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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**

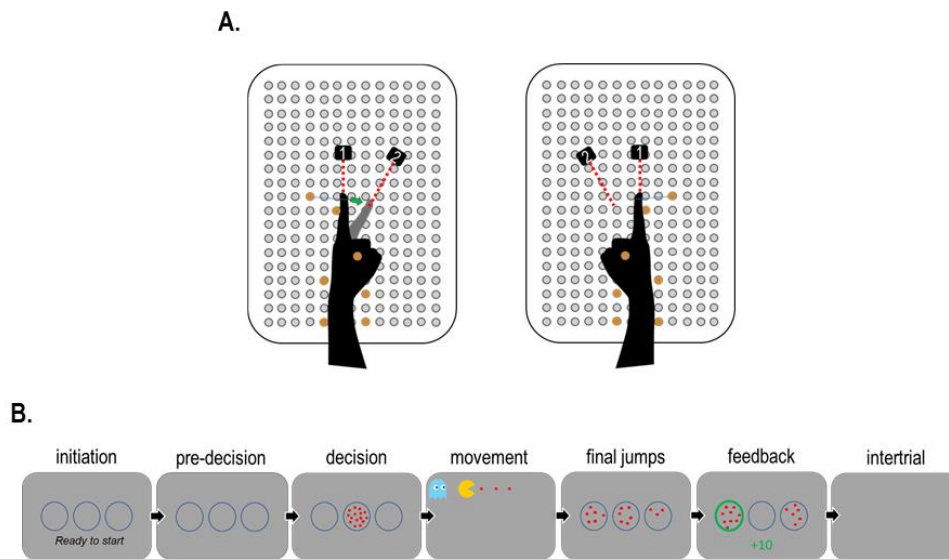
169 A total of 62 healthy human volunteers were recruited for this study, but due to
170 technical issues the data were processed on 56 subjects (30 women, 24.6 ± 3.4 years
171 old). All participants were right-handed according to the Edinburgh Questionnaire
172 (Oldfield, 1971) and had normal or corrected-to-normal 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 15th token jump; Jump₋₁₅). Note that subjects are told that they
229 are expected to respond before Jump₋₁₅, 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**

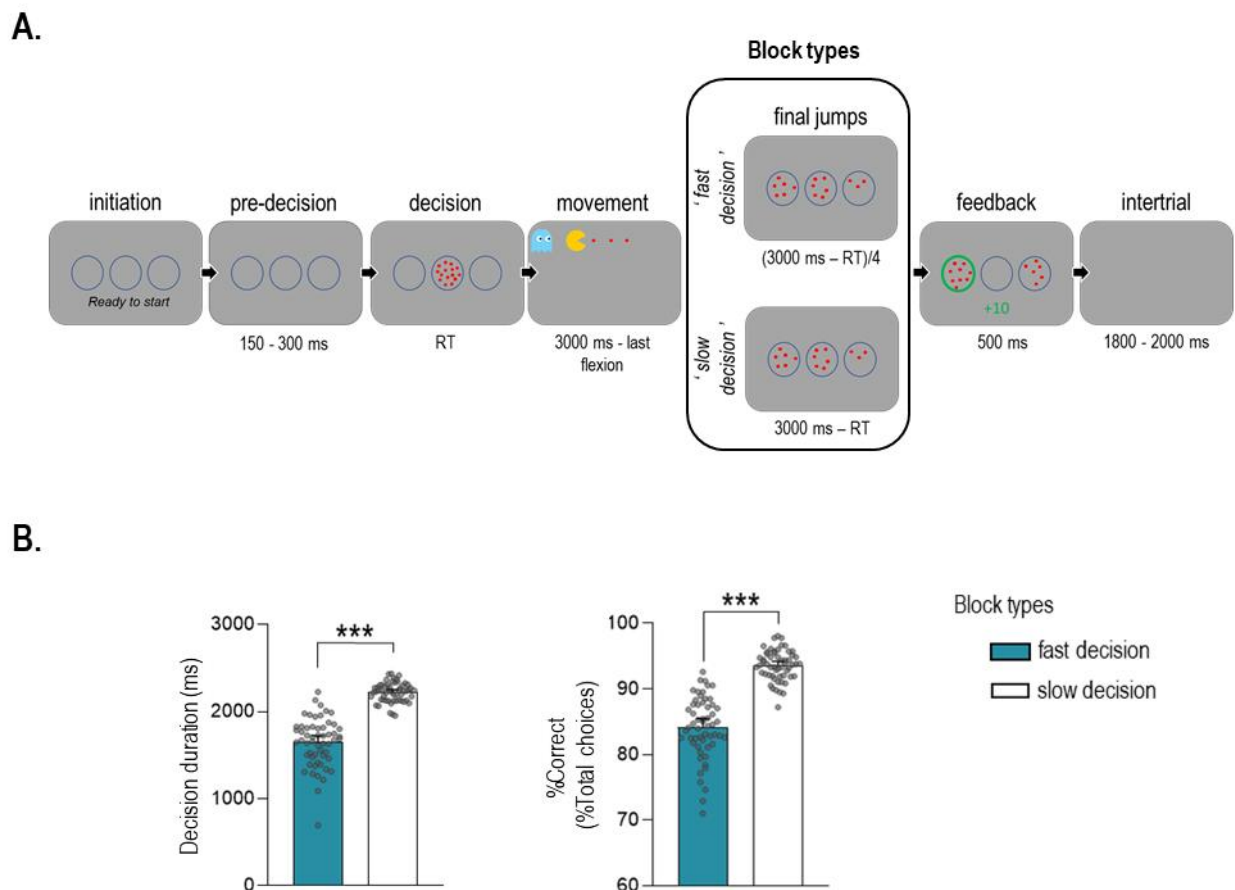
308 Participants performed two experiments as part of the current study. These
309 experiments occurred on separate days (average interval of 9 ± 8 days) and in a
310 counterbalanced order. In Experiment 1, we designed the task such that, in separate
311 blocks, subjects were either encouraged to make 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

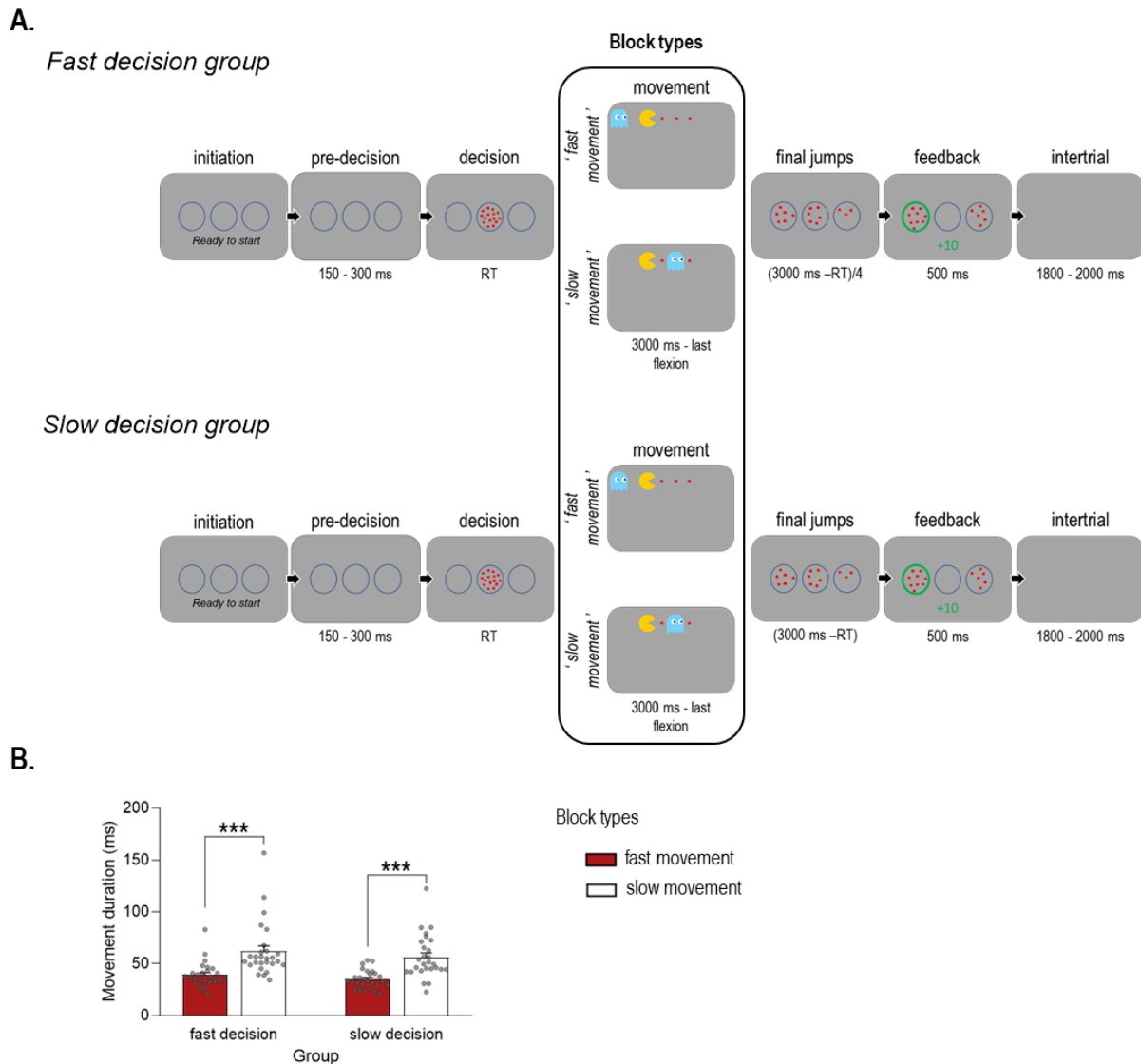
355 by making faster (shorter decision duration) and less accurate (lower %Correct) decisions in
356 fast (blue bars) relative to slow (white bars) decision blocks. Error bars represent SE. *** $p <$
357 0.001.

