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Élise Leroy, Éric Koun, David Thura

► **To cite this version:**

Élise Leroy, Éric Koun, David Thura. Humans anticipate the consequences of motor control demands when making perceptual decisions between actions. 2024. hal-04784435

**HAL Id: hal-04784435**

**<https://hal.science/hal-04784435v1>**

Preprint submitted on 15 Nov 2024

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5

6 **Élise Leroy<sup>1,2</sup>, Éric Koun<sup>1,2</sup> and David Thura<sup>1,2</sup>**

7 <sup>1</sup> University Claude Bernard Lyon 1, Lyon, France

8 <sup>2</sup> Lyon Neuroscience Research Center, Impact Team, Inserm U1028, CNRS UMR5292, Bron,  
9 France  
10

11  
12 ***Corresponding author:***

13 David Thura

14 E-mail: david.thura@inserm.fr  
15

16 ***Manuscript information:***

17 Abstract: 271 words; Introduction, Results, Discussion and Methods: ~6600 words  
18 22 pages – 4 main figures – 2 supplemental figures  
19

20 ***Keywords:***

21 Decision-making, motor control, volition, motor costs, success rate  
22

23 ***Acknowledgements/Funding:***

24 The authors have no financial or non-financial interests to declare. The authors wish to thank  
25 Sonia Alouche and Jean-Louis Borach for their administrative assistance, and Frédéric Volland  
26 for his expertise during the technical preparation of this experiment. This work is supported by a  
27 CNRS/Inserm ATIP/Avenir grant to DT.  
28

29 **ABSTRACT**

30 Animals, including humans, are often faced with situations where they must decide between  
31 potential actions to perform based on various sources of information, including movement  
32 parameters that incur time and energy costs. Consistent with this fact, many behavioral studies  
33 indicate that decisions and actions show a high level of integration during goal-directed behavior.  
34 In particular, motor costs very often bias the choice process of human and non-human subjects  
35 facing successive decisions between actions. However, it appears as well that depending on the  
36 design in which the experiment occurs, the effect of motor costs on decisions can vary or even  
37 vanish. This suggests a contextual dependence of the influence of motor costs on decision-making.  
38 Moreover, it is not currently known whether or not the impact of motor costs on perceptual  
39 decisions depend on the difficulty of the decision. We addressed these two important issues by  
40 studying the behavior of healthy human subjects engaged in a new perceptual decision-making  
41 paradigm in which the constraint level associated with the movement executed to report a choice  
42 was volitionally chosen by the participants, and in which the difficulty of the perceptual decision  
43 to make continuously evolved depending on their motor performance. The results indicate that the  
44 level of constraint associated with a movement executed to express a perceptual decision strongly  
45 impacts the duration of these decisions, with a shortening of decisions when these are expressed  
46 by demanding movements. This influence appears most important when the decisions are difficult,  
47 but it is also present for easy decisions. We interpret this strategy as an adaptive way to optimize  
48 the participants' overall rate of success at the session level.

## 49 INTRODUCTION

50 Although choices are always ultimately expressed via actions, decision-making and motor control  
51 are most often studied separately from each other (Gold and Shadlen, 2007; Shadmehr and  
52 Krakauer, 2008; Franklin and Wolpert, 2011; Lee et al., 2012). Recent behavioral studies,  
53 including ours, indicate however that decisions and actions are closely linked, sharing economic  
54 principles and showing a high level of integration during goal-directed behavior (Shadmehr, 2010;  
55 Gallivan et al., 2018; Carland et al., 2019; Shadmehr et al., 2019; Wispinski et al., 2020; Gordon  
56 et al., 2021).

