. Yet,  
412 by responding faster, subjects could save time and finish the experiment earlier. Even  
413 if these specificities remained implicit in this experiment, we expected that they would  
414 lead subjects to adjust their decision speed such that it would be generally faster in the  
415 fast decision group ( $n=27$ ; 15 women,  $25.1 \pm 3.6$  years old), and generally slower in  
416 the slow decision group ( $n=27$ ; 17 women,  $23.9 \pm 2.9$  years old). With these two  
417 groups, we aimed at testing the hypothesis that a default mode of coregulation can be  
418 observed when it naturally serves the reward rate; but it would disappear in situations  
419 where it is detrimental to the reward rate. As such, we predicted that tapping faster in

420 the fast movement blocks will translate into faster decisions, compared to the decisions  
421 in the slow movement blocks, but that this effect will only be observed in the group of  
422 subjects incited to make fast decisions but not in the slow decision group where  
423 subjects should better favor decision accuracy. Importantly, each subject completed  
424 the short version of the UPPS-P Impulsive Behavior (UPPS) scale (Eben et al., 2020).  
425 We also evaluated their ability to follow movement instructions in order to make sure  
426 that the repartition of participants in the two groups was not creating a bias in our  
427 results. The analyses showed no significant difference between the two groups of  
428 participants, considering their UPPS scores (see Table S1 in supplementary materials)  
429 or their movement performance (see Fig. S2 in supplementary materials).

#### 430 ***Time course of the experiments***

431 Experiments 1 and 2 had a largely similar time course. They both started with a  
432 familiarization phase during which subjects performed a neutral block of 10 trials to  
433 become acquainted with the basic features of the Tokens task. Subjects were then  
434 informed about the two types of blocks they would realize in the experiment. This led,  
435 after a phase of calibration (in Experiment 2 only to establish the fast tapping speed),  
436 to a training phase during which subjects practiced for 4 blocks (2 blocks of each type),  
437 each involving 15 trials (or a few more in fast decision blocks of Experiment 1). The  
438 actual experiment then started and involved a total of 18 blocks (9 blocks of each type),  
439 each involving 26 trials (or a few more in fast decision blocks of Experiment 1). Each  
440 block lasted on average 4,36 minutes and a break of 2 to 5 minutes was provided  
441 between blocks.

442 Both experiments then ended with blocks consisting of a choice reaction time (CRT)  
443 version of the Tokens task. The task in these blocks (always 40 trials) was the same  
444 as in the main experiment: subjects had to respond with a left or right index finger

445 tapping movement according to token jumps but here the 15 tokens jumped all at once  
446 in the left or right circle. Experiment 1 entailed 1 CRT block with no restriction on  
447 movement speed (i.e., “free” movements), whereas Experiment 2 entailed 1 CRT block  
448 for each tapping speed (slow or fast) condition, considering that tapping speed may  
449 impact reaction time (RT).

## 450 **Computational approach**

451 In our work we simulated the decision data by using an implementation of the urgency  
452 gating model (UGM; Cisek et al., 2009; Thura et al., 2014), in which evidence is  
453 multiplied by a linearly increasing urgency, as follows:

$$454 \quad x_i(t) = E_i(t) \times [gt + b]^+ < T, \quad (3)$$

455 where  $x_i(t)$  represents the activity of motor neurons at time  $t$  in trial  $i$ , obtained by  
456 multiplying the momentary evidence  $E_i(t)$  by an urgency signal.  $g$  and  $b$  are the slope  
457 and the y-intercept of the urgency signal, and  $[ ]^+$  denotes half-wave rectification (which  
458 set all negative values to zero). To estimate the level of evidence accumulation, we  
459 used the computation of the SumLogLR (see above, equation 2) that we low-pass  
460 filtered for dealing with intra-trial stimulus noise when calculating evidence such as the  
461 evidence accumulation. The accumulation of evidence can thus be expressed as  
462 follows:

$$463 \quad \tau \frac{dE_i(t)}{dt} = -E_i(t) + (SumLogLR(t) + N(t)) \quad (4)$$

464 The Term  $N(t)$  represents Gaussian noise with a mean of zero and a SD of 0.7 and,  
465 we used a linear differential equation with a time constant  $\tau = 200$  ms as low-pass filter  
466 (Cisek et al., 2009).

467 The model has three parameters:  $g$ ,  $b$  and  $T$ . To fit the data, we performed an  
468 exhaustive parameter grid search, with  $g$  ranging from  $1 \times 10^{-7}$  to 4,  $b$  from - 1 to 3 and  
469  $T$  from 1 to 3. This was performed separately for each subject and each block condition,  
470 and the quality of fit was assessed by using the mean square-error between data  
471 distributions of the model and the real data distributions for all decision durations in the  
472 interval between 600 and 3000 ms. Importantly, the threshold was not fixed between  
473 participants (i.e., ranged from 1 to 3) but was fixed across block conditions (i.e., for fast  
474 and slow conditions of the same experiment) to be able to compare the urgency  
475 parameters between them. After determining the best fitting parameters for each  
476 dataset, we generated a subsequent grid search from the average of the gain and  
477 slope of all subjects to determine the best pairs of parameters for a given threshold.  
478 This procedure was repeated up to 100 times to ensure parameter optimality  
479 convergence, we computed the mean shape (linear function based on  $g$  and  $b$   
480 parameters) of the resulting urgency functions.

## 481 **Data analyses**

482 Behavioral data were collected by means of custom Matlab scripts (MathWorks,  
483 Natick, Massachusetts, USA). Statistical analyses were performed using JASP  
484 (Wagenmakers et al., 2018) for repeated-measures analyses of variance (ANOVA<sub>RM</sub>),  
485 t-tests and Spearman's correlations, and using the package gamlj in jamovi (ŞAHİN &  
486 AYBEK, 2020) for linear mixed models.

## 487 ***Data processing and definition of endpoint measures***

488 In general, trials with poor performance in the decision phase and/or in the movement  
489 phase of the Tokens task were excluded in both experiments. This concerned trials  
490 with no response before Jump<sub>-15</sub> or with an anticipated response (before Jump<sub>-3</sub>). This

491 also involved removing trials where the pacman was caught by the ghost and, for  
492 Experiment 2, also trials in which the participants did not move at the required speed.  
493 Finally, the laser sometimes failed to report the index finger movements and these  
494 trials were removed too. As a result, overall, 24% of trials were removed for the  
495 analyses (17% for Experiments 1 and 31% for Experiment 2). The same procedure  
496 was followed to clean the data in the CRT task, which led to an overall removal of 11%  
497 of trials (1% and 20% for Experiments 1 and 2, respectively).

498 The endpoint measures were the same for Experiment 1 and 2. To characterize the  
499 speed at which subjects made their choice, we considered the time they took to decide.  
500 This *decision duration* was computed as the average RT in the Tokens task (computed  
501 separately for fast and slow blocks with all trial types pooled together) minus the  
502 average RT in the corresponding CRT block (Ferrucci et al., 2021). It should be noted  
503 that the majority of studies have used the RT in simple reaction time (SRT) tasks to  
504 compute the decision duration (Carsten et al., 2023; Cisek et al., 2009; Derosiere et  
505 al., 2022; Thura, 2020), but as we were using different constraints on movement speed,  
506 we chose the CRT in order to obtain a measure of the time required to prepare each  
507 type of movement (i.e., for free, fast and slow movements). Indeed, there is some  
508 evidence that even if subjects prepare their movement in advance in both the SRT and  
509 the CRT tasks, their level of preparation is lower in the CRT than in the SRT (Quoilin  
510 et al., 2019). Then, *decision accuracy* was calculated as the percentage of trials in  
511 which subjects choose the correct lateral circle, referred to as *%Correct*. Thanks to the  
512 UGM, we also obtained the intercept and the slope of an urgency signal for each  
513 participant and each type of block, as an additional primary endpoint measure. These  
514 two parameters then enabled us to estimate the evolution of the *urgency level* over  
515 time. To characterize the speed at which subjects moved, we considered the time it

516 took for participants to perform the index flexion movements. Hence, *movement*  
517 *duration* corresponds to the mean duration of a single tap averaged over the four  
518 flexions participants performed in each trial of the task.

## 519 ***Statistical analyses***

### 520 **Experiment 1**

521 The purpose of this experiment was to further investigate the existence of a shared  
522 invigoration process linking decision and movement by looking at how contextual  
523 changes in decision speed influence movement speed.

#### 524 *Effect of decision-related instructions on decision endpoint measures*

525 In order to check whether subjects followed instructions and changed their decision  
526 policy between fast and slow decision blocks, we first ran paired t-tests on decision  
527 duration and decision accuracy. We then considered the urgency signal estimated for  
528 each type of block, running a mixed model with BlockType (fast decision, slow  
529 decision) as a factor, Time (elapsed during the decision phase) as a covariate and  
530 subject number as a cluster variable ( $Urgency \sim BlockType * Time + (BlockType * Time|Subject)$ ). Since we hypothesized a relationship between urgency and decision  
531 duration that would hold true across subjects, the covariable was not scaled.

#### 533 *Effect of decision-related instructions on movement endpoint measures*

534 To investigate the context and time-sensitive effect of decision duration, we ran general  
535 mixed models on movement duration with BlockType (fast decision, slow decision) as  
536 a factor, decision duration as a covariate and subject number as a cluster variable  
537 ( $Movement\ duration \sim BlockType * Decision\ duration + (BlockType * Decision\ duration|Subject)$ ). Our hypothesis was that movement and decision duration correlate



539 within- but not necessarily between-subjects. Hence to get rid of individual average  
540 differences in decision duration, we used Z-scores clusterwise to scale the covariable  
541 (i.e., decision duration). Post-hoc comparisons were conducted using t-tests with  
542 Bonferroni correction for multiple comparisons. Monotonic relationships between  
543 block-related changes in movement and block-related changes in urgency/decision  
544 were tested using Spearman's rank correlations.

## 545 **Experiment 2**

546 Here, we aimed at investigating the reverse relationship, as compared to Experiment  
547 1; that is, how contextual changes to movement speed influence decision speed. In  
548 addition, this experiment aimed at testing the hypothesis that such a link is masked  
549 when detrimental to the reward rate.

### 550 *Effect of movement-related instructions on movement endpoint measures*

551 In order to check whether subjects followed instructions in both groups and changed  
552 their movement speed between fast and slow movement blocks, we performed a two-  
553 way ANOVA<sub>RM</sub> on movement duration with BlockType (fast movement, slow  
554 movement) and Group (fast decision group, slow decision group) as within-subject  
555 factors.

### 556 *Effect of movement-related instructions on decision endpoint measures*

557 The analyses for Experiment 2 were similar to those for Experiment 1, except that here,  
558 we looked at the reverse relationship by running a general mixed model on decision  
559 duration with BlockType (fast movement, slow movement) and Group (fast decision,  
560 slow decision) as factors, movement duration as covariable and subject number as a  
561 cluster variable (*Decision duration ~ Group \* BlockType \* Movement duration + (Group*  
562 *\* BlockType \* Movement duration|Subject)*).