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 ± 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 **Figure 3. Protocol of Experiment 2. A. Task.** In this experiment, participants performed two
 383 block types that differed according to the speed at which they had to perform the finger tapping
 384 movement; that is, at twice the spontaneous speed (fast movement blocks: pacman chased
 385 by ghost) or at about the spontaneous speed (slow movement blocks; pacman preceded by
 386 ghost). Moreover, subjects were split into two experimental groups according to whether they
 387 performed the version of the task that led them to prioritize decision speed due to fast (every
 388 50 ms) final jumps (fast decision group, upper panel), or to prioritize decision accuracy due to
 389 slow (every 200 ms) final jumps (slow decision group, lower panel). **B. Manipulation check.**
 390 As required by the instruction in this Experiment, participants displayed shorter (faster) tapping
 391 movements in the fast (red bar) than slow (white bar) movement blocks, regardless of whether
 392 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 ± 3.6 years old), and generally slower in
416 the slow decision group ($n=27$; 17 women, 23.9 ± 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:

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

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 1×10^{-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_{RM}),
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₋₁₅ or with an anticipated response (before Jump₋₃). 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_{RM} 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 ± 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**

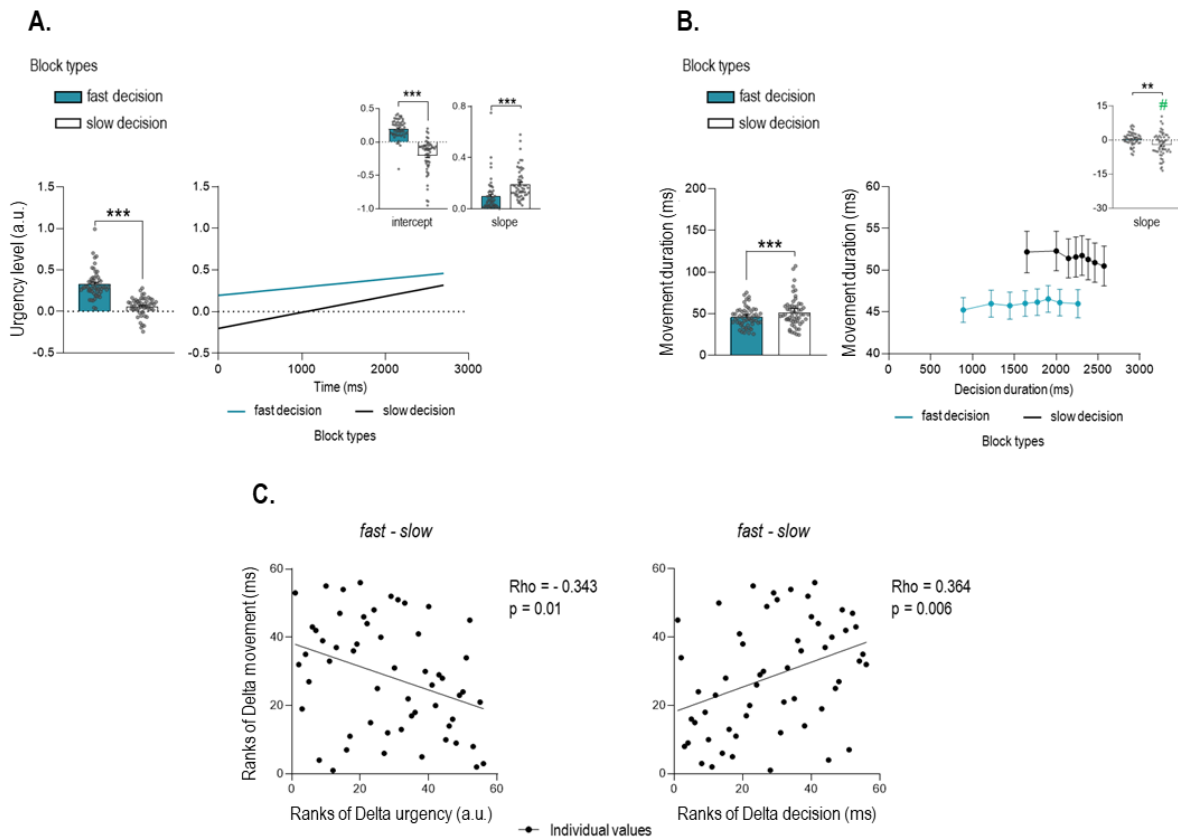
594 ***Subjects adjusted their decision duration according to the block instruction***

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 ± 276
598 ms) than in the slow decision blocks (2220 ± 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 ± 5 % of correct choices) than in the slow decision ones (94 ± 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 ± 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 ± 0.125 a.u.) than in the slow decision blocks (0.192 ± 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 ± 12 ms) than in slow decision blocks (51 ± 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 ± 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_{RM} revealed that movements were on average of shorter duration in the fast
705 (37 ± 11 ms) than in the slow movement blocks (59 ± 24 ms; $F_{1,53} = 106.879$, $p < 0.001$,
706 partial eta-squared (η_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 $\eta_p^2 = [0.002, 0.024]$).