57 For instance, it has been proposed that movement selection, preparation, and execution are  
58 parameterized following economical rules, varying depending on utility estimation: high valued  
59 options lead to faster reaction times and movement speed, and high-perceived effort discounts an  
60 option value, leading to slower reaction and longer movements (Shadmehr et al., 2010; Haith et  
61 al., 2012; Choi et al., 2014; Morel et al., 2017). If the sensory information guiding the choice is  
62 weak and the decision takes time, humans and monkeys shorten the duration of the movements  
63 expressing this choice (Thura et al., 2014; Thura, 2020; Herz et al., 2022). If the context in which  
64 the task occurs encourages fast and risky decisions, humans and monkeys report these choices with  
65 faster movements compared to when the task is performed in a slow speed-accuracy context (Thura  
66 et al., 2014; Thura, 2020; Herz et al., 2022; Carsten et al., 2023; Saleri and Thura, 2024).

67 Conversely, several studies have demonstrated that motor costs influence decision-making as well,  
68 whether choices only rely on movement properties (Cos et al., 2011; Morel et al., 2017; Michalski  
69 et al., 2020; Canaveral et al., 2024), options value (Pierrieau et al., 2021; Griebbach et al., 2022)  
70 or perceptual stimuli (Burk et al., 2014; Lepora and Pezzulo, 2015; Marcos et al., 2015; Hagura et  
71 al., 2017). In our lab, we have demonstrated that humans and monkeys decide faster and/or with  
72 less precision in order to focus on their actions when the movement expressing a choice is  
73 demanding (Reynaud et al., 2020; Saleri Lunazzi et al., 2023) or time consuming (Saleri Lunazzi  
74 et al., 2021; Saleri and Thura, 2024).

75 Although these studies indicate a significant level of integration between perceptual decision-  
76 making and motor control processes, with notably a significant influence of motor costs on  
77 perceptual decision-making, two questions need to be addressed. First, it is unknown whether the  
78 impact of the motor costs on decision-making depends on the obligation for the subjects to express

79 choices in a difficult motor condition structured in a succession of many consecutive trials. Indeed,  
80 in the studies cited above (Reynaud et al., 2020; Saleri Lunazzi et al., 2021, 2023; Saleri and Thura,  
81 2024), the demanding motor condition was always imposed on the subjects, in dedicated blocks  
82 of trials. However, it is possible that if the subject deliberately chooses to express a choice in a  
83 demanding motor condition, on a trial by trial basis, to obtain a larger reward for example, the  
84 impact of these motor demands on the decision process differs. In support of such a possibility, a  
85 recent result indicates for instance that the level of movement effort may not influence perceptual  
86 decisions when that effort is explicitly felt and integrated by human subjects (Manzone and Welsh,  
87 2023), suggesting that the results of the experiments mentioned above may be specific to how  
88 motor costs are manipulated. Secondly, it is currently unknown to what extent the impact of the  
89 motor control demands on decision-making depends on the difficulty of the choice to make. It is  
90 for instance possible that subjects sacrifice their decisions in favor of more demanding motor  
91 control only when the decision is hard but that when the decision is easy, the influence of the motor  
92 context is less pronounced or even disappears.

93 We investigated these two questions by studying the behavior of healthy human subjects engaged  
94 in a new perceptual decision-making paradigm in which the constraint level of the movement  
95 executed to report a choice was chosen by the participants, and in which the difficulty of the  
96 perceptual decision to make continuously evolved depending on their motor performance. This  
97 design therefore allowed us to test the effect of motor constraints on perceptual decision-making  
98 when these constraints were volitionally chosen by the subjects, and it offered at the same time the  
99 possibility of testing this effect on multiple levels of decisional difficulty manipulated in a gradual  
100 manner.