## 563 **Exploratory investigation of pupil dilation**

564 In Experiment 1, we recorded pupil diameter from 19 of the 62 participants during task  
565 performance. However, one participant did not finish the experiment, so pupil data  
566 were analyzed on 18 participants (11 Women,  $24.5 \pm 3.7$  years old). This allowed us  
567 to investigate the involvement of the arousal system (proxied by pupil size) in  
568 generating the urgency signal (McGinley et al., 2015; Wagenmakers et al., 2018). To  
569 this end, the pupil diameter was acquired with an EyeLink 1000+ eye tracker video-  
570 based system (SR Research), recording monocularly pupil size (in arbitrary units) and  
571 eye movements with a sampling frequency of 1000 Hz. Before analyzing the data, pupil  
572 traces were preprocessed to remove eye-blinks, which were identified by the blink  
573 detection algorithm implemented in Matlab ([https://github.com/alexandre-](https://github.com/alexandre-zenon/pupil/)  
574 [zenon/pupil/](https://github.com/alexandre-zenon/pupil/)), and replaced by linear interpolations. Furthermore, traces were first  
575 filtered by a high-pass filter of 0.01 Hz, then downsampled to 10 Hz to facilitate the  
576 analysis. In order to characterize block-related changes in pupil size during the  
577 decision phase, we extracted the peak of pupil dilation following the first flexion  
578 initiation in each trial (see Fig. S3 in supplementary materials). We then analyzed these  
579 Peak pupil data by means of a mixed model with BlockType (fast decision, slow  
580 decision) as a factor, decision duration as covariable and subject number as a cluster  
581 variable ( $Peak\ pupil \sim BlockType * Decision\ duration + (BlockType * Decision$   
582  $duration|Subject)$ ). Similarly to the urgency signal analysis, we did not scale the  
583 covariable. This analysis allowed us to investigate whether Peak pupil size would  
584 evolve as a function of decision duration, as shown for urgency, both in the fast and  
585 slow decision blocks. Then, in an additional analysis aimed at further characterizing  
586 the evolution of Peak pupil size over time elapsed during deliberation, we obtained for  
587 each subject the mean Peak pupil dilation in 8 bins of decision duration (from short to

588 long) and fitted these pupil data with a linear regression to obtain an intercept and a  
589 slope. These pupil parameters (intercept and slope) were put in relation to those  
590 extracted from the urgency signal (intercept and slope) with Spearman's rank  
591 correlations.

## 592 **Results**

### 593 **Experiment 1**

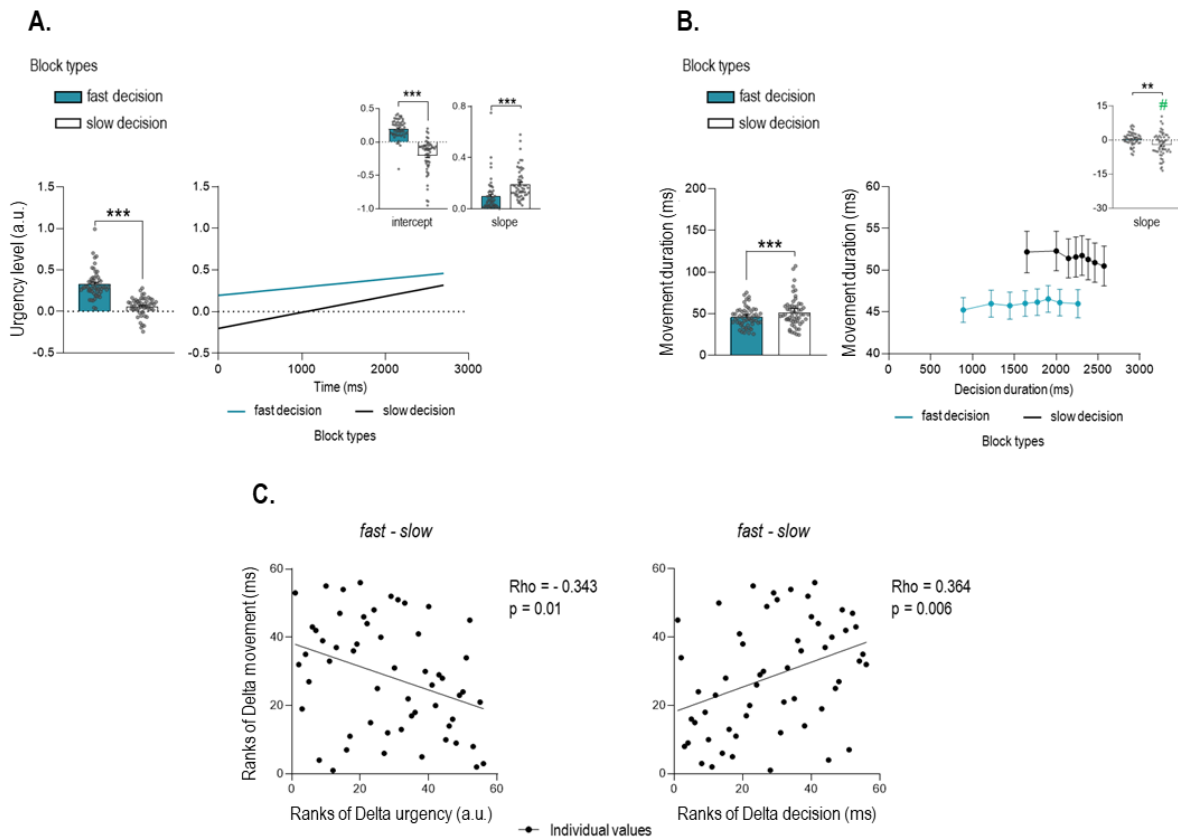
#### 594 ***Subjects adjusted their decision duration according to the block instruction***

595 In this experiment, we had participants perform the Tokens task in fast and slow  
596 decision blocks, which required them to favor either decision speed or accuracy,  
597 respectively. Consistently, participants took less time to decide in the fast ( $1647 \pm 276$   
598 ms) than in the slow decision blocks ( $2220 \pm 111$  ms;  $t_{1,55} = -15.236$ ,  $p < 0.001$ ,  
599 Cohen's  $d = -2.036$ , see Fig. 2.B). This shortening in decision duration influenced  
600 choice accuracy: participants were less accurate when deciding in the fast decision  
601 blocks ( $84 \pm 5$  % of correct choices) than in the slow decision ones ( $94 \pm 2$  %;  $t_{1,55} = -$   
602  $14.175$ ,  $p < 0.001$ , Cohen's  $d = -1.894$ ). These findings indicate that participants  
603 followed the instructions by adopting a strategy favoring speed in the fast decision  
604 blocks and accuracy in the slow decision blocks.

605 Block-related changes in decision duration were reflected in the level of urgency (Thura  
606 et al., 2014; Derosiere et al., 2022). Indeed, the mixed model analysis on the urgency  
607 signal revealed a main effect of the factor BlockType (see Fig. 4.A,  $F_{1,55} = 101$ ,  $p <$   
608  $0.001$ ): as expected, the level of urgency was on average higher in the fast ( $0.327 \pm$   
609  $0.166$  a.u.) than in the slow decision blocks ( $0.059 \pm 0.107$  a.u.). Importantly, this effect  
610 was also true when considering the decision period in separate temporal bins (see  
611 Table S2 in supplementary materials): the urgency level was higher in the fast than in

612 the slow decision blocks, regardless of the bin considered, up to the last temporal one  
613 (all  $t_{1,55} > 3.760$ , all  $p < 0.001$ , all Cohen's  $d > 0.500$ ). Moreover, the mixed model  
614 analysis revealed a significant effect of the factor Time ( $F_{1,55} = 112$ ,  $p < 0.001$ ),  
615 indicating that urgency increased as the time elapsed during deliberation in both fast  
616 and slow decision blocks, as also previously shown (Cisek et al., 2009; Thura et al.,  
617 2014; Derosiere et al., 2022; Murphy et al., 2016; Steinemann et al., 2018). Finally, we  
618 observed a significant BlockType x Time interaction ( $F_{1,951} = 475$ ,  $p < 0.001$ ),  
619 suggesting that the time course of urgency differed between the two block types. To  
620 further address this point, we considered the intercept and the slope of the urgency  
621 signal (estimated with the urgency gating model) in both block types. Interestingly,  
622 paired-t-tests revealed a significantly higher intercept in fast decision blocks ( $0.195 \pm$   
623  $0.140$  a.u.) compared to the slow decision ones ( $- 0.200 \pm 0.251$  a.u.;  $t_{1,55} = 11.097$ ,  $p$   
624  $< 0.001$ , Cohen's  $d = 1.483$ ), indicating a greater urgency at decision onset in the  
625 former blocks. However, the urgency exhibited a slower increase in the fast than in the  
626 slow decision blocks. That is, although the slope was significantly positive in both block  
627 types (both  $t_{1,55} > 5.000$ , both  $p < 0.001$ , both Cohen's  $d > 0.700$ ), it was nevertheless  
628 smaller in the fast ( $0.097 \pm 0.125$  a.u.) than in the slow decision blocks ( $0.192 \pm 0.119$   
629 a.u.;  $t_{1,55} = - 5.241$ ,  $p < 0.001$ , Cohen's  $d = - 0.700$ ). Hence, the urgency was generally  
630 higher when subjects were in a context promoting fast decisions, with a peak difference  
631 at decision onset; from there on urgency increased over time in both block types but  
632 did so slower in the fast decision blocks, thus reducing the gap with the slow decision  
633 blocks, although the difference remained significant until the end of the decision  
634 process.

635



636

637 **Figure 4. Results for Experiment 1. A. Urgency signal.** The block-related changes in  
 638 decision duration were reflected in the level of urgency (left panel), with a higher level of  
 639 urgency in fast (blue bar) than slow decision blocks (white bar). Consistent with the literature,  
 640 the evolution of the urgency signal over time (right panel) depended on the type of block: it  
 641 was higher at decision phase onset (greater intercept, top left inset) and increased more slowly  
 642 (lower slope, top right inset) in fast compared to the slow decision blocks. **B. Movement**  
 643 **duration.** Decisions were implemented by shorter (faster) movements in fast decision  
 644 compared to slow decision blocks (left panel) even if such a coregulation was not beneficial to  
 645 the reward rate. Notable, we also found that movement duration shortened with increasing  
 646 decision duration, but this was only true in slow decision blocks (negative slope, the inset) **C.**  
 647 **Correlations.** The more participants responded with a high level of urgency in fast decision  
 648 compared to slow decision blocks, the more their movements became shorter (faster) in the  
 649 fast compared to the slow decision blocks (left panel). Similarly, those participants with the  
 650 largest reduction in decision duration were also those who shortened their movements the  
 651 most in the fast compared to the slow decision blocks (right panel). Error bars represent SE. #  
 652 t-test against 0  $p < 0.025$ . \*\*\* $p < 0.001$ .