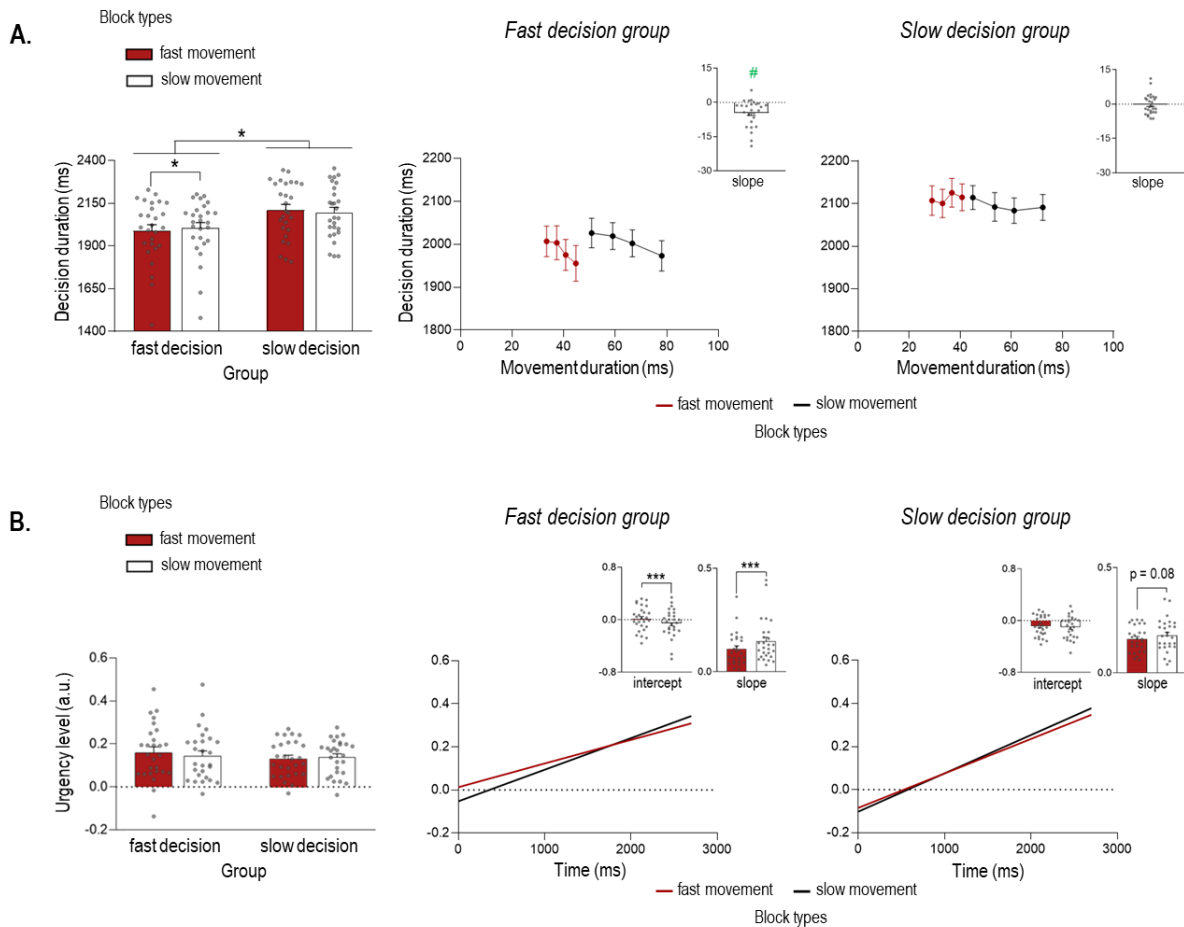
713 ***Decision duration was influenced by movement duration***

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 ± 175 ms) than in the slow decision group
727 (2104 ± 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 ± 183 ms) than slow movement blocks (2004 ± 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 ± 164 ms) and slow movement blocks (2096 ± 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 ± 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 ± 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.

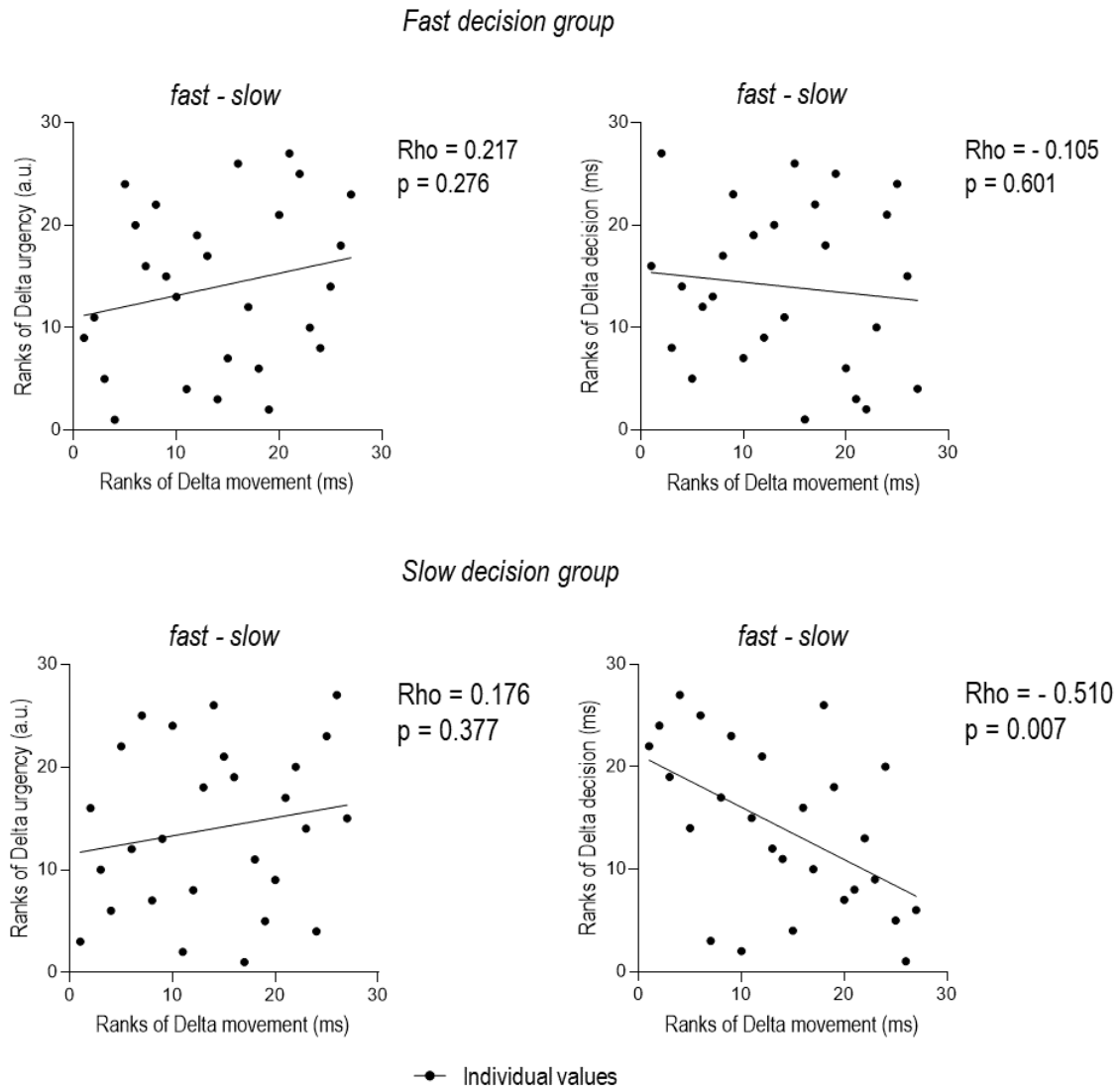
772

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 ± 0.186 a.u.) than slow movement blocks ($-$
784 0.053 ± 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 ± 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 ± 0.079 ; $t_{1,26} = -3.645$) than slow movement
791 blocks (0.147 ± 0.103 a.u.; $t_{1,26} = -3.645$, $p = 0.001$, Cohen's $d = -0.701$). The
792 difference between fast (0.160 ± 0.061 a.u.) and slow movement blocks (0.178 ± 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.