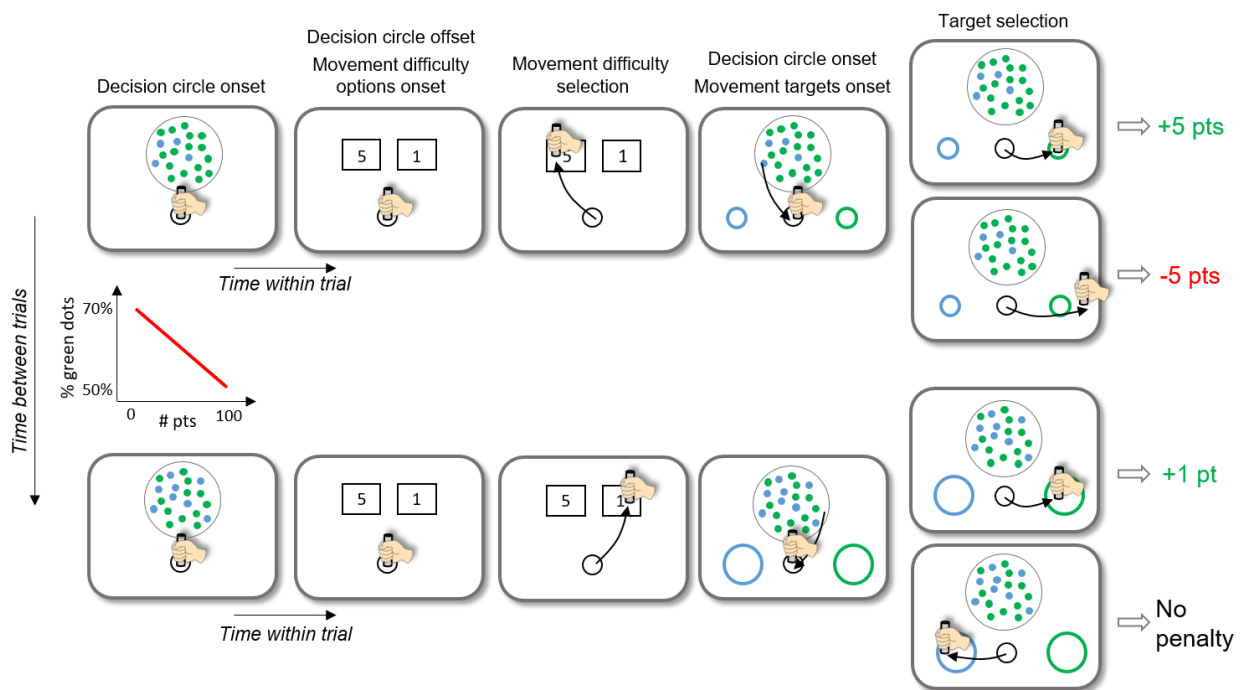
## 101 RESULTS

102 Thirty-two healthy human participants performed a new behavioral paradigm (Fig. 1) during a  
103 single experimental session. The goal of the subjects was to accumulate a total of 200 points to  
104 complete the session. To earn points, they had to choose at the beginning of each trial the constraint  
105 level of the movement executed to report a perceptual decision: either a demanding arm movement,  
106 in terms of motor control, potentially earning 5 points if accurately executed, or an easy movement,  
107 earning only 1 point if accurately executed. After making that choice, they had to make the  
108 corresponding perceptual decision and report it by executing the arm movement toward a visual

109 target. Crucially and unknown to the subjects, the coherence of the visual stimulus was linearly  
 110 and inversely indexed to the number of accumulated points during the session, progressively  
 111 increasing the difficulty of each perceptual decision. The points (5 or 1) that the subjects chose to  
 112 engage at the beginning of each trial were lost in case of a movement error, i.e. if they failed to  
 113 reach the chosen target and stay in it within the required time windows, but not in case of a wrong  
 114 perceptual decision.

115 This design allowed us to assess the impact of the motor control required to express a perceptual  
 116 decision on participants' decision-making performance, for decisions whose difficulty varied in  
 117 small steps from an easy level to a difficult level, and when the demanding motor control condition  
 118 was deliberately chosen by the subject from one trial to the next to potentially gain more points.