653

#### 654 ***Movement duration was influenced by increasing decision urgency***

655 In this first experiment, we assessed the coregulation hypothesis by investigating the  
 656 impact of changes in decision urgency on movement duration. Based on this

657 hypothesis and in line with prior work (Carsten et al., 2023; Thura et al., 2014; Thura,  
658 2020), we expected that the higher urgency in the fast decision blocks would also  
659 fasten the motor response, resulting in shorter (faster) movements in fast decision  
660 blocks. Consistently, the mixed model analysis on movement duration revealed a main  
661 effect of the factor BlockType ( $F_{1,55.1} = 24.46$ ,  $p < 0.001$ ), with shorter values in fast ( $46$   
662  $\pm 12$  ms) than in slow decision blocks ( $51 \pm 18$  ms, see Fig. 4.B). Moreover, the analysis  
663 revealed a significant BlockType x decision duration interaction ( $F_{1,47.2} = 11.14$ ,  $p =$   
664  $0.002$ ). In order to consider further this interaction, we grouped the movement duration  
665 data in 8 bins of decision duration (see Fig. 4.B). Then, we calculated a delta on the  
666 global movement duration of the first and the last bins in order to express the change  
667 in movement duration (Delta movement). The same delta was calculated on decision  
668 duration (Delta decision) to finally compute a slope representing how much movement  
669 duration varied as a function of changes in decision duration (i.e., Delta movement  
670 /Delta decision). A negative slope would indicate a shortening of movement duration  
671 with increasing decision duration while a positive slope would reflect the opposite  
672 relationship, that is, a lengthening of movement duration with decision duration.  
673 Interestingly, the slope was negative in the slow decision blocks ( $- 2.11 \pm 5.14$ ;  $t_{1,55} = -$   
674  $3.076$ ,  $p < 0.025$  with Bonferroni correction, Cohen's  $d = - 0.411$  when compared to 0  
675 using Student's t-tests) but it was null in the fast decision blocks ( $0.438 \pm 2.779$ ;  $t_{1,55} =$   
676  $1.180$ ,  $p = 0.243$ , Cohen's  $d = 0.158$ ). Consistently, the slope was found significantly  
677 lower in the slow than in the fast decision blocks (paired  $t_{1,55} = 3.159$ ,  $p < 0.01$ , Cohen's  
678  $d = 0.422$ ). Hence, altogether the analyses indicate globally shorter movement  
679 durations in the fast (higher urgency) than in the slow decision blocks but with an  
680 acceleration of movement execution over deliberation time occurring in the latter but  
681 not in the former decision blocks.

682 We then continued to investigate the relationship between decision urgency and  
683 movement duration by means of correlations. To do so, we computed deltas of  
684 movement duration between the fast and slow decision blocks (delta fast-slow decision  
685 blocks) and considered the degree to which changes in movement duration between  
686 the two block types were related to the instructed changes in decision speed. To  
687 characterize the latter, we computed both the delta of urgency and the delta of decision  
688 duration, as depicted on the left and right sides of Figure 4.C., respectively.  
689 Interestingly, Delta movement duration correlated negatively with Delta urgency ( $Rho$   
690  $= -0.343$ ,  $p = 0.01$ , 95%-confidence intervals [CI] =  $[-0.553, -0.079]$ ), indicating that  
691 the more urgency got high in fast compared to slow decision blocks (higher delta  
692 values), the more movements became short (fast) in this type of block (lower delta  
693 values). Considering deltas in decision duration instead of urgency led to the same  
694 result, which here was manifest as a positive correlation ( $Rho = 0.364$ ,  $p = 0.006$ , CI =  
695  $[0.114, 0.577]$ ): the more subjects shortened their decision duration in fast compared  
696 to slow decision blocks (lower deltas), the more the movements became shorter (lower  
697 deltas). Altogether, these findings are consistent with a coregulation of decision and  
698 movement speed (Carsten et al., 2023; Spieser et al., 2017; Thura, 2020).

## 699 **Experiment 2**

### 700 ***Subjects adjusted their movement duration according to the block instruction***

701 In this experiment, we had participants perform the Tokens task in fast and slow  
702 movement blocks, which required them to report their decision with either fast or slow  
703 index finger flexions. Consistent with these instructions and as shown on Figure 3.B,  
704 the ANOVA<sub>RM</sub> revealed that movements were on average of shorter duration in the fast  
705 ( $37 \pm 11$  ms) than in the slow movement blocks ( $59 \pm 24$  ms;  $F_{1,53} = 106.879$ ,  $p < 0.001$ ,  
706 partial eta-squared ( $\eta_P^2$ ) = 0.673). Moreover, participants in this experiment were split

707 in two groups where they were implicitly encouraged to either favor decision speed  
708 (fast decision group) or decision accuracy (slow decision group). Participants in both  
709 groups displayed equivalent movement durations according to the specific instructions  
710 of the two block types, as indicated by the absence of factor Group or BlockType X  
711 Group interaction on movement duration (all  $F_{1,53} = [0.111, 1.257]$ ,  $p = [0.267, 0.740]$ ,  
712  $\eta^2 = [0.002, 0.024]$ ).

### 713 ***Decision duration was influenced by movement duration***

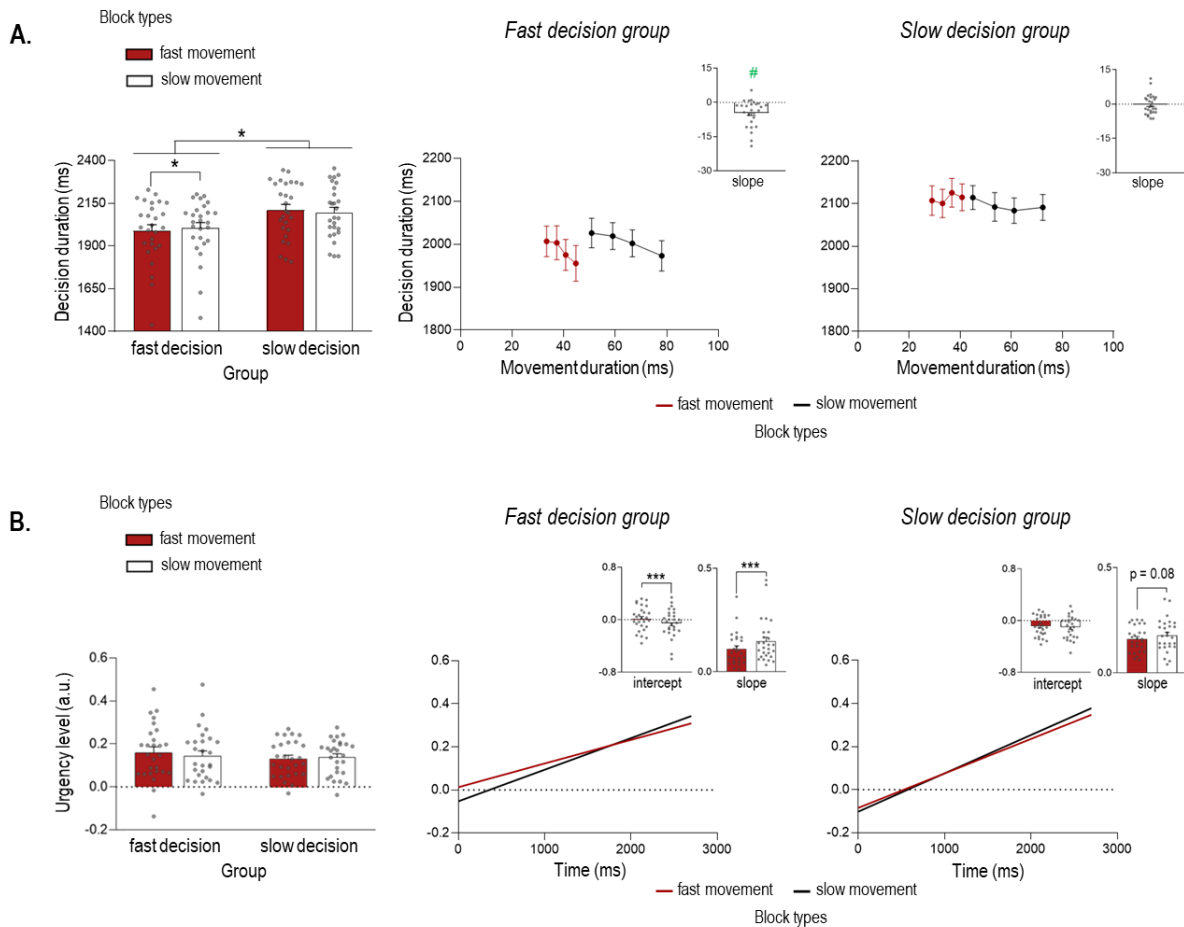
714 In this experiment, we assessed the coregulation hypothesis by investigating the  
715 impact of block-related changes in movement duration on decision urgency. Based on  
716 this hypothesis and in line with prior work (Carsten et al., 2023; Kita, et al., 2023.), we  
717 expected that the requirement to move fast would naturally increase the urgency,  
718 resulting in shorter (faster) decisions in fast than slow movement blocks. Yet, as  
719 explained in the introduction, we expected that this should only occur if such a  
720 coregulation is not detrimental to the reward rate. In other words, we predicted that  
721 moving faster in the fast movement blocks would only translate into faster decisions  
722 (higher urgency) in the group favoring decision speed anyway (fast decision group) but  
723 not in the group prioritizing decision accuracy (slow decision group).

724 Unsurprisingly, the mixed model analysis revealed a significant effect of the factor  
725 Group on decision duration ( $F_{1,55.9} = 6.32$ ,  $p = 0.015$ ). As such, decision durations were  
726 shorter in the fast decision group ( $1997 \pm 175$  ms) than in the slow decision group  
727 ( $2104 \pm 158$  ms), as implicitly promoted in this experiment. Furthermore, we found a  
728 significant Group x BlockType interaction on decision duration ( $F_{1,143.3} = 6.82$ ,  $p =$   
729  $0.010$ ; see Fig. 5.A). As such, changes in movement duration from the slow to the fast  
730 movement blocks elicited distinct effects on decision duration depending on the group.  
731 That is, post-hoc analyses revealed that participants in the fast decision group made



732 shorter decisions in fast ( $1990 \pm 183$  ms) than slow movement blocks ( $2004 \pm 170$  ms;  
733  $t_{161.1} = 2.957$ ,  $p < 0.025$  with Bonferroni correction). Such an effect was not found in the  
734 slow decision group, where decision durations were not significantly different between  
735 the fast ( $2112 \pm 164$  ms) and slow movement blocks ( $2096 \pm 154$  ms;  $t_{126.4} = -0.667$ ,  
736  $p = 1.000$ ). Hence, faster movements led participants to decide faster when such a  
737 coregulation was consistent with their task goal, in the fast decision group, but not  
738 when it would have been detrimental, in the slow decision group.

739 The mixed model analysis also revealed a main effect of the factor movement duration  
740 ( $F_{1,16459.4} = 8.21$ ,  $p = 0.004$ ) on decision duration. Similar to the analysis run in  
741 Experiment 1, we grouped decision duration in bins of movement duration (here we  
742 used 4 bins) in order to calculate a delta between the first and the last bins on decision  
743 (Delta decision) and movement durations (Delta movement). These deltas were then  
744 used to compute a slope expressing changes in decision duration as a function of  
745 changes in movement duration (Delta decision/Delta movement). A Student's t-test  
746 against 0 showed that the slope was significantly negative ( $t_{1,53} = -3.152$ ,  $p < 0.01$ ,  
747 Cohen's  $d = -0.429$ ) indicating that long movement durations were associated with  
748 short decision durations. However, this effect interacted with the factor Group  
749 (Movement duration  $\times$  Group  $F_{1,16459.4} = 5.00$ ,  $p < 0.05$ ). More precisely, following  
750 Student's t-tests against 0, the slope was significantly negative in the fast decision  
751 group ( $-4.606 \pm 5.824$ ;  $t_{1,26} = -4.109$ ,  $p < 0.001$ , Cohen's  $d = -0.791$ ) but not in the  
752 slow decision group ( $-0.177 \pm 4.392$ ;  $t_{1,26} = -0.210$ ,  $p = 0.835$ , Cohen's  $d = -0.040$ ).  
753 This suggests that, only in the fast decision group, movement duration varied as a  
754 function of deliberation time, as observed in Experiment 1. All other effects of the mixed  
755 model were nonsignificant ( $p = [0.092 \text{ } 0.509]$ ).