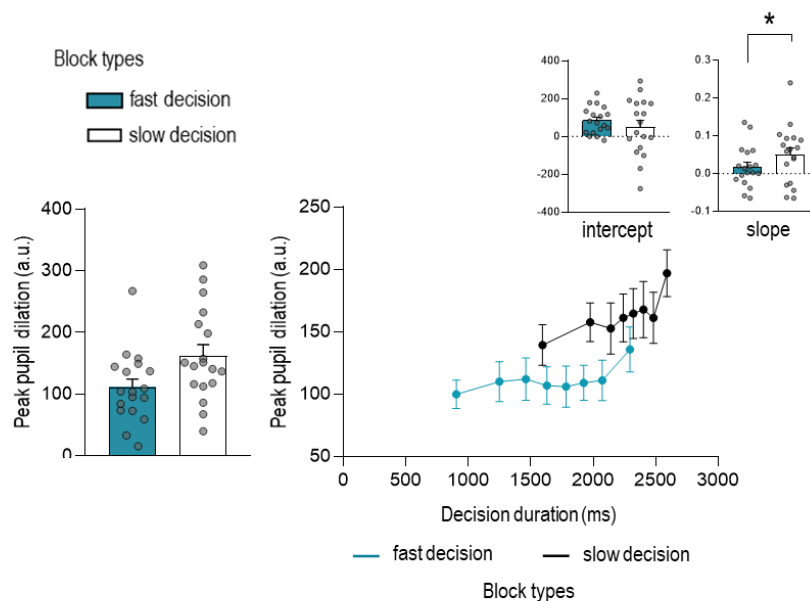
835 **Analyses of pupil dilation**

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 ± 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 ± 71 a.u.
858 and 50 ± 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 ± 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).

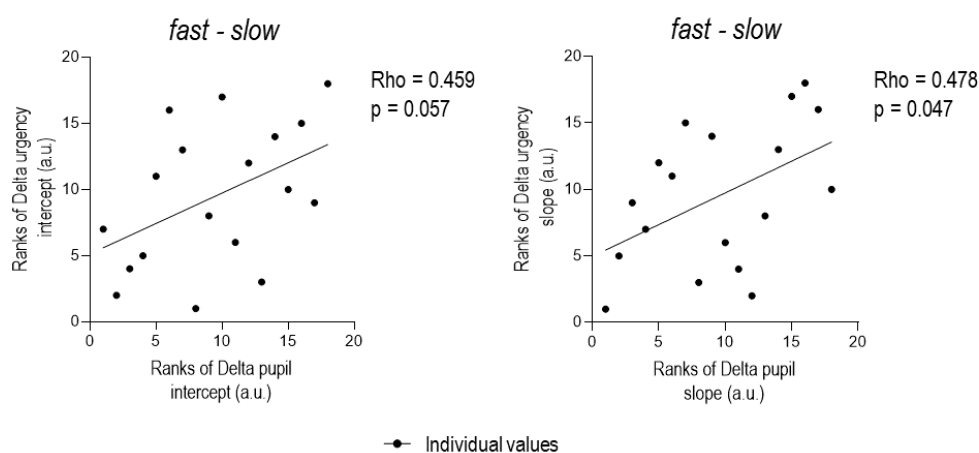


867

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).

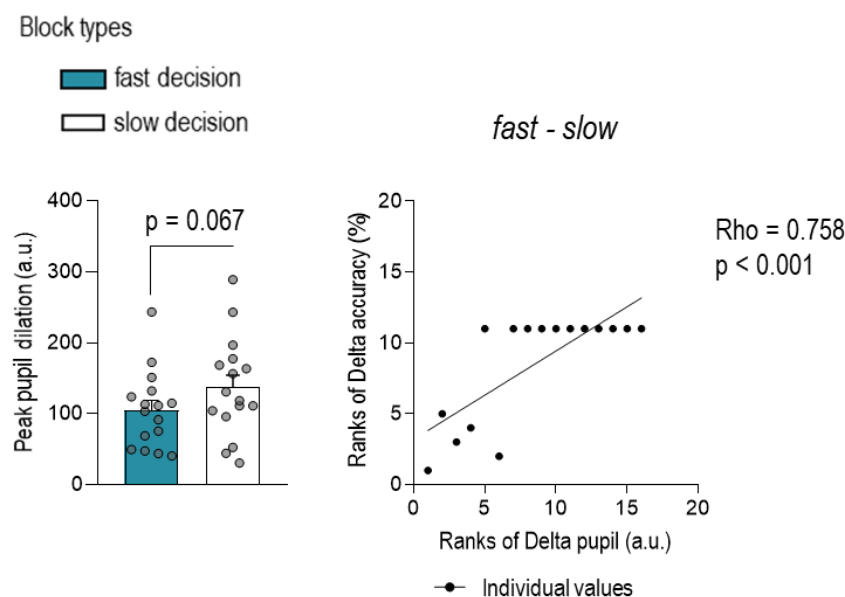
900

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₋₉ and Jump₋₁₀) 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 ± 70 a.u. and 105 ± 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.

1139

1140

1141

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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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1168 **References**

- 1169 Aron, A. R., Herz, D. M., Brown, P., Forstmann, B. U., & Zaghoul, K. (2016).
1170 Frontosubthalamic Circuits for Control of Action and Cognition. *The Journal of*
1171 *Neuroscience*, 36(45), 11489-11495. [https://doi.org/10.1523/JNEUROSCI.2348-](https://doi.org/10.1523/JNEUROSCI.2348-16.2016)
1172 16.2016
- 1173 Berridge, K. C., & Robinson, T. E. (2016). Liking, wanting, and the incentive-sensitization
1174 theory of addiction. *American Psychologist*, 71(8), 670-679.
1175 <https://doi.org/10.1037/amp0000059>
- 1176 Bourgeois, A., Chelazzi, L., & Vuilleumier, P. (2016). Chapter 14—How motivation and
1177 reward learning modulate selective attention. In B. Studer & S. Knecht (Éds.),
1178 *Progress in Brain Research* (Vol. 229, p. 325-342). Elsevier.
1179 <https://doi.org/10.1016/bs.pbr.2016.06.004>
- 1180 Carland, M. A., Thura, D., & Cisek, P. (2019). The Urge to Decide and Act : Implications for
1181 Brain Function and Dysfunction. *The Neuroscientist*, 25(5), 491-511.
1182 <https://doi.org/10.1177/1073858419841553>
- 1183 Carsten, T., Fievez, F., & Duque, J. (2023). Movement characteristics impact decision-
1184 making and vice versa. *Scientific Reports*, 13(1), 3281.
1185 <https://doi.org/10.1038/s41598-023-30325-4>
- 1186 Cavanagh, J. F., Wiecki, T. V., Cohen, M. X., Figueroa, C. M., Samanta, J., Sherman, S. J.,
1187 & Frank, M. J. (2011). Subthalamic nucleus stimulation reverses mediofrontal
1188 influence over decision threshold. *Nature Neuroscience*, 14(11), 1462-1467.
1189 <https://doi.org/10.1038/nn.2925>
- 1190 Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population*
1191 *Biology*, 9(2), 129-136. [https://doi.org/10.1016/0040-5809\(76\)90040-X](https://doi.org/10.1016/0040-5809(76)90040-X)
- 1192 Chen, X., & Yang, T. (2021). A neural network model of basal ganglia's decision-making
1193 circuitry. *Cognitive Neurodynamics*, 15(1), 17-26. [https://doi.org/10.1007/s11571-020-](https://doi.org/10.1007/s11571-020-09609-2)
1194 09609-2
- 1195 Churchland, A. K., Kiani, R., & Shadlen, M. N. (2008). Decision-making with multiple
1196 alternatives. *Nature Neuroscience*, 11(6), 693-702. <https://doi.org/10.1038/nn.2123>
- 1197 Cisek, P., Puskas, G. A., & El-Murr, S. (2009). Decisions in Changing Conditions : The
1198 Urgency-Gating Model. *The Journal of Neuroscience*, 29(37), 11560-11571.
1199 <https://doi.org/10.1523/JNEUROSCI.1844-09.2009>
- 1200 Cisek, P., & Thura, D. (2022). Models of Decision-Making Over Time. In P. Cisek & D. Thura,
1201 *Oxford Research Encyclopedia of Neuroscience*. Oxford University Press.
1202 <https://doi.org/10.1093/acrefore/9780190264086.013.346>
- 1203 Coddington, L. T., & Dudman, J. T. (2019). Learning from Action : Reconsidering Movement
1204 Signaling in Midbrain Dopamine Neuron Activity. *Neuron*, 104(1), 63-77.
1205 <https://doi.org/10.1016/j.neuron.2019.08.036>
- 1206 Derosiere, G., Thura, D., Cisek, P., & Duque, J. (2019). Motor cortex disruption delays motor
1207 processes but not deliberation about action choices. *Journal of Neurophysiology*,
1208 122(4), 1566-1577. <https://doi.org/10.1152/jn.00163.2019>
- 1209 Derosiere, G., Thura, D., Cisek, P., & Duque, J. (2021). Trading accuracy for speed over the
1210 course of a decision. *Journal of Neurophysiology*, 126(2), 361-372.
1211 <https://doi.org/10.1152/jn.00038.2021>