119



120

121 **Figure 1.** The top row illustrates the time course of a trial at the beginning of the session. Each trial starts  
 122 when the subject brings with her/his dominant hand a handle and maintains it still in a start circle. The  
 123 decision circle containing 100 blue and green tokens is first displayed for 300ms to inform the subject about  
 124 the difficulty of the perceptual decision to make later in the trial. At this stage the dominant color among  
 125 the tokens (i.e. the coherence) is not informative of the correct target to select at the end of the trial. The  
 126 proportion of tokens of the dominant color is 77% on the first trial of the session. The decision circle  
 127 disappears and the movement constraint options are then displayed. In this example the subject chooses “5”  
 128 (by moving the handle in the rectangle surrounding the number 5), which corresponds to a demanding  
 129 movement to execute, i.e. toward a small visual target ( $\phi = 1.25\text{cm}$ ). Once selected, the subject leaves the

130 motor constraint option rectangle and comes back to the start circle. The decision circle containing the 100  
131 tokens, and the blue and green movement targets then appear. The dominant color among the tokens (with  
132 the same proportion as at the beginning of the trial) now determines the correct target to select. The subject  
133 reports the decision by moving the handle in the target whose color corresponds to her/his choice. The  
134 subject earns the amount of points she/he chose (“5” in this example) if she/he accurately reaches to the  
135 correct target. She/he loses the points if she/he executes an inaccurate movement, regardless of the chosen  
136 side. After the first trial, the coherence within the decision circle evolves from trial to trial, being linearly  
137 and inversely indexed to the number of points accumulated during the session. As a consequence, at the  
138 end of the session (bottom row), when the subject gets close to 200 points, the coherence in the visual  
139 stimulus is low (proportion of tokens of the dominant color equal to 51%) and the decision difficulty is  
140 high. As illustrated in this example, we assumed that in this situation, subjects would choose an easy  
141 movement (the “1” rectangle), executed toward a large target ( $\sigma = 3.75\text{cm}$ ) more frequently than at the  
142 beginning of the session, when the decisional effort was low and the number of points to accumulate to  
143 complete the session was high. Regardless of the movement constraint level chosen by the subject, if she/he  
144 selects the wrong target (decision error) with an accurate movement, points are not deducted.

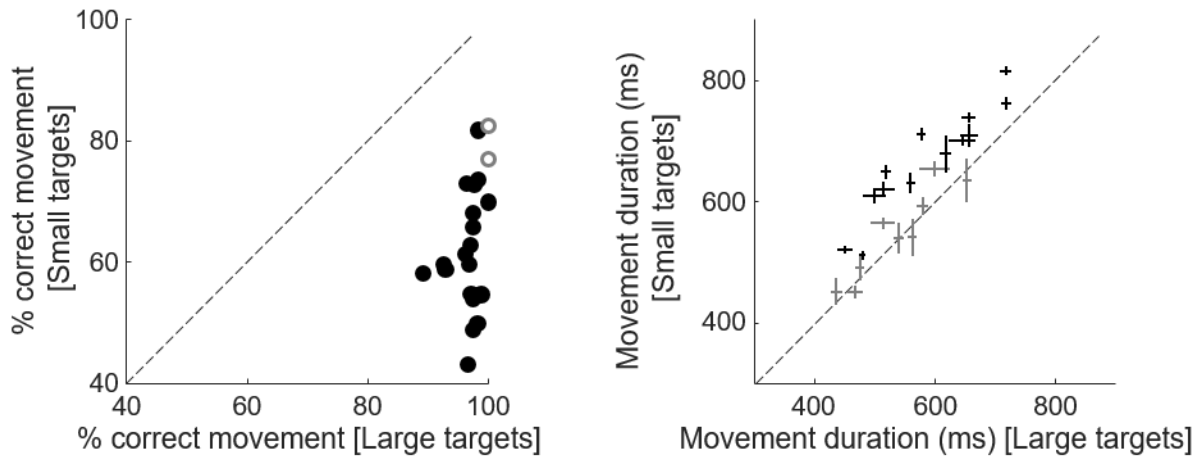
#### 145 [General observations](#)