756

757 **Figure 5. Results for Experiment 2. A. Decision duration.** As expected, participants in the  
 758 fast decision group made faster decisions than those in the slow decision group (left panel).  
 759 Moreover, as also shown on the left panel, only in the fast decision group were decision  
 760 durations affected by the movement block type, with shorter (faster) decisions accompanying  
 761 faster movements (red bar). On the right panel you can also see that long movement durations  
 762 were associated with short decision durations only in fast decision group (see insets displaying  
 763 specifically the slope in the fast and slow decision groups). **B. Urgency signal.** The overall  
 764 urgency level did not differ significantly between the two groups and the two types of block (left  
 765 panel). However, as shown on the right panel, its evolution over time differed between the two  
 766 groups of subjects. More precisely, the movement block type affected the intercept and the  
 767 slope of the urgency signal in the fast decision group with only a marginal effect on the slope  
 768 in the slow decision group. Indeed, the urgency signal was higher at the decision phase onset  
 769 (greater intercept, top left inset) and increased more slowly (lower slope, top right inset) in fast  
 770 (red bar) block relative to slow (black bar) movement blocks in the former group only. Error  
 771 bars represent SE. # t-test against 0 p < 0.05, \*p < 0.05, \*\*\*p < 0.001.

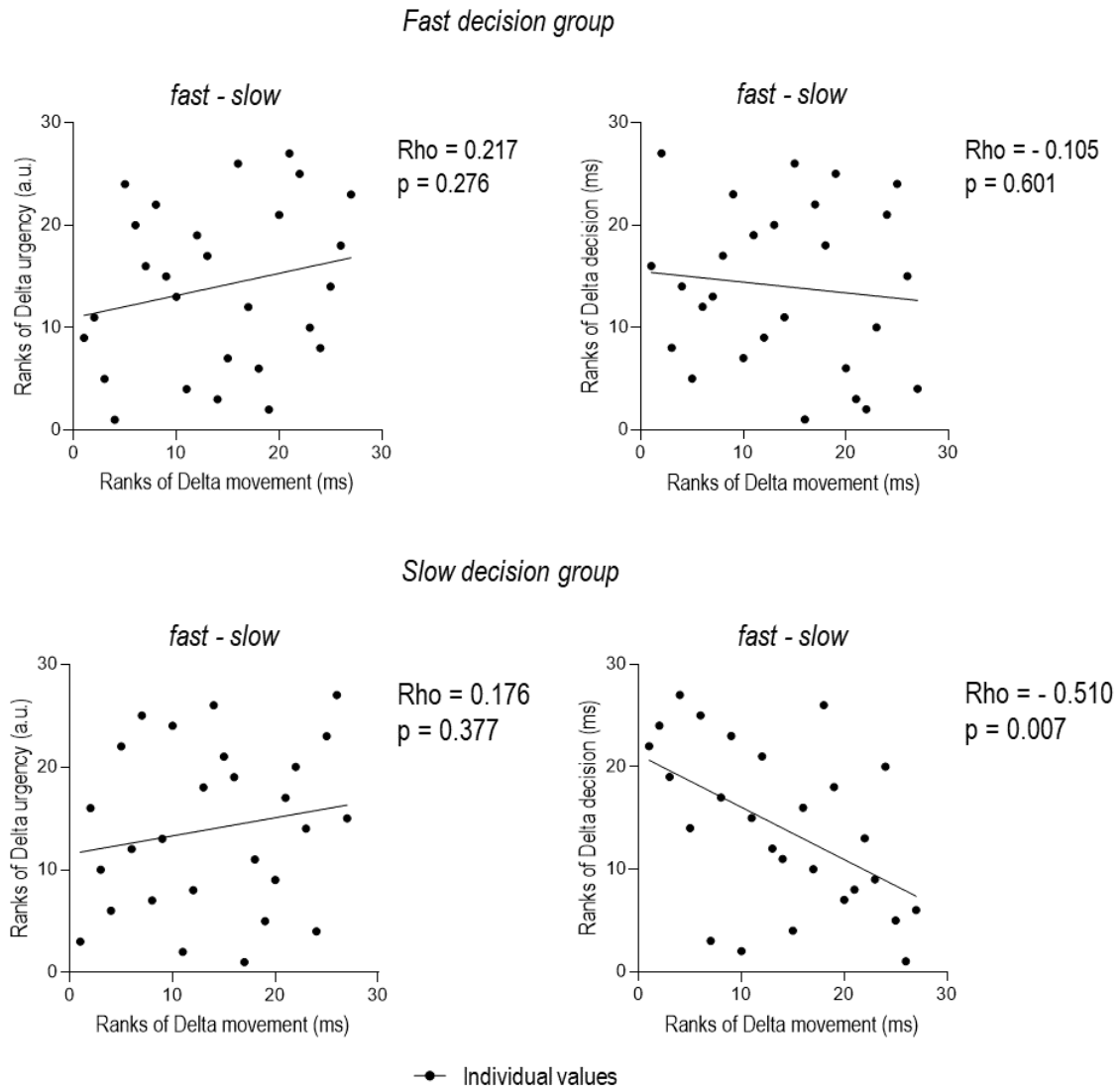
772

773 We then assessed the impact of varying the movement speed in the two different block  
 774 types on decision urgency itself (see Fig. 5.B). The mixed model analysis revealed a

775 main effect of the factor Time on the urgency signal, consistent with an increasing  
776 urgency over time ( $F_{1,47.9} = 197.94$ ,  $p < 0.001$ ). Moreover, we found that this main effect  
777 interacted with the factor BlockType, indicating that the urgency signal generally  
778 increased faster in slow relative to fast movement blocks (BlockType x Time  
779 interaction;  $F_{1,916} = 266.65$ ,  $p < 0.001$ ). Most interestingly, this interaction depended on  
780 the Group (Group x BlockType x Time interaction;  $F_{1,916} = 32.30$ ,  $p < 0.001$ ). To better  
781 understand this triple interaction, we ran further analyses on the intercept and the slope  
782 of the urgency signal (as in Experiment 1). More precisely, paired t-tests revealed a  
783 higher urgency intercept in fast ( $0.013 \pm 0.186$  a.u.) than slow movement blocks ( $-$   
784  $0.053 \pm 0.215$  a.u.;  $t_{1,26} = 2.854$ ,  $p < 0.01$ , Cohen's  $d = 0.549$ ) for the fast decision  
785 group, whereas the urgency intercept was around  $0.093 \pm 0.163$  a.u. in both block  
786 types for the slow decision group ( $t_{1,26} = 0.915$ ,  $p = 0.369$ , Cohen's  $d = 0.176$ ). Hence,  
787 urgency was greater at the decision onset in the fast than in the slow movement blocks  
788 only for the fast decision group. Yet, it seems that urgency then increased more slowly  
789 in fast movement blocks, especially in fast decision group. Indeed, for this group, the  
790 urgency slope was lower in fast ( $0.110 \pm 0.079$ ;  $t_{1,26} = -3.645$ ) than slow movement  
791 blocks ( $0.147 \pm 0.103$  a.u.;  $t_{1,26} = -3.645$ ,  $p = 0.001$ , Cohen's  $d = -0.701$ ). The  
792 difference between fast ( $0.160 \pm 0.061$  a.u.) and slow movement blocks ( $0.178 \pm 0.078$   
793 a.u.) was still present in the slow decision group, although smaller and marginal ( $t_{1,26}$   
794  $= -1.83$ ,  $p = 0.079$ , Cohen's  $d = -0.351$ ). In other words, the urgency signal was higher  
795 at the decision phase onset (greater intercept) and increased slower (lower slope) in  
796 fast relative to slow movement blocks in the group pushed to decide quickly while it  
797 remained mostly unchanged between the two block types in the group pushed to  
798 decide slowly. All other effects of the mixed model were nonsignificant ( $p = [0.154$   
799  $0.558]$ ). These results suggest that the instruction to boost movement speed in the fast

800 movement blocks induced a parallel increase of urgency when this was consistent with  
801 the task goals, in the fast decision group. By contrast, boosting movement speed did  
802 not have such an effect in the slow decision group, when it would have been  
803 detrimental. In this case, the subjects decided at a similar speed during both slow and  
804 fast movement blocks.

805 Finally, we investigated how the switch in movement speed between fast and slow  
806 movement blocks impacted urgency and decision duration. To do so, we computed,  
807 as in the Experiment 1, the deltas between the fast and slow movement blocks (delta  
808 fast-slow movement blocks) and looked at how Delta urgency and Delta decision  
809 duration correlated with Delta movement duration in both decision groups, as depicted  
810 on Figure 6. Interestingly, their relationship differed from the Experiment 1. In the fast  
811 decision group, there was no relationship with Delta movement duration whether we  
812 considered the Delta urgency ( $Rho = 0.217$ ,  $p = 0.276$ ,  $CI = [-0.191, 0.538]$ ) or the  
813 Delta decision duration ( $Rho = -0.105$ ,  $p = 0.601$ ,  $CI = [-0.451, 0.318]$ ). In the slow  
814 decision group, we also found no significant correlation between Delta urgency and  
815 Delta movement duration ( $Rho = 0.176$ ,  $p = 0.377$ ,  $CI = [-0.213, 0.539]$ ). Surprisingly,  
816 we found in this group a relationship between changes in movement duration and  
817 decision duration, but here Delta decision duration correlated negatively with Delta  
818 movement duration ( $Rho = -0.510$ ,  $p = 0.007$ ,  $CI = [-0.779, -0.141]$ ), suggesting that  
819 participants with shorter movements in fast relative to slow movement blocks (lower  
820 deltas) were those who waited the longest to make their decisions (higher deltas).



821

822 **Figure 6. Correlations for Experiment 2.** For the fast decision group (upper panel), we did  
823 not find any relationship between block-related changes in movement duration (Ranks of Delta  
824 movement) and block-related changes in decision features, whether we considered changes  
825 in urgency level (Ranks of Delta urgency, left) or changes in decision duration (Ranks of Delta  
826 decision, right). For the slow decision group (lower panel), Delta Movement did not correlate  
827 with Delta urgency (left) but correlated negatively with Delta decision (right).

828

829 In summary, our data in Experiment 2 also indicate a natural coregulation between  
830 decision and movement speed when considering the fast decision group in Experiment  
831 2. In contrast, movement speed instructions in the slow decision group did not seem  
832 to have any impact on decision speed or on urgency. If anything, the correlations

833 revealed a negative relationship between block-related changes in movement and  
834 decision speed in that group favoring accuracy in Experiment 2.