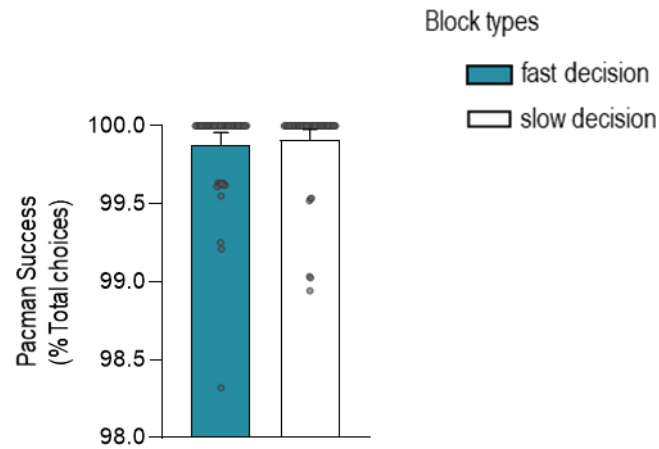
- 1212 Derosiere, G., Thura, D., Cisek, P., & Duque, J. (2022). Hasty sensorimotor decisions rely on
1213 an overlap of broad and selective changes in motor activity. *PLOS Biology*, *20*(4),
1214 e3001598. <https://doi.org/10.1371/journal.pbio.3001598>
- 1215 Desmurget, M., & Turner, R. S. (2010). Motor Sequences and the Basal Ganglia :
1216 Kinematics, Not Habits. *The Journal of Neuroscience*, *30*(22), 7685.
1217 <https://doi.org/10.1523/JNEUROSCI.0163-10.2010>
- 1218 Ditterich, J. (2006). Evidence for time-variant decision making. *European Journal of*
1219 *Neuroscience*, *24*(12), 3628-3641. <https://doi.org/10.1111/j.1460-9568.2006.05221.x>
- 1220 Drugowitsch, J., Moreno-Bote, R., Churchland, A. K., Shadlen, M. N., & Pouget, A. (2012).
1221 The Cost of Accumulating Evidence in Perceptual Decision Making. *The Journal of*
1222 *Neuroscience*, *32*(11), 3612-3628. <https://doi.org/10.1523/JNEUROSCI.4010-11.2012>
- 1223 Dudman, J. T., & Krakauer, J. W. (2016). The basal ganglia : From motor commands to the
1224 control of vigor. *Current Opinion in Neurobiology*, *37*, 158-166.
1225 <https://doi.org/10.1016/j.conb.2016.02.005>
- 1226 Duque, J., Greenhouse, I., Labruna, L., & Ivry, R. B. (2017). Physiological Markers of Motor
1227 Inhibition during Human Behavior. *Trends in Neurosciences*, *40*(4), 219-236.
1228 <https://doi.org/10.1016/j.tins.2017.02.006>
- 1229 Duque, J., Petitjean, C., & Swinnen, S. P. (2016). Effect of Aging on Motor Inhibition during
1230 Action Preparation under Sensory Conflict. *Frontiers in Aging Neuroscience*, *8*.
1231 <https://www.frontiersin.org/articles/10.3389/fnagi.2016.00322>
- 1232 Eben, C., Billieux, J., & Verbruggen, F. (2020). Clarifying the Role of Negative Emotions in
1233 the Origin and Control of Impulsive Actions. *Psychologica Belgica*, *60*(1), 1-17.
1234 <https://doi.org/10.5334/pb.502>
- 1235 Ferrucci, L., Genovesio, A., & Marcos, E. (2021). The importance of urgency in decision
1236 making based on dynamic information. *PLOS Computational Biology*, *17*(10),
1237 e1009455. <https://doi.org/10.1371/journal.pcbi.1009455>
- 1238 Fievez, F., Derosiere, G., Verbruggen, F., & Duque, J. (2022). Post-error Slowing Reflects
1239 the Joint Impact of Adaptive and Maladaptive Processes During Decision Making.
1240 *Frontiers in Human Neuroscience*, *16*, 864590.
1241 <https://doi.org/10.3389/fnhum.2022.864590>
- 1242 Forstmann, B. U., van den Wildenberg, W. P. M., & Ridderinkhof, K. R. (2008). Neural
1243 Mechanisms, Temporal Dynamics, and Individual Differences in Interference Control.
1244 *Journal of Cognitive Neuroscience*, *20*(10), 1854-1865.
1245 <https://doi.org/10.1162/jocn.2008.20122>
- 1246 Frank, M. J., Samanta, J., Moustafa, A. A., & Sherman, S. J. (2007). Hold Your Horses :
1247 Impulsivity, Deep Brain Stimulation, and Medication in Parkinsonism. *Science*,
1248 *318*(5854), 1309-1312. <https://doi.org/10.1126/science.1146157>
- 1249 Gold, J. I., & Shadlen, M. N. (2007). The Neural Basis of Decision Making. *Annual Review of*
1250 *Neuroscience*, *30*(1), 535-574.
1251 <https://doi.org/10.1146/annurev.neuro.29.051605.113038>
- 1252 Greenhouse, I. (2022). Inhibition for gain modulation in the motor system. *Experimental Brain*
1253 *Research*, *240*(5), 1295-1302. <https://doi.org/10.1007/s00221-022-06351-5>
- 1254 Gross, M. P., & Dobbins, I. G. (2021). Pupil dilation during memory encoding reflects time
1255 pressure rather than depth of processing. *Journal of Experimental Psychology:*
1256 *Learning, Memory, and Cognition*, *47*(2), 264-281.
1257 <https://doi.org/10.1037/xlm0000818>
- 1258 Hanks, T., Kiani, R., & Shadlen, M. N. (2014). A neural mechanism of speed-accuracy
1259 tradeoff in macaque area LIP. *eLife*, *3*, e02260. <https://doi.org/10.7554/eLife.02260>