146 Among subjects who performed the task ( $n=32$ ), the median number of trials to reach 200 points  
147 across the population was 184, with a large variability between subjects (min = 87; max = 426; SD  
148 = 84 trials). The median proportion of demanding movement choices during a session was 62%,  
149 again with high variability between subjects (min: 5%; max: 100%; SD = 34%). With this design  
150 we expected to observe a mixture of choices of the constraint level of the movements to be  
151 performed to express the perceptual decisions, regardless of the coherence of the decision stimulus.  
152 This is because the demanding movements would be chosen to gain more points, perhaps more at  
153 the beginning of the session when the number of points to accumulate to complete the session is  
154 high and the perceptual decisions are the easiest, while the easy movements would be chosen to  
155 guarantee the obtaining of points in case of correct perceptual decisions. However, we observed  
156 that out of 32 participants, 9 almost did not vary their movement difficulty choices through the  
157 session (1/32 subject chose the easy option in more than 95% of the trials, 8/32 chose that option  
158 in less than 5% of trials). In the following analyses, we excluded those 9 subjects who  
159 systematically chose the same level of motor constraint level through their experimental session,  
160 as they were likely either insensitive (for the 8 subjects who chose the difficult option in more than  
161 95% of the trials) or too sensitive (for the subject who chose the easy option in more than 95% of  
162 the trials) to the decisional and/or motor difficulties manipulated in the experiment.

#### 163 [Effect of motor control demands \(i.e. target size\) on subjects’ motor behavior](#)

164 We first verified that the two constraint levels of motor control required to report perceptual  
165 decisions did indeed impact the motor behavior of the remaining 23 subjects. To do this, we

166 analyzed the precision and duration of their reaching movements as a function of these two levels  
 167 of constraint. As expected, we found that participants' movement accuracy was lower when they  
 168 reported their perceptual decisions by moving toward the small targets compared to when they had  
 169 to make a movement toward a large target (median accuracies at the population level: 60% versus  
 170 97%, Chi-square test for independence on the population:  $\chi^2 = 1004$ ,  $p < 0.0001$ ; Chi-square tests  
 171 for independence on individual subjects, 21/23 with  $p < 0.05$ , Fig. 2, left panel). We also observed  
 172 that the majority of subjects' movements (whether accurate or not) were slower, in terms of  
 173 duration, when executed toward a small target than toward a large target (Wilcoxon rank-sum tests  
 174 on individual subjects, 14/23 with  $p < 0.05$ , Fig. 2, right panel), even if the difference of movement  
 175 duration between the two motor conditions is not significant at the population level (median  
 176 durations: 630ms vs. 563ms, Chi-square test for independence on the population:  $\chi^2 = 1.5$ ,  $p =$   
 177 0.13). Given these results, we make the assumption in the following paragraphs that movements  
 178 executed toward the small targets were more demanding, in terms of motor control, compared to  
 179 movements executed toward the large targets.