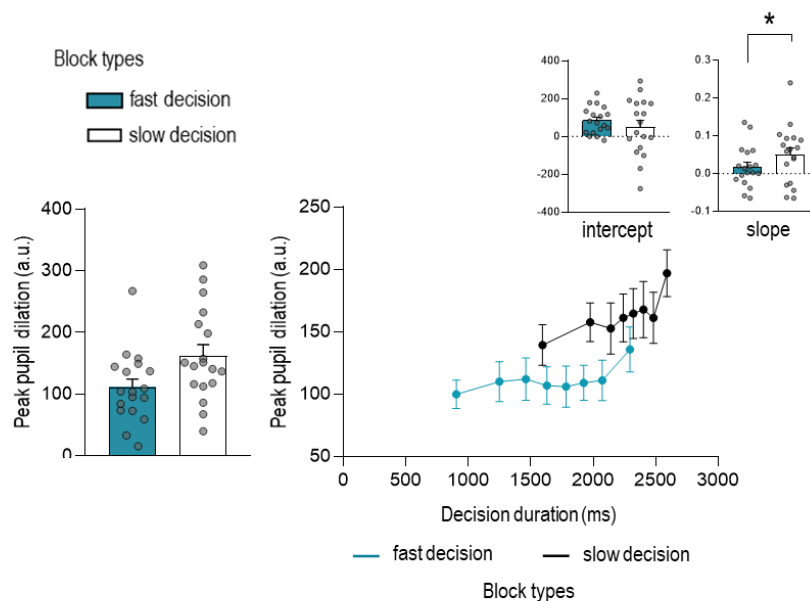
## 835 **Analyses of pupil dilation**

### 836 ***Pupil dilation increased with both urgency and accuracy requirements***

837 Previous studies have shown that increases in urgency induce pupillary dilation (Gross  
838 & Dobbins, 2021; Murphy et al., 2016; Reppert et al., 2023; Steinemann et al., 2018).  
839 However, the link between pupil dilation and decision urgency is still much debated in  
840 the literature. That is, while some have suggested that pupil dilation reflects the  
841 involvement of the arousal system in the generation of the urgency signal (Murphy et  
842 al., 2016), others have proposed that the urgency-related pupillary dilation rather  
843 results from an increased recruitment of the arousal system to ensure decision  
844 accuracy under time pressure (Steinemann et al., 2018). In order to directly address  
845 this question in the current study, we analyzed pupil dilation as a function of decision  
846 duration, in 18 of the subjects who took part in Experiment 1.

847 The mixed model on Peak pupil dilation did not reveal any significant effect of the factor  
848 BlockType ( $F_{1,8257} = 0.616$ ,  $p = 0.433$ ;  $111 \pm 57$  a.u. for fast decision blocks and  $163 \pm$   
849  $74$  a.u. for slow decision blocks; see Fig. 7). However, the analysis revealed a main  
850 effect of the factor decision duration ( $F_{1,8265} = 30.173$ ,  $p < 0.001$ ), indicating that pupil  
851 dilation increased with decision duration in both types of blocks. Interestingly, this effect  
852 interacted with the factor BlockType (BlockType x decision duration interaction;  $F_{1,8265}$   
853  $= 30.173$ ,  $p < 0.001$ ). In order to understand this interaction, we estimated the intercept  
854 and slope of the pupil function in each block type by means of linear regressions (see  
855 related section in Methods for more details) and compared them across block types.  
856 The intercept, which thus reflects pupil size at the onset of the decision phase did not

857 differ between block types ( $t_{1,17} = 1.049$ ,  $p = 0.309$ , Cohen's  $d = 0.247$ ;  $85 \pm 71$  a.u.  
858 and  $50 \pm 152$  a.u. in fast and slow decision blocks). However, the slope (reflecting the  
859 speed at which the pupil expanded over decision duration) was steeper in slow ( $50 \pm$   
860  $152$  a.u.) relative to fast decision blocks ( $5 \pm 71$ ;  $t_{1,17} = -2.107$ ,  $p = 0.05$ , Cohen's  $d = -$   
861  $0.497$ ). This result was supported by multiple paired t-tests (Bonferroni corrected)  
862 looking at the difference in Peak pupil dilation between fast and slow decision blocks  
863 in the 8 bins of decision duration. As such, this additional analysis showed that, in early  
864 bins, pupil dilation did not differ significantly between block types but that it became  
865 progressively larger in slow than fast decision blocks in the last bins of decision  
866 duration (see Table S3 in supplementary material).

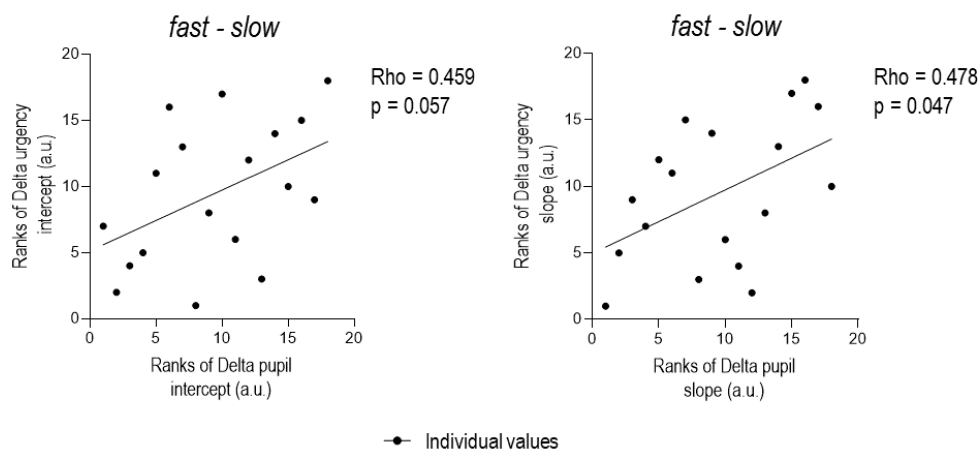


867

868 **Figure 7. Peak pupil data in Experiment 1 (n=18).** Peak pupil dilation was comparable in  
869 fast (blue bar) and slow (white bar) decision blocks (left panel). Consistent with the literature,  
870 Peak pupil dilation increased with decision duration in both types of blocks (right panel).  
871 However, while the pupil dilation seemed similar between the two types of block at the  
872 beginning of the decision phase (similar pupil intercepts, top left inset), its dilation tended to  
873 increase faster in slow decision blocks relative to fast decision ones (higher pupil slope, top  
874 right inset), leading to a progressively more dilated pupil in the former. Error bars represent  
875 SE.

876

877 To further investigate the link between pupil dilation and urgency, we put into relation  
878 the block-related changes in parameters of both functions. In other words, we looked  
879 at how block-related changes in pupil intercept (slope) were linked to block-related  
880 changes in urgency intercept (slope). These changes were quantified by obtaining  
881 delta values (delta fast-slow decision blocks) for the intercept and slope of both the  
882 pupil (Delta pupil intercept and Delta pupil slope) and urgency (Delta urgency intercept  
883 and Delta urgency slope) functions in all subjects, with thus positive deltas indicating  
884 greater values in fast than slow decision blocks. Interestingly, a Spearman correlation  
885 on Delta intercept values revealed a tendency toward a positive correlation (Figure 8;  
886  $Rho = 0.459$ ,  $p = 0.057$ ,  $CI = [0.012, 0.779]$ ), suggesting that participants who showed  
887 a greater urgency increase at the onset of decisions in fast than slow decision blocks  
888 were also those displaying the larger increase in pupil dilation. Moreover, a positive  
889 correlation was found when considering the Delta slope values ( $Rho = 0.478$ ,  $p =$   
890  $0.047$ ,  $CI = [-0.022, 0.803]$ ), indicating that participants whose urgency signal  
891 increased more over time in fast relative to slow decision blocks also showed a larger  
892 increase in pupil dilation over time.



893

894 **Figure 8. Correlations for Peak pupil data in Experiment 1 (n=18).** Block-related changes  
895 in the intercept and slope of the Peak Pupil function (Ranks of Delta pupil intercept and slope)  
896 were related to block-related changes in the same parameters of the urgency function (Ranks



897 of Delta urgency intercept and slope). That is, the participants showing a greater increase in  
898 pupil intercept (slope) in fast compared to slow decision blocks were also those showing a  
899 greater increase in urgency intercept (slope).

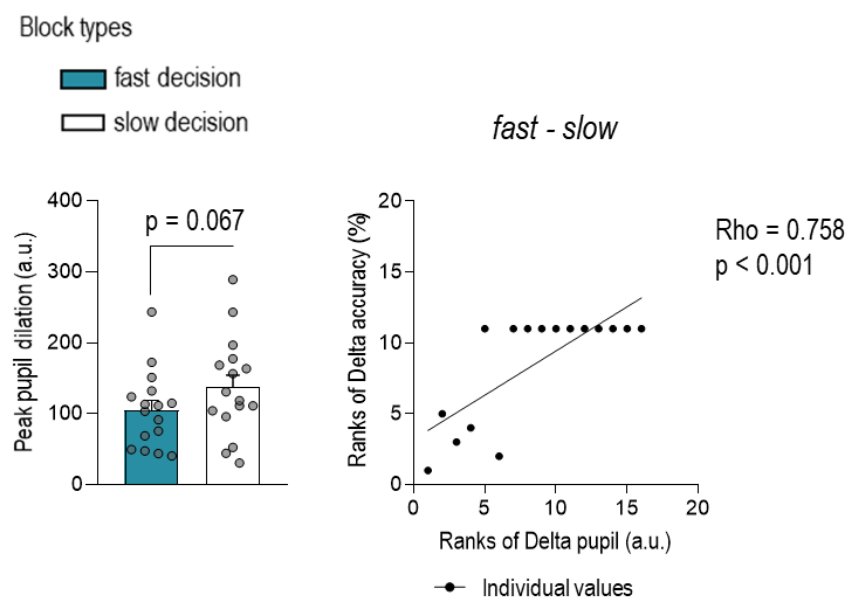
900

901 Altogether, the effects described above are consistent with a tight relationship  
902 between urgency and pupil dilation. Indeed, both urgency and pupil dilation clearly  
903 increased with decision duration, and more so in slow decision blocks. Moreover,  
904 block-related increases in urgency intercept and slopes were associated with parallel  
905 enlargements in pupil size (though marginal for the intercept). However, we also found  
906 that, pupil size tended to be smaller in fast than in slow decision blocks (and  
907 significantly so in later bins), contrary to urgency which showed the reverse effect.  
908 Such an effect on the Peak pupil data was not related to differences in baseline (tonic)  
909 levels of pupil dilation as these values were equivalent in both block types (see Fig. S4  
910 in supplementary materials). Nor was this effect due to the fact that decision durations  
911 differed across block types within the same bins (see Fig. 7). Indeed, when considering  
912 only a set of equivalent ambiguous trials with long decision durations (i.e., decisions  
913 falling between Jump<sub>-9</sub> and Jump<sub>-10</sub>) and a constant level of evidence (i.e., with a  
914 success of probability at decision time equal to 0.8125 in all trials), we found that pupil  
915 dilation remained greater in slow decision blocks, although the difference with fast  
916 decision blocks was marginal ( $137 \pm 70$  a.u. and  $105 \pm 54$  a.u., respectively;  $t_{1,15} =$   
917  $1.97$ ,  $p = 0.067$ , Cohen's  $d = 0.493$ ; 2 subjects had to be excluded from this analysis,  
918 because of a lack of data).