- 1260 Herz, D. M., Tan, H., Brittain, J.-S., Fischer, P., Cheeran, B., Green, A. L., FitzGerald, J.,
1261 Aziz, T. Z., Ashkan, K., Little, S., Foltynie, T., Limousin, P., Zrinzo, L., Bogacz, R., &
1262 Brown, P. (2017). Distinct mechanisms mediate speed-accuracy adjustments in
1263 cortico-subthalamic networks. *eLife*, 6, e21481. <https://doi.org/10.7554/eLife.21481>
- 1264 Hilz, M. J. (2022). Transcutaneous vagus nerve stimulation—A brief introduction and
1265 overview. *Autonomic Neuroscience: Basic and Clinical*, 243.
1266 <https://doi.org/10.1016/j.autneu.2022.103038>
- 1267 Kaduk, K., Henry, T., Guitton, J., Meunier, M., Thura, D., & Hadj-Bouziane, F. (2023).
1268 Atomoxetine and reward size equally improve task engagement and perceptual
1269 decisions but differently affect movement execution. *Neuropharmacology*, 241,
1270 109736. <https://doi.org/10.1016/j.neuropharm.2023.109736>
- 1271 Kelly, S. P., Corbett, E. A., & O'Connell, R. G. (2021). Neurocomputational mechanisms of
1272 prior-informed perceptual decision-making in humans. *Nature Human Behaviour*,
1273 5(4), 467-481.
- 1274 Kita, K., Du, Y., & Haith, A. M. (2023). Evidence for a common mechanism supporting
1275 invigoration of action selection and action execution. *Journal of neurophysiology*,
1276 130(2), 238–246. <https://doi.org/10.1152/jn.00510.2022>
- 1277 Klein, P.-A., Petitjean, C., Olivier, E., & Duque, J. (2014). Top-down suppression of
1278 incompatible motor activations during response selection under conflict. *NeuroImage*,
1279 86, 138-149. <https://doi.org/10.1016/j.neuroimage.2013.08.005>
- 1280 Lawlor, J., Zagala, A., Jamali, S., & Boubenec, Y. (2023). Pupillary dynamics reflect the
1281 impact of temporal expectation on detection strategy. *iScience*, 26(2), 106000.
1282 <https://doi.org/10.1016/j.isci.2023.106000>
- 1283 Lemon, W. C. (1991). Fitness consequences of foraging behaviour in the zebra finch. *Nature*,
1284 352(6331), 153-155. <https://doi.org/10.1038/352153a0>
- 1285 Mazzoni, P., Hristova, A., & Krakauer, J. W. (2007). Why Don't We Move Faster ?
1286 Parkinson's Disease, Movement Vigor, and Implicit Motivation. *The Journal of*
1287 *Neuroscience*, 27(27), 7105. <https://doi.org/10.1523/JNEUROSCI.0264-07.2007>
- 1288 McGinley, M. J., David, S. V., & McCormick, D. A. (2015). Cortical Membrane Potential
1289 Signature of Optimal States for Sensory Signal Detection. *Neuron*, 87(1), 179-192.
1290 <https://doi.org/10.1016/j.neuron.2015.05.038>
- 1291 Mosher, C. P., Mamelak, A. N., Malekmohammadi, M., Pouratian, N., & Rutishauser, U.
1292 (2021). Distinct roles of dorsal and ventral subthalamic neurons in action selection
1293 and cancellation. *Neuron*, 109(5), 869-881.e6.
1294 <https://doi.org/10.1016/j.neuron.2020.12.025>
- 1295 Murphy, P. R., Boonstra, E., & Nieuwenhuis, S. (2016). Global gain modulation generates
1296 time-dependent urgency during perceptual choice in humans. *Nature*
1297 *Communications*, 7(1), 13526. <https://doi.org/10.1038/ncomms13526>
- 1298 Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'Connell, R. G. (2011). Pupillometry and
1299 P3 index the locus coeruleus–noradrenergic arousal function in humans.
1300 *Psychophysiology*, 48(11), 1532-1543. <https://doi.org/10.1111/j.1469-8986.2011.01226.x>
- 1301
- 1302 Niv, Y. (2007). Cost, Benefit, Tonic, Phasic : What Do Response Rates Tell Us about
1303 Dopamine and Motivation? *Annals of the New York Academy of Sciences*, 1104(1),
1304 357-376. <https://doi.org/10.1196/annals.1390.018>
- 1305 O'Connell, R. G., Shadlen, M. N., Wong-Lin, K., & Kelly, S. P. (2018). Bridging Neural and
1306 Computational Viewpoints on Perceptual Decision-Making. *Trends in Neurosciences*,
1307 41(11), 838-852. <https://doi.org/10.1016/j.tins.2018.06.005>

- 1308 Oldfield, R. C. (1971). The assessment and analysis of handedness : The Edinburgh
1309 inventory. *Neuropsychologia*, 9(1), 97-113. [https://doi.org/10.1016/0028-](https://doi.org/10.1016/0028-3932(71)90067-4)
1310 [3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
- 1311 Park, J., Coddington, L. T., & Dudman, J. T. (2020). Basal Ganglia Circuits for Action
1312 Specification. *Annual Review of Neuroscience*, 43(1), 485-507.
1313 <https://doi.org/10.1146/annurev-neuro-070918-050452>
- 1314 Quoilin, C., Fievez, F., & Duque, J. (2019). Preparatory inhibition : Impact of choice in
1315 reaction time tasks. *Neuropsychologia*, 129, 212-222.
1316 <https://doi.org/10.1016/j.neuropsychologia.2019.04.016>
- 1317 Ratcliff, R., & Smith, P. L. (2004). A Comparison of Sequential Sampling Models for Two-
1318 Choice Reaction Time. *Psychological Review*, 111(2), 333-367.
1319 <https://doi.org/10.1037/0033-295X.111.2.333>
- 1320 Ratcliff, R., Smith, P. L., Brown, S. D., & McKoon, G. (2016). Diffusion Decision Model :
1321 Current Issues and History. *Trends in Cognitive Sciences*, 20(4), 260-281.
1322 <https://doi.org/10.1016/j.tics.2016.01.007>
- 1323 Reppert, T. R., Heitz, R. P., & Schall, J. D. (2023). Neural mechanisms for executive control
1324 of speed-accuracy trade-off. *Cell Reports*, 42(11), 113422.
1325 <https://doi.org/10.1016/j.celrep.2023.113422>
- 1326 Reynaud, A. J., Saleri Lunazzi, C., & Thura, D. (2020). Humans sacrifice decision-making for
1327 action execution when a demanding control of movement is required. *Journal of*
1328 *Neurophysiology*, 124(2), 497-509. <https://doi.org/10.1152/jn.00220.2020>
- 1329 ŞAHİN, M., & AYBEK, E. (2020). Jamovi : An Easy to Use Statistical Software for the Social
1330 Scientists. *International Journal of Assessment Tools in Education*, 6(4), 670-692.
1331 <https://doi.org/10.21449/ijate.661803>
- 1332 Salamone, J. D., & Correa, M. (2024). The Neurobiology of Activational Aspects of
1333 Motivation : Exertion of Effort, Effort-Based Decision Making, and the Role of
1334 Dopamine. *Annual Review of Psychology*, 75(1), annurev-psych-020223-012208.
1335 <https://doi.org/10.1146/annurev-psych-020223-012208>
- 1336 Saleri Lunazzi, C., Reynaud, A. J., & Thura, D. (2021). Dissociating the Impact of Movement
1337 Time and Energy Costs on Decision-Making and Action Initiation in Humans.
1338 *Frontiers in Human Neuroscience*, 15. <https://doi.org/10.3389/fnhum.2021.715212>
- 1339 Schultz, W., Stauffer, W. R., & Lak, A. (2017). The phasic dopamine signal maturing : From
1340 reward via behavioural activation to formal economic utility. *Current Opinion in*
1341 *Neurobiology*, 43, 139-148. <https://doi.org/10.1016/j.conb.2017.03.013>
- 1342 Shadmehr, R., Huang, H. J., & Ahmed, A. A. (2016). A Representation of Effort in Decision-
1343 Making and Motor Control. *Current Biology*, 26(14), 1929-1934.
1344 <https://doi.org/10.1016/j.cub.2016.05.065>
- 1345 Shadmehr, R., Reppert, T. R., Summerside, E. M., Yoon, T., & Ahmed, A. A. (2019).
1346 Movement Vigor as a Reflection of Subjective Economic Utility. *Trends in*
1347 *Neurosciences*, 42(5), 323-336. <https://doi.org/10.1016/j.tins.2019.02.003>
- 1348 Spieser, L., Servant, M., Hasbroucq, T., & Burle, B. (2017). Beyond decision ! Motor
1349 contribution to speed-accuracy trade-off in decision-making. *Psychonomic Bulletin &*
1350 *Review*, 24(3), 950-956. <https://doi.org/10.3758/s13423-016-1172-9>
- 1351 Steinemann, N. A., O'Connell, R. G., & Kelly, S. P. (2018). Decisions are expedited through
1352 multiple neural adjustments spanning the sensorimotor hierarchy. *Nature*
1353 *Communications*, 9(1), 3627. <https://doi.org/10.1038/s41467-018-06117-0>