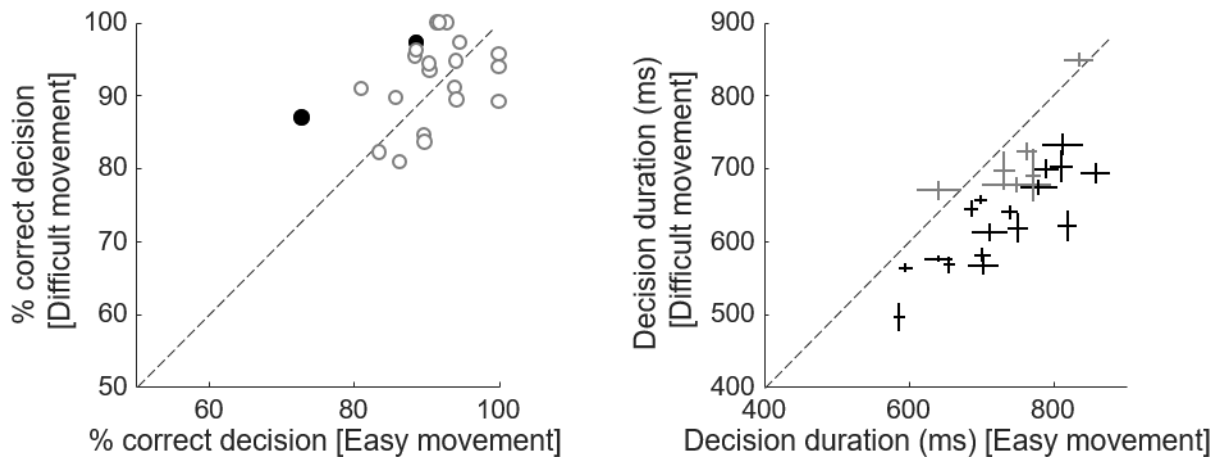
180

181 **Figure 2.** *Left panel:* Comparison of subjects' movement accuracy as a function of movement constraint  
 182 level (difficult movement/small targets: ordinate; easy movement/large targets: abscissa). Circles illustrate  
 183 individual subjects' data. Filled black circles highlight subjects for which the difference between conditions  
 184 is statistically significant (Chi-squared test,  $p < 0.05$ ). *Right panel:* Comparison of subjects' movement  
 185 duration (whether accurate or not) as a function of movement constraint level (difficult movement/small  
 186 targets: ordinate; easy movement/large targets: abscissa). Crosses illustrate individual subjects' medians  $\pm$   
 187 SE. Black crosses highlight subjects for which the difference between conditions is statistically significant  
 188 (rank-sum test,  $p < 0.05$ ).



189 [Effect of motor control demands on subjects' decision behavior](#)

190 We then analyzed the impact of this demanding level of motor control on the perceptual decisions  
191 of the 23 participants. To do this, we first analyzed the accuracy and duration of their perceptual  
192 decisions as a function of the motor condition in which decisions were made, regardless of the  
193 difficulty of these decisions. We found at the population level that participants' perceptual decision  
194 accuracy was similar whether they were reported with reaching movements executed toward small  
195 or large targets (medians: 93.4% versus 90.4%, Chi-square test for independence on the  
196 population:  $\chi^2 = 1.9$ ,  $p = 0.16$ ). Only two subjects were significantly more accurate to decide when  
197 choices were expressed with difficult movements (Chi-square tests for independence on individual  
198 subjects, 2/23 with  $p < 0.05$ , [Fig. 3, left panel](#)). By contrast, we observed that the level of motor  
199 control demand strongly impacted the duration of the perceptual decisions preceding the execution  
200 of movements executed to report these choices. Indeed, participants were overall faster to decide  
201 (accurately or not) when the subsequent movements were demanding compared to when they were  
202 easier (median durations: 657ms vs. 739ms, Chi-square test for independence on the population:  
203  $\chi^2 = -3.4$ ,  $p < 0.0001$ ). This effect was robust at the individual level, as the effect was significant  
204 for the vast majority of subjects (Wilcoxon rank-sum tests on individual subjects, 17/23 with  $p <$   
205  $0.05$ , [Fig. 3, right panel](#)).



206

207 **Figure 3.** *Left panel:* Comparison of subjects' perceptual decision accuracy as a function of movement  
208 difficulty (difficult movement/small targets: ordinate; easy movement/large targets: abscissa). Same  
209 convention as in Fig. 2, left panel. *Right panel:* Comparison of subjects' perceptual decision durations  
210 (correct or not) as a function of movement difficulty (difficult movement/small targets: ordinate; easy  
211 movement/large targets: abscissa). Same conventions as in Fig. 2, right panel.