919 We then considered the possibility that the larger pupil size observed in slow  
920 decision blocks was due to a special focus on accuracy in this condition. As such,  
921 subjects had a fixed number of trials here (contrary to fast decision blocks) and they  
922 then plausibly recruited all available resource's to be as accurate as possible, including

923 increased arousal. To test this hypothesis, we considered again the subgroup of  
924 ambiguous trials described above for which we computed a block-related delta (fast-  
925 slow) for the accuracy and pupil data. Interestingly, in those particular trials, the Delta  
926 pupil size was positively correlated with the Delta accuracy ( $Rho = 0.758$ ,  $p < 0.001$ ,  
927  $CI = [0.501, 0.873]$ ). In other words, the more the pupil was dilated in the slow decision  
928 blocks compared to the fast decision blocks (i.e., the more the delta pupil was  
929 negative), the more subjects exhibited better accuracy in the slow than in the fast  
930 blocks (i.e., the more the delta accuracy was negative). In conclusion, variations in  
931 pupil-related arousal in the current study seemed to be driven by two overlapping  
932 factors: the level of urgency, as expected, and the strategic allocation of resources to  
933 promote accuracy.

934



935

936 **Figure 9. Peak pupil data in ambiguous trials of Experiment 1 (n=16).** Peak pupil dilation  
937 tended to be larger in slow decision blocks (white bar) than in fast decision blocks (blue bar).  
938 Given that deltas were computed by measuring the difference in peak pupil dilation between  
939 fast and slow conditions, the more the subjects showed a greater peak pupil in slow decision  
940 blocks, the more they displayed a negative delta, which corresponds to a low rank value.  
941 Interestingly, we found that the greater this pupil enlargement in slow compared to fast decision  
942 blocks (i.e., lower rank value), the greater the gain in accuracy in slow compared to fast  
943 decision blocks (i.e., lower rank value).

944 **Discussion**

945         The aim of our study was to provide a principled explanation to the relation  
946 between decision and movement speed. Consistent with this, our data supports the  
947 hypothesis that coregulation operates as a default mode. However, our findings also  
948 show that this form of control can fade or even be replaced by a tradeoff relationship,  
949 depending on the task goals. Based on these behavioral observations, we propose  
950 that several processes come into play to shape the speed of our decisions and  
951 movements either selectively or jointly, the latter mode being best observed when a  
952 default coregulation of decision and movement allows to maximize the reward rate, or  
953 at least, when it is not detrimental to it.

954 ***The relationship between decision and movement speed adapts to context-***  
955 ***dependent task goals***

956         Context-dependent changes in decision speed, as elicited in Experiment 1, led  
957 to clear changes in movement speed that are consistent with a coregulation of both  
958 levels of control. Indeed, subjects made faster movements in fast decision blocks than  
959 in slow decision blocks, and these changes in movement speed were correlated with  
960 the strength of changes in decision speed: the more subjects adjusted their decision  
961 speed according to the instruction, the more they showed a parallel change in  
962 movement speed. Note that, similar to Carsten et al (2023), changes in movement  
963 speed accompanied block-related variations in decision speed despite its absence of  
964 impact on the reward rate, substantiating the view that such coregulation type of control  
965 occurs naturally.

966         Context-dependent changes in movement speed, as required in Experiment 2,  
967 also affected decision speed. Yet, the direction of the effect differed according to the

968 group that was considered. That is, the group whose reward rate was maximized by a  
969 strategy favoring decision speed (i.e., the fast decision group) showed faster decisions  
970 in fast movement compared to slow movement blocks. Even if this coregulation effect  
971 was not as strong as in Experiment 1, it was still significant, pointing to a similar form  
972 of coregulation. In contrast, the group whose reward rate was maximized by a strategy  
973 favoring decision accuracy (i.e., the slow decision group) did not show such a  
974 covariation of decision speed between the slow and fast movement blocks. Quite the  
975 contrary, in this group we even observed the reverse relationship. More precisely,  
976 although decision speed was similar between fast and slow movement blocks, the  
977 changes in movement speed correlated negatively with changes in decisions speed:  
978 the more subjects accelerated their movement speed in fast compared to slow  
979 movement blocks, the more they slowed down their decision. This is consistent with a  
980 tradeoff type of relationship in this (slow decision) group, contrasting with the  
981 coregulation effect observed in the other (fast decision) group, despite the fact that  
982 subjects from both groups displayed a coregulation effect when manipulating decision  
983 speed in Experiment 1.

984 Interestingly, similar observations regarding context-dependent variations in  
985 Experiments 1 and 2 were made when considering directly the relationship between  
986 movement speed and decision urgency itself (and not only decision speed), as done  
987 for the first time in this study. As such, in Experiment 1, the decision urgency was  
988 clearly higher in fast decision blocks compared to slow decision blocks and this  
989 upregulation was found to significantly correlate with the changes in movement speed  
990 that occurred between the two contexts: the greater the context-dependent increase in  
991 urgency level, the more subjects accelerated their movement speed from one block  
992 type to the other. Similarly, the coregulation observed in the fast decision group of

993 Experiment 2 was also apparent when considering the urgency: fast movement blocks  
994 were associated with a higher urgency intercept than slow movement blocks in this  
995 group of individuals. Such a relationship was not found when the other (slow decision)  
996 group was considered. Hence, altogether, these findings indicate that the relationship  
997 between decision speed/urgency and movement speed can shift from a coregulation  
998 to a tradeoff according to the task goals, which provides an explanation for the  
999 apparent discrepancy between findings of past studies (Carsten et al., 2023; Kita et  
1000 al.,2023.; Reynaud et al., 2020; Saleri Lunazzi et al., 2021).

### 1001 ***The deliberation time impacts on movement speed***

1002 In our experiment, the level of urgency did not only vary in a context-dependent  
1003 manner (i.e., between blocks) but also in a time-dependent manner (i.e., over the  
1004 course of a trial). That is, as shown in many past studies, urgency increased during a  
1005 trial, pushing the subjects to respond as the trial comes to an end. Consistent with a  
1006 natural coregulation of decision speed and movement, we observed a time-dependent  
1007 speeding up of movements over the course of a trial, as already reported in past  
1008 studies (Thura et al., 2014; Thura, 2020; Thura et al., 2012). Interestingly, this was  
1009 generally true, whether considering results from Experiment 1 or Experiment 2: overall,  
1010 movement speed increased as deliberation time (and thus urgency) increased, in a  
1011 given context.

1012 Yet, an intriguing finding here, is that in Experiment 1, this effect was only  
1013 observed in the slow decision blocks (generally associated with slow movements) but  
1014 not in the fast decision blocks (where movements were generally faster due to the  
1015 context-dependent change in urgency elicited by the task instruction to decide fast). A  
1016 possible explanation for this is that the slope of the urgency function was smaller in the  
1017 fast than slow decision blocks of this experiment, as shown in the past. That is, when

1018 subjects put the emphasis on decision speed, the intercept is higher but then the  
1019 urgency increases more slowly as evident by a smaller slope in fast decision blocks  
1020 (Thura et al., 2014; Thura, 2020). Hence, the weaker increase in urgency over the  
1021 course of the trial in the latter block type may be responsible for the absence of time-  
1022 dependent effect on movement speed in that condition, compared to the slow decision  
1023 blocks where the slope is steeper following a lower intercept. Nevertheless, previous  
1024 studies have shown an acceleration of movements with the passage of time,  
1025 irrespective of the slope size of the urgency signal (Thura et al., 2014; Thura, 2020).  
1026 Another plausible explanation is that the impact of urgency on movement speed is  
1027 counteracted by a process controlling the energy cost. More precisely, the energy  
1028 expenditure as a function of movement duration is represented by a concave upward  
1029 function for many types of movement (Shadmehr et al., 2016; Steudel-Numbers &  
1030 Wall-Scheffler, 2009; Yoon et al., 2018; Zarrugh et al., 1974). As the speed of  
1031 movement is slower in the slow decision blocks than in the fast decision blocks, it is  
1032 possible that accelerating the movement speed decreases energy expenditure in the  
1033 former and increases it in the latter. Increasing the energetic cost of movement in the  
1034 fast decision blocks would lead to a decrease in the value of the reward, and thus the  
1035 rate of reward. Therefore, limiting the impact of the urgency signal depending on the  
1036 energy cost seems entirely credible. The fact that previous studies did not observe a  
1037 ceiling effect for the urgency signal could be linked to the type of movement involved  
1038 in the task. Indeed, in these studies, the task involved reaching movements, whereas  
1039 our experiment required index finger tapping movements. Unlike the latter, reaching  
1040 movements are large and involve several joints (at least the three articulations of the  
1041 arm). It is likely that such multi-joint movements offer a wider range of movement  
1042 speeds than single-joint (tapping) movements.

1043 **Pupil dilation reflects an increase in arousal related to urgency and decision**  
1044 **accuracy**

1045 Converse to previous studies (Gross & Dobbins, 2021; Murphy et al., 2016;  
1046 Steinemann et al., 2018), the pupil dilation did not differ significantly between fast and  
1047 slow decision blocks. However, we found an increase in dilation as a function of  
1048 decision duration, suggesting that pupil dilation may be partly linked to the urgency  
1049 signal (Gross & Dobbins, 2021; Lawlor et al., 2023; Murphy et al., 2011, 2016;  
1050 Steinemann et al., 2018). This idea is supported by the similarity found between pupil  
1051 dilation and urgency signal as well as the positive correlations that were found between  
1052 their parameters (see Fig. S5 in supplementary material). Yet surprisingly, unlike the  
1053 urgency signal, pupil size tended to be more dilated in slow compared to fast decision  
1054 blocks. Contrasting with previous studies (Gross & Dobbins, 2021; Murphy et al., 2016;  
1055 Steinemann et al., 2018), this result suggests a recruitment of the arousal system as a  
1056 function of both urgency and accuracy. One possible explanation is that the emphasis  
1057 on decision accuracy in slow decision blocks was particularly high in our design. This  
1058 pressure could arise from the fact that using a fixed number of trials limits the possibility  
1059 of increasing the rate of reward, giving importance to each trial. The positive correlation  
1060 between pupil dilation and performance in ambiguous trials supports this idea, showing  
1061 that the more the pupil was dilated in slow decision blocks, the more subjects increased  
1062 their accuracy in this condition for a same level of evidence.

1063 Altogether, these results suggest that pupil dilatation reflects two overlapping actions.  
1064 More precisely, the recruitment of the arousal system would, on the one side, increase  
1065 the gain of sensory information at the decision level with the increase in urgency in the  
1066 fast decision blocks, and on the other side, increase the attention to enhance accuracy  
1067 in a context where it is prioritized regardless of urgency, as in our slow decision blocks.

1068 The mechanisms through which the arousal system can enhance performance  
1069 accuracy are still unclear, but may involve enhancing processing of sensory  
1070 information (Zénon, 2019). This hypothesis is in line with a report by Steinemann and  
1071 his colleagues, who showed that pupil dilation is associated with better encoding of  
1072 sensory evidence in the visual cortex. Nevertheless, further studies are needed to  
1073 investigate the involvement of the arousal system in decision making using causal  
1074 approaches, using for example techniques such as transcutaneous vagus nerve  
1075 stimulation (Hilz, 2022).