- 1354 Steudel-Numbers, K. L., & Wall-Scheffler, C. M. (2009). Optimal running speed and the
1355 evolution of hominin hunting strategies. *Journal of Human Evolution*, 56(4), 355-360.
1356 <https://doi.org/10.1016/j.jhevol.2008.11.002>
- 1357 Thura, D. (2020). Decision urgency invigorates movement in humans. *Behavioural Brain*
1358 *Research*, 382, 112477. <https://doi.org/10.1016/j.bbr.2020.112477>
- 1359 Thura, D., Beauregard-Racine, J., Fradet, C.-W., & Cisek, P. (2012). Decision making by
1360 urgency gating : Theory and experimental support. *Journal of Neurophysiology*,
1361 108(11), 2912-2930. <https://doi.org/10.1152/jn.01071.2011>
- 1362 Thura, D., Cabana, J.-F., Feghaly, A., & Cisek, P. (2022). Integrated neural dynamics of
1363 sensorimotor decisions and actions. *PLoS Biology*, 20(12), e3001861.
1364 <https://doi.org/10.1371/journal.pbio.3001861>
- 1365 Thura, D., & Cisek, P. (2017). The Basal Ganglia Do Not Select Reach Targets but Control
1366 the Urgency of Commitment. *Neuron*, 95(5), 1160-1170.e5.
1367 <https://doi.org/10.1016/j.neuron.2017.07.039>
- 1368 Thura, D., Cos, I., Trung, J., & Cisek, P. (2014). Context-Dependent Urgency Influences
1369 Speed–Accuracy Trade-Offs in Decision-Making and Movement Execution. *The*
1370 *Journal of Neuroscience*, 34(49), 16442. [https://doi.org/10.1523/JNEUROSCI.0162-](https://doi.org/10.1523/JNEUROSCI.0162-14.2014)
1371 14.2014
- 1372 Vassiliadis, P., Derosiere, G., Grandjean, J., & Duque, J. (2020). Motor training strengthens
1373 corticospinal suppression during movement preparation. *Journal of Neurophysiology*,
1374 124(6), 1656-1666. <https://doi.org/10.1152/jn.00378.2020>
- 1375 Wagenmakers, E.-J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Love, J., Selker, R.,
1376 Gronau, Q. F., Šmíra, M., Epskamp, S., Matzke, D., Rouder, J. N., & Morey, R. D.
1377 (2018). Bayesian inference for psychology. Part I: Theoretical advantages and
1378 practical ramifications. *Psychonomic Bulletin & Review*, 25(1), 35-57.
1379 <https://doi.org/10.3758/s13423-017-1343-3>
- 1380 Weinstein, A. M. (2023). Reward, motivation and brain imaging in human healthy participants
1381 – A narrative review. *Frontiers in Behavioral Neuroscience*, 17, 1123733.
1382 <https://doi.org/10.3389/fnbeh.2023.1123733>
- 1383 Wessel, J. R., & Aron, A. R. (2017). On the Globality of Motor Suppression : Unexpected
1384 Events and Their Influence on Behavior and Cognition. *Neuron*, 93(2), 259-280.
1385 <https://doi.org/10.1016/j.neuron.2016.12.013>
- 1386 Wilhelm, E., Quoilin, C., Derosiere, G., Paço, S., Jeanjean, A., & Duque, J. (2022).
1387 Corticospinal Suppression Underlying Intact Movement Preparation Fades in
1388 Parkinson’s Disease. *Movement Disorders*, 37(12), 2396-2406.
1389 <https://doi.org/10.1002/mds.29214>
- 1390 Yoon, T., Geary, R. B., Ahmed, A. A., & Shadmehr, R. (2018). Control of movement vigor
1391 and decision making during foraging. *Proceedings of the National Academy of*
1392 *Sciences*, 115(44). <https://doi.org/10.1073/pnas.1812979115>
- 1393 Yttri, E. A., & Dudman, J. T. (2018). A Proposed Circuit Computation in Basal Ganglia :
1394 History-Dependent Gain. *Movement Disorders*, 33(5), 704-716.
1395 <https://doi.org/10.1002/mds.27321>
- 1396 Zarrugh, M. Y., Todd, F. N., & Ralston, H. J. (1974). Optimization of energy expenditure
1397 during level walking. *European Journal of Applied Physiology and Occupational*
1398 *Physiology*, 33(4), 293-306. <https://doi.org/10.1007/BF00430237>
- 1399 Zénon, A. (2019). Eye pupil signals information gain. *Proceedings of the Royal Society B:*
1400 *Biological Sciences*, 286(1911), 20191593. <https://doi.org/10.1098/rspb.2019.1593>
1401

1402 **Supplementary materials**

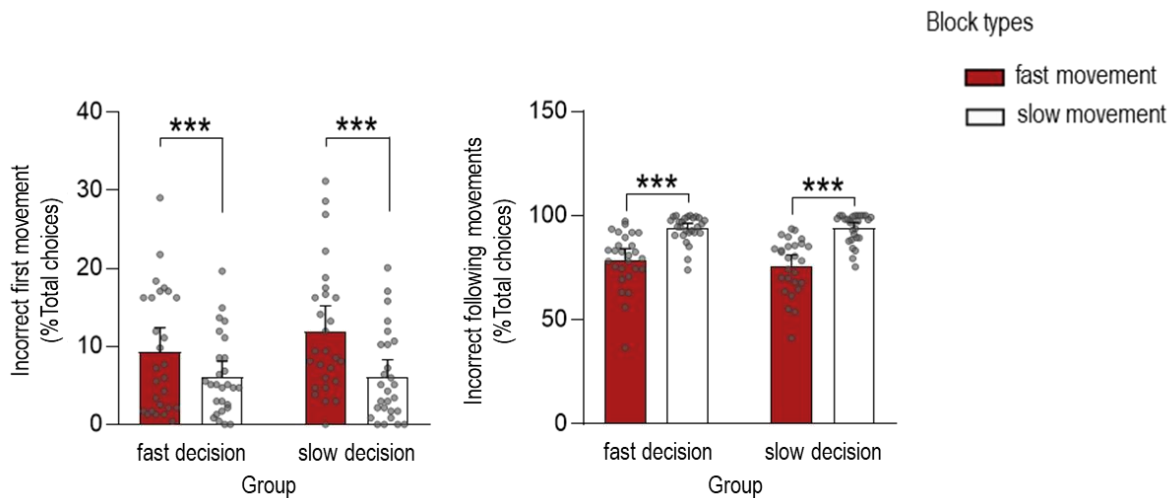


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1404 **Figure S1. Movement performance in Experiment 1.** Participants successfully escaped the
1405 ghost (Pacman Success) equally in fast decision blocks (blue bar) and slow decision blocks
1406 (white bar). Error bars represent SE.

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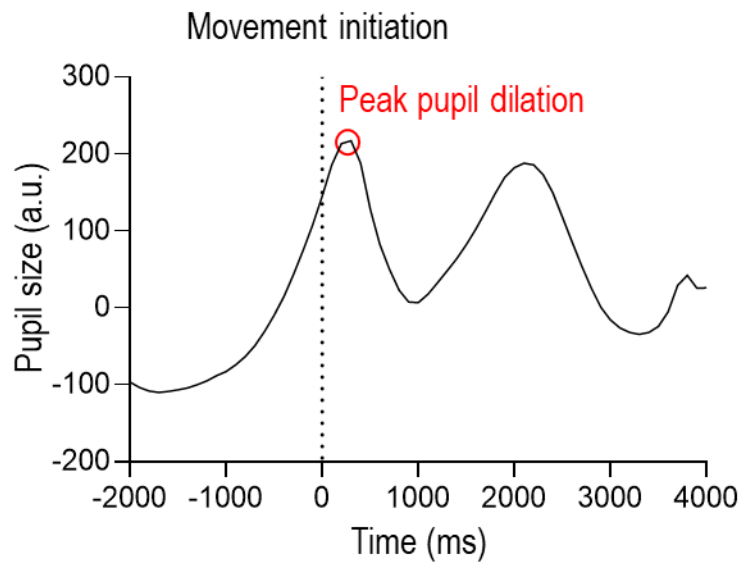
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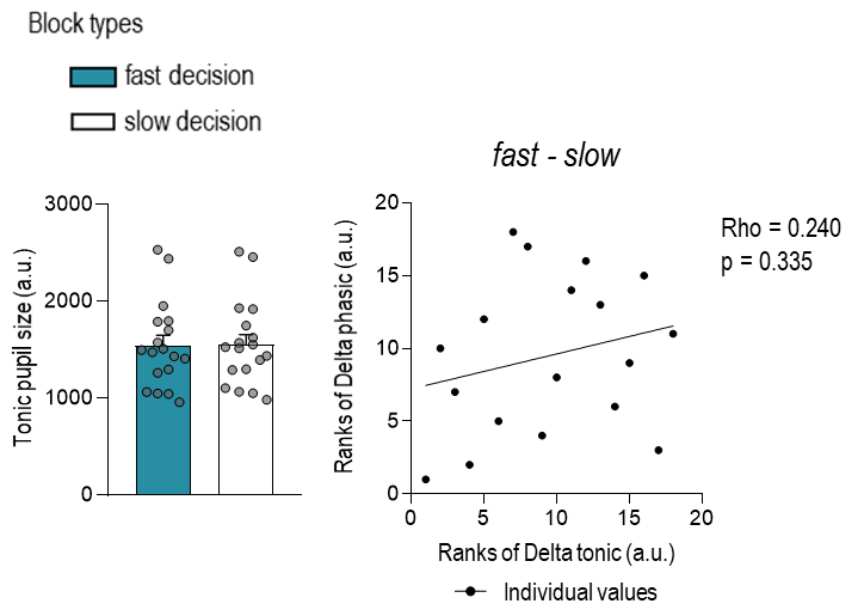
1410 **Figure S2. Movement performance in Experiment 2.** On average, participants had more
1411 difficulty keeping up with the speed imposed in the fast movement blocks (red bars) than in the
1412 slow movement blocks (white bars). More precisely, the success rate was lower in fast relative
1413 to 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.