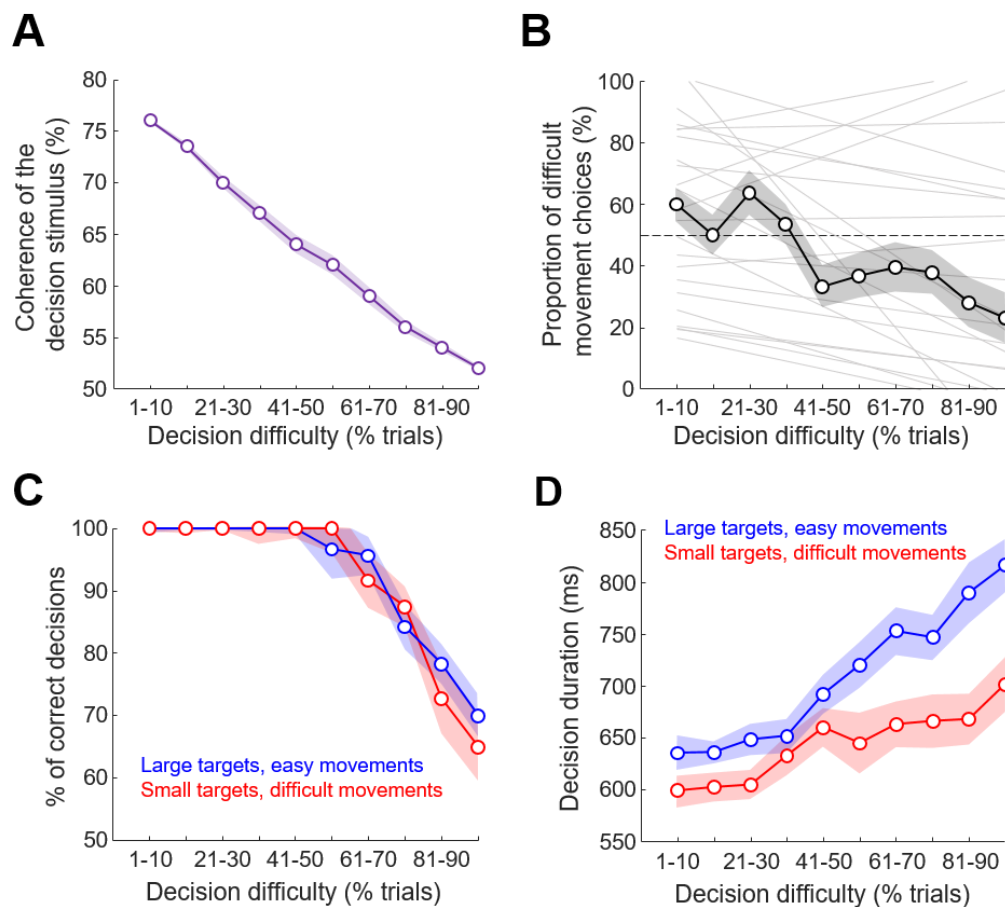
212 The above results indicate that the level of motor control required to express perceptual decisions,  
213 deliberately chosen by individuals, impacts the duration of these decisions preceding the  
214 movements. To answer the second question addressed in the present study, namely whether this  
215 impact of motor costs on decision-making depends on the difficulty of decisions, we analyzed the  
216 behavior of the subjects according to the evolution of their decisional and motor performances in  
217 the task.

218 Our goal with this experimental design was to obtain trials in which subjects would volitionally  
219 choose to report their perceptual decisions with easy or difficult movements, while gradually  
220 increasing the difficulty of these perceptual decisions in small increments. Because the coherence  
221 in the decision stimulus continuously varied from trial to trial, we normalized the number of trials  
222 performed by each subject by chronologically grouping them in 10 quantiles. As shown in [figure](#)  
223 [4A](#), the first 10% of trials were trials for which the coherence of the decisional stimulus was the  
224 highest (because subjects' scores were the lowest) and thus perceptual decisions were the easiest;  
225 Conversely, the last 10% of trials were the trials for which the coherence of the decision stimulus  
226 was the lowest, and thus decisions were the most difficult.

227 We found at the population level that the proportion of difficult movement choices did not  
228 significantly vary depending on the level of decision difficulty (Kruskal-Wallis test,  $\chi^2 = 11.2$ ,  $p =$   
229  $0.26$ ), despite the fact that a tendency for a decrease of that proportion with the increase of decision  
230 difficulty is visible ([Fig. 4B](#)). Indeed, at the individual level, we found that the evolution of the  
231 perceptual decision difficulty influenced the proportion of movement difficulty choices in 17 out  
232 of 23 subjects (Chi-squared tests for independence,  $p < 0.05$ ). Among them, the vast majority  
233 (13/17) overall decreased their proportion of “small targets” choices with the increase of the  
234 perceptual decision difficulty ([Fig. 4B](#)).