1076 ***Several neural mechanisms are likely to shape the relationship between decision***  
1077 ***and movement speed***

1078 *Plausible neural source underlying the natural coregulation of decision speed and*  
1079 *movement speed*

1080 A possible candidate for the coregulation effects observed in our two  
1081 experiments is the basal ganglia (Chen & Yang, 2021; Dudman & Krakauer, 2016;  
1082 Kaduk et al., 2023; Desmurget & Turner, 2010). As such, this structure could be at the  
1083 source of a signal invigorating behavior as a whole to maximize reward rate, as  
1084 hypothesized in several studies of the last decade (Carsten et al., 2023; Cisek & Thura,  
1085 2022; Thura, 2020; Thura et al., 2022; Thura & Cisek, 2017). Reward-sensitivity of the  
1086 dopaminergic system has been extensively studied in the past (Berridge & Robinson,  
1087 2016; Salamone & Correa, 2024; Schultz et al., 2017; Weinstein, 2023) Consistently,  
1088 dopamine seems strongly implicated in the control of decision speed and movement  
1089 vigor (Bourgeois et al., 2016; Coddington & Dudman, 2019; Niv, 2007; Pietro Mazzoni  
1090 et al., 2007). Interestingly, it is believed that it amplifies motor gain (Park et al., 2020;  
1091 Yttri & Dudman, 2018), which seems to rely, at least in part, on inhibitory influences  
1092 increasing the signal-to-noise ratio in motor neural activity (Duque et al., 2017;



1093 Greenhouse, 2022; Vassiliadis et al., 2020; Wilhelm et al., 2022). This dopamine-  
1094 mediated invigoration may be thus responsible for the increased surround inhibition, a  
1095 phenomenon observed in studies applying transcranial magnetic stimulation (TMS)  
1096 during movement preparation, which has traditionally been associated with an increase  
1097 in movement vigor (Dudman & Krakauer, 2016; Shadmehr et al., 2019) but which has  
1098 also recently been linked to an increase in decision urgency (Derosiere et al., 2022).

1099 *Neural source underlying the occurrence of a tradeoff between decision urgency and*  
1100 *movement speed*

1101 The context-dependent modulations of decision speed as a function of the  
1102 movement blocks in the slow decision group of Experiment 2 reflects a tradeoff rather  
1103 than a coregulation of decision and movement speed, despite the fact that there is  
1104 evidence for a coregulation in this same group in Experiment 1 (see Fig. S6 in  
1105 supplementary materials). This suggests that the requirement to focus on decision  
1106 accuracy led this group of subjects to recruit processes allowing to maintain the  
1107 appropriate level of accuracy despite the fact that switching from slow to fast movement  
1108 blocks led to a joint invigoration of decision with movement speed. Such hypothesis is  
1109 supported by a negative correlation found between the UPPS score for urgency and  
1110 the delta of decision duration in the slow decision group (see Fig. S.7 in supplementary  
1111 material). Although marginally nonsignificant (p-tendency of 0.083), this correlation  
1112 suggests that the more impulsive the subjects (higher UPPS urgency score), the less  
1113 they were able to slow down their decisions (lower delta) in fast movement blocks. In  
1114 other words, this suggests lesser ability to counteract the effect of common  
1115 invigoration. Therefore, it is plausible that a cognitive control process (less efficient in  
1116 impulsive individuals) can come into play and selectively shape decision parameters  
1117 in a goal-directed manner, helping to “hold your horses”. This type of inhibitory control

1118 mechanism has been widely studied during conflict resolution and during action  
1119 stopping as an extreme case of braking (Frank et al., 2007; Mosher et al., 2021).  
1120 Several lines of evidence indicate that it relies on the hyperdirect pathway from medial  
1121 frontal cortex to subthalamic nucleus (Cavanagh et al., 2011; Forstmann et al., 2008;  
1122 Herz et al., 2017), producing broad, non-specific inhibition in motor areas to slow down  
1123 the action selection process (Aron et al., 2016; Duque et al., 2016; Klein et al., 2014;  
1124 Wessel & Aron, 2017). This effect would be associated with a broad motor cortex  
1125 suppression as already observed in past TMS studies, showing for instance reduced  
1126 excitability in leg muscles during cautious finger responses (Derosiere et al., 2022;  
1127 Duque et al., 2017).

## 1128 **Conclusion**

1129 In conclusion, the interaction between decision and movement speed seems  
1130 influenced by different mechanisms. Our findings highlight two of them; a common  
1131 invigoration mechanism responsible for a natural coregulation between decision and  
1132 movement speed, and a cognitive mechanism, which slows down decisions when the  
1133 reward is linked to the precision of the choices. Contrary to expectations, although the  
1134 urgency signal was influenced by changes in movement speed, it did not always  
1135 correlate with it, suggesting that this signal reflects a combination of the different  
1136 mechanisms involved in decision making and not just that of invigoration. Interestingly,  
1137 our results support a link between pupil dilation and decision urgency, but here also  
1138 with the additional influence of an accuracy-promoting factor.

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1148

1149 **Declaration of interests**

1150 The authors declare no competing interests.

1151

1152 **Author contributions**

1153 FF designed the study, acquired and analyzed the data, and wrote the first draft of the  
1154 manuscript. IC contributed to the study design and data analyses, TC and GD  
1155 contributed to the study design, AZ contributed to the data analyses, and JD  
1156 contributed to the study design and data analyses. All authors contributed to the article  
1157 and approved the submitted version.

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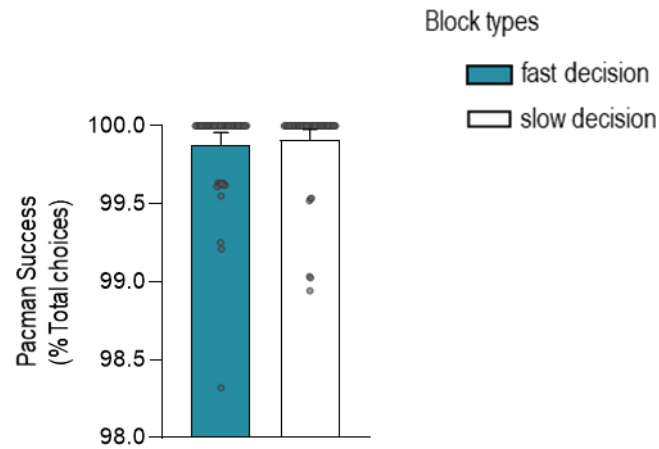
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1402 **Supplementary materials**

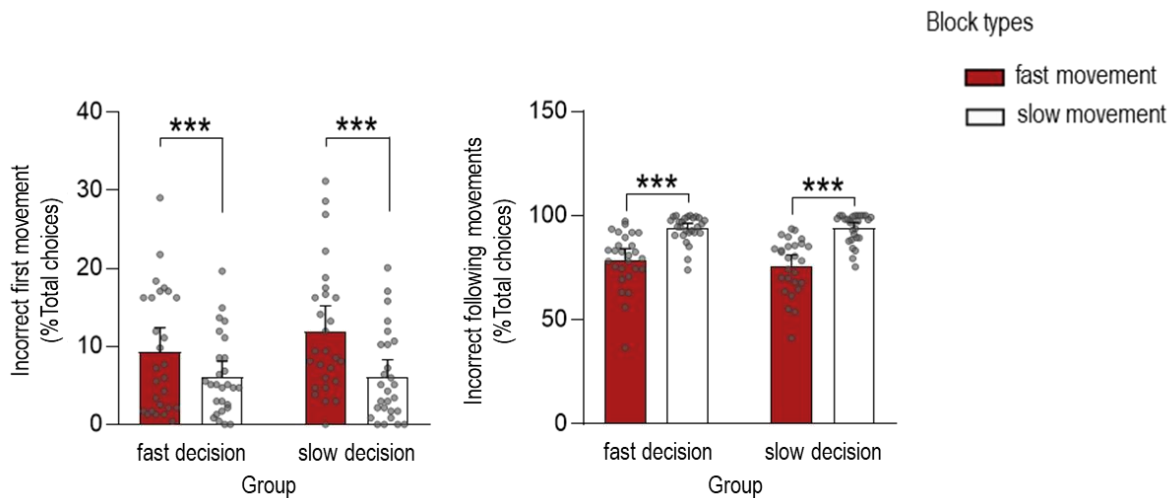


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1404 **Figure S1. Movement performance in Experiment 1.** Participants successfully escaped the  
1405 ghost (Pacman Success) equally in fast decision blocks (blue bar) and slow decision blocks  
1406 (white bar). Error bars represent SE.

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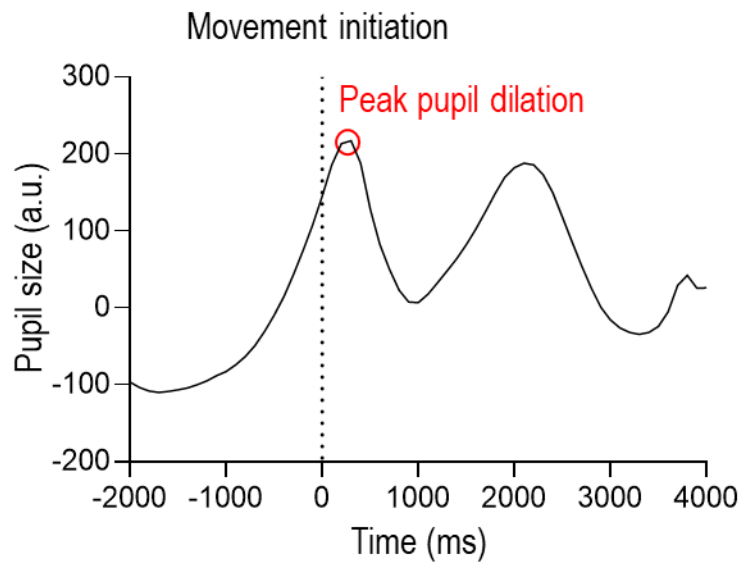
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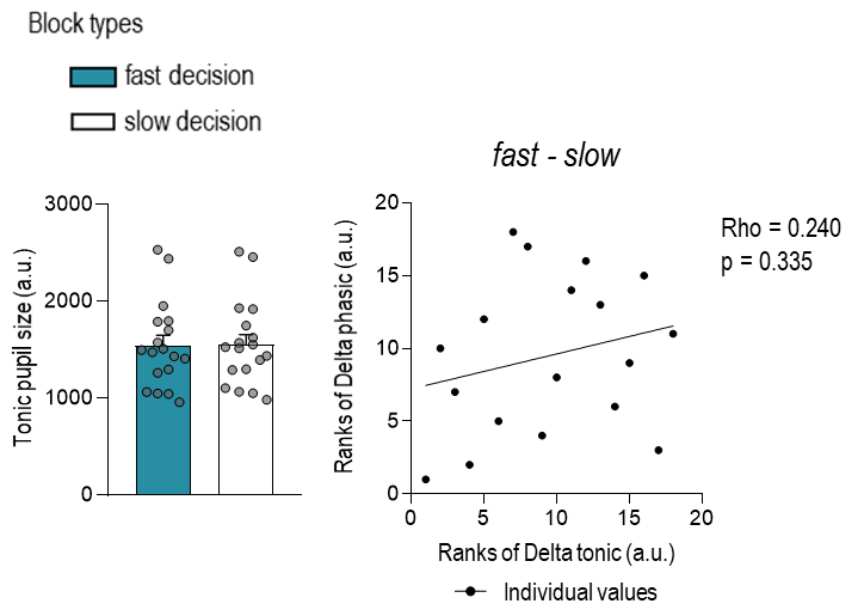
1410 **Figure S2. Movement performance in Experiment 2.** On average, participants had more  
1411 difficulty keeping up with the speed imposed in the fast movement blocks (red bars) than in the  
1412 slow movement blocks (white bars). More precisely, the success rate was lower in fast relative  
1413 to slow movement blocks for both the first tapping movement (higher percentage of incorrect  
1414 first movement, left panel) and the following ones in the movement phase (lower percentage  
1415 of incorrect following movements, right panel). Error bars represent SE. \*\*\* $p < 0.001$ .