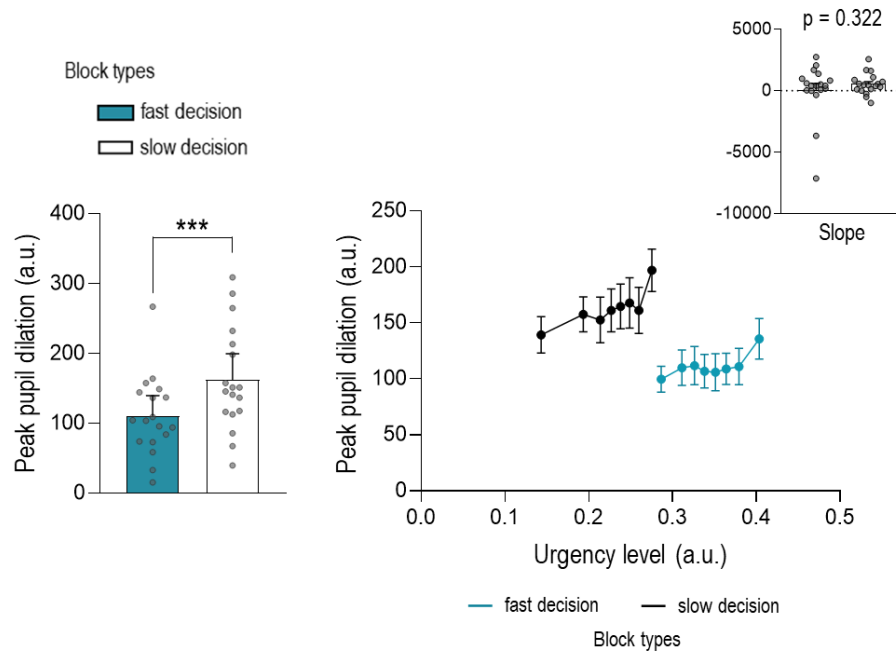


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1423 **Figure S4. Control analyses on pupil dilation in Experiment 1 (n=18).** As a control analysis,
1424 we considered a window of 250 ms before the trial onset to measure tonic pupil dilation. As
1425 shown on the left panel, such tonic pupil dilation 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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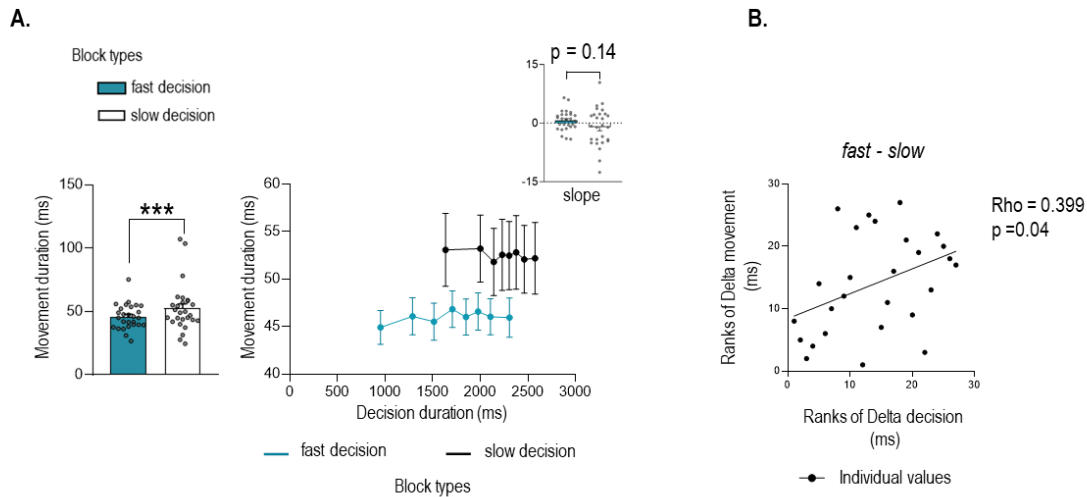
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1446 **Figure S6. Control analyses on behavior in Experiment 1 (n=27). A. Movement duration.**

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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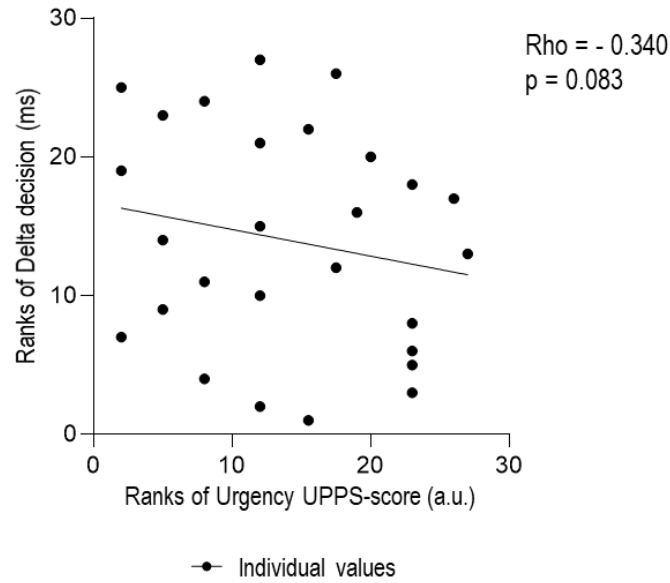
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1465 **Figure S7. Correlation with UPPS-score in slow decision group of Experiment 2.** Given
1466 that deltas were computed by measuring the difference in duration between fast and slow
1467 conditions, the more the subjects showed an effect of the 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_{DD}</i>	<i>t-value</i>	<i>df</i>	<i>p-value</i>	<i>Cohen's d</i>
1	12.784	55	< 0.001	1.708
2	10.122	55	< 0.001	1.353
3	8.298	55	< 0.001	1.109
4	7.261	55	< 0.001	0.970
5	6.421	55	< 0.001	0.858
6	5.676	55	< 0.001	0.758
7	4.816	55	< 0.001	0.644
8	3.761	55	< 0.001	0.503

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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_{DD}*). Significant p-value (with a Bonferroni-corrected threshold of .05/8) are highlighted in bold and blue.

<i>Bin_{DD}</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	-4.007	17	< 0.001	-0.944
3	-2.352	17	0.031	-0.554
4	-3.561	17	0.002	-0.839
5	-4.408	17	< 0.001	-1.039
6	-3.884	17	0.001	-0.915
7	-3.191	17	0.005	-0.752
8	-5.583	17	< 0.001	-1.316

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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_{DD}*). Significant p-value (with a Bonferroni-corrected threshold of .05/8) are highlighted in bold and blue.

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