235 We then analyzed the decision-making behavior of the participants as a function of the difficulty  
236 of the perceptual decision and as a function of the level of motor control required to report these  
237 choices by performing analyses of covariance (ANCOVAs). As expected, the proportion of correct  
238 decisions across the population significantly decreased depending on the number of trials  
239 performed during the session (i.e. as a function of the decreasing coherence in the stimulus, see  
240 [Fig. 4A](#)), regardless of the motor control condition (ANCOVA, Trials:  $F=199$ ,  $p < 0.0001$ ;  
241 Movement difficulty:  $F=2.5$ ,  $p = 0.12$ ; Movement difficulty x Trials:  $F=0.78$ ,  $p=0.38$ , [Fig. 4C](#)). As

242 expected too, we observed that the duration of decisions (whether correct or not) increased as a  
 243 function of the number of trials performed during the session (Trials:  $F=32.3$ ,  $p < 0.0001$ , Fig. 4D).  
 244 As mentioned above (Fig. 3, right panel), we also found a strong effect of the motor condition on  
 245 the duration of the perceptual decisions, with decisions being longer when reported via movements  
 246 executed toward large targets (Movement difficulty:  $F=104$ ,  $p < 0.0001$ , Fig. 4D). But  
 247 interestingly, we found that this effect was not dependent on the difficulty level of the perceptual  
 248 decisions, even if a trend for a more pronounced impact when decisions are difficult is observed  
 249 (Movement difficulty x Trials:  $F=3.79$ ,  $p = 0.052$ , Fig. 4D).



250

251 **Figure 4.** A. Relationship between the number of completed trials (averaged  $\pm$  SE, shaded area, across the  
 252 population) and the coherence of the decision stimulus. Coherence is defined as the ratio between the  
 253 number of tokens of each color in the decision stimulus. It is expressed as the percentage of tokens of one  
 254 color compared to the other. Trials are sorted chronologically and a normalization is performed by grouping  
 255 them in 10 quantiles. B. Proportion of demanding movement choices as a function of decision difficulty.  
 256 As in A, trials are sorted chronologically and normalized by grouping them in 10 quantiles. Because the  
 257 coherence of the decision stimulus strongly co-varies with the number of completed trials, trial number is  
 258 a proxy of the decision difficulty. Open circles illustrate the median values ( $\pm$  SE, gray shaded area) at the

259 population level, and light gray lines illustrate linear regressions through the data for each individual  
260 subject. *C*. Median ( $\pm$  SE, colored shaded area) proportion of correct perceptual decisions across subjects,  
261 as a function of decision difficulty, with trials sorted as a function of the motor condition chosen by the  
262 subjects (blue: large targets/easy movement; red: small targets/difficult movement). *D*: Perceptual decision  
263 durations as a function of decision difficulty, with trials sorted as a function of the motor condition chosen  
264 by the subjects (blue: large targets/easy movement; red: small targets/difficult movement). Same  
265 convention as in *C*.

## 266 DISCUSSION

267 The present study was designed to test the impact of motor demands on the accuracy and duration  
268 of perceptual decisions whose difficulty was manipulated in a gradual manner, and when costly  
269 movements were volitionally chosen by human subjects from one trial to the next to gain more  
270 points. Our study indicates that the level of constraint associated with a movement executed to  
271 express a perceptual decision strongly impacts the duration of these decisions. This influence  
272 appears most important when the decisions are difficult, but it is also present for easy decisions.  
273 In the following paragraphs, we discuss these results in the context of recent work on decision and  
274 action interactions, and we propose an interpretation of these data in terms of behavior  
275 optimization.

### 276 Motor constraints influence perceptual decision-making

277 Recent behavioral studies indicate that decisions and actions are closely linked, showing a high  
278 level of integration during goal-directed behavior (for reviews, see [Shadmehr, 2010](#); [Gallivan et al., 2018](#);  
279 [Carland et al., 2019](#); [Shadmehr et al., 2019](#); [Wispiński et al., 2020](#); [Gordon et al., 2021](#)).  
280 On the one hand, the properties of movement, such as speed and duration, are influenced by  
281 decision-making characteristics ([Thura et al., 2014](#); [Thura