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1418 **Figure S3. Typical pupil dilation signal.** In order to characterize block-related changes in  
1419 pupil size during the decision phase, we extracted the peak of pupil dilation (Peak pupil dilation)  
1420 following the first flexion initiation (Movement initiation) in each trial. This figure shows the  
1421 evoked pupil dilation aligned to movement initiation (0) in one subject.

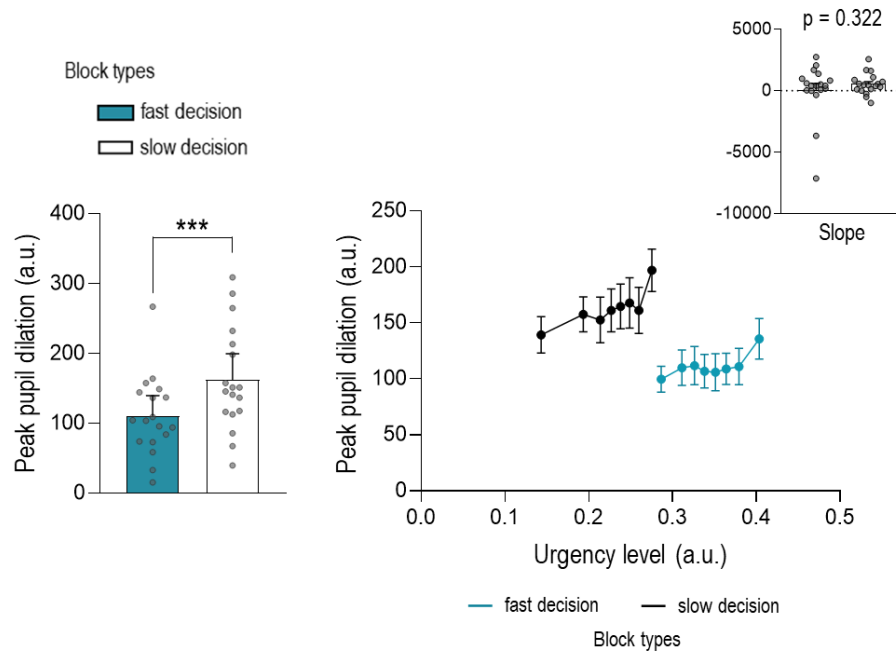


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1423 **Figure S4. Control analyses on pupil dilation in Experiment 1 (n=18).** As a control analysis,  
1424 we considered a window of 250 ms before the trial onset to measure tonic pupil dilation. As  
1425 shown on the left panel, such tonic pupil dilation was similar in fast (blue bar) and slow decision  
1426 blocks (white bar). Furthermore, block-related changes in tonic dilation (Ranks of Delta tonic)  
1427 did not correlate significantly with change in Peak pupil dilation (Ranks of Delta phasic), ruling  
1428 out any pupil bias in our results (right panel).

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1432 **Figure S5. Peak pupil data in Experiment 1 (n=18) as a function of urgency at decision**  
1433 **time.** Peak pupil dilation was smaller in fast (blue bar) than slow (white bar) decision blocks  
1434 (left panel). Consistent with the positive correlation found between pupil dilation and urgency  
1435 signal, Peak pupil dilation increased with urgency level in both types of blocks (right panel).  
1436 Furthermore, this increase in pupil dilatation with urgency was similar between the two block  
1437 types as emphasize by the similar slopes (see inset). Error bars represent SE. \*\*\*p < 0.001.

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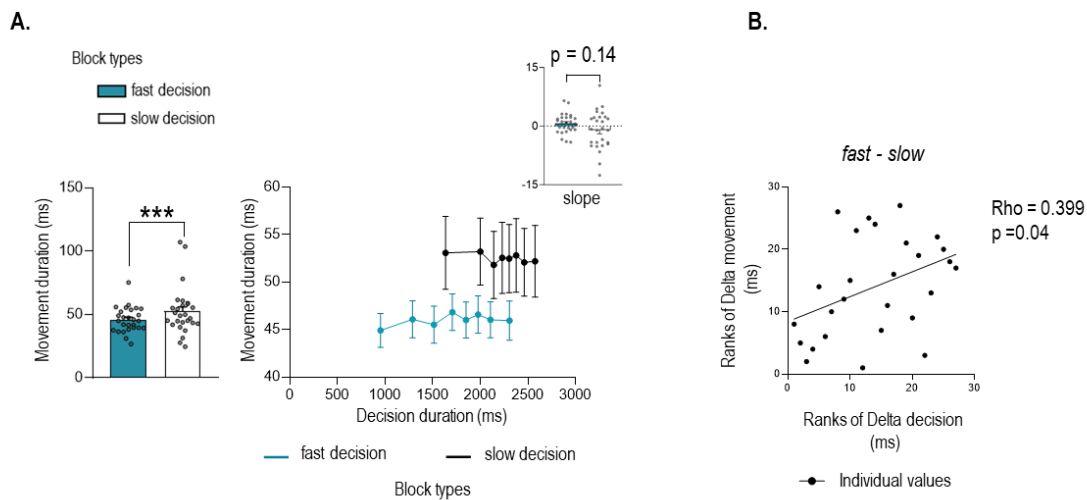
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1446 **Figure S6. Control analyses on behavior in Experiment 1 (n=27). A. Movement duration.**

1447 The results showed faster movements in fast decision (blue bar) relative to slow decision (white

1448 bar) blocks (left panel). The duration of movements as a function of decision duration evolved

1449 differently between the two types of blocks (right panel). Although the slopes did not differ from

1450 0 for both fast and slow decision blocks (see inset), the slope for slow decision blocks still

1451 tended to be lower. **B. Correlations.** Given that deltas were computed by measuring the

1452 difference in duration between fast and slow conditions, the more the subjects showed an

1453 effect of the condition (or coregulation), the more they displayed a negative delta, which

1454 corresponds to a low rank value. So, here you can see that the more participants responded

1455 faster in fast decision blocks compare to slow ones (i.e., the smaller the rank value), the more

1456 they accelerated their movement (i.e., the smaller the rank value) in this block type. Error bars

1457 represent SE. #: t-test against 0  $p < 0.025$ . \*\*\* $p < 0.001$ .

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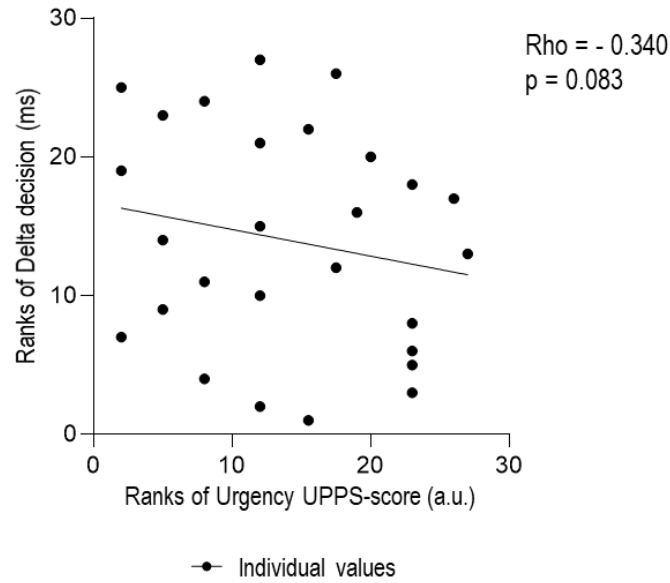
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1465 **Figure S7. Correlation with UPPS-score in slow decision group of Experiment 2.** Given  
1466 that deltas were computed by measuring the difference in duration between fast and slow  
1467 conditions, the more the subjects showed an effect of the condition (or tradeoff), the more they  
1468 displayed a positive delta, which corresponds to a high rank value. Subjects who were more  
1469 impulsive (higher rank value) tended to show less ability to slow down (lower rank value).

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	<i>Fast decision</i>	<i>Slow decision</i>	$BF_{10}$	<i>Error %</i>
<i>gender (M/F)</i>	12/15	10/17	0.309	0.008
<i>Age</i>	25.11 ± 3.65	23.81 ± 2.87	0.651	0.008
<i>Urgency</i>	8.52 ± 3.19	8.37 ± 3.20	0.277	0.008
<i>Positive urgency</i>	10.63 ± 2.82	10.56 ± 1.85	0.275	0.008
<i>Lack of Perseverance</i>	7.85 ± 2.52	7.30 ± 2.45	0.361	0.008
<i>Lack of Premeditation</i>	6.70 ± 2.46	7.33 ± 2.45	0.396	0.008
<i>Sensation seeking</i>	11.07 ± 2.05	10.33 ± 3.06	0.430	0.008

1485 **Table S1. Demographic description of fast decision and slow decision groups.** The table  
1486 includes the Bayesian independent t-tests for the sex, the age and the five facets of trait  
1487 impulsivity of the short-UPPS.  $BF_{10}$  grades the strength of evidence for the alternative  
1488 hypothesis against the null hypothesis. The error percentage (Error %) indicates the numeric  
1489 robustness of the results, with low values of the Error % corresponding to a greater numerical  
1490 stability of results. The gender of the participants was transformed into a numerical score to  
1491 compare the average between the two groups (i.e., 1 for female (F) and 0 for male (M)).

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<i>Bin<sub>DD</sub></i>	<i>t-value</i>	<i>df</i>	<i>p-value</i>	<i>Cohen's d</i>
1	<b>12.784</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>1.708</b>
2	<b>10.122</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>1.353</b>
3	<b>8.298</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>1.109</b>
4	<b>7.261</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>0.970</b>
5	<b>6.421</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>0.858</b>
6	<b>5.676</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>0.758</b>
7	<b>4.816</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>0.644</b>
8	<b>3.761</b>	<b>55</b>	<b>&lt; 0.001</b>	<b>0.503</b>

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**Table S2. Paired Student's t-tests of urgency level over decision duration.** The critical t-value, the p-value and the Cohen's d as a measure of the effect size are represented for each bin of decision duration (*Bin<sub>DD</sub>*). Significant p-value (with a Bonferroni-corrected threshold of .05/8) are highlighted in bold and blue.

<i>Bin<sub>DD</sub></i>	<i>t-value</i>	<i>df</i>	<i>p-value</i>	<i>Cohen's d</i>
1	-3.086	17	0.007	-0.727
2	<b>-4.007</b>	<b>17</b>	<b>&lt; 0.001</b>	<b>-0.944</b>
3	-2.352	17	0.031	-0.554
4	<b>-3.561</b>	<b>17</b>	<b>0.002</b>	<b>-0.839</b>
5	<b>-4.408</b>	<b>17</b>	<b>&lt; 0.001</b>	<b>-1.039</b>
6	<b>-3.884</b>	<b>17</b>	<b>0.001</b>	<b>-0.915</b>
7	<b>-3.191</b>	<b>17</b>	<b>0.005</b>	<b>-0.752</b>
8	<b>-5.583</b>	<b>17</b>	<b>&lt; 0.001</b>	<b>-1.316</b>

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**Table S3. Paired Student's t-tests of pupil dilation over decision duration.** The critical t-value, the p-value and the Cohen's d as a measure of the effect size are represented for each bin of decision duration (*Bin<sub>DD</sub>*). Significant p-value (with a Bonferroni-corrected threshold of .05/8) are highlighted in bold and blue.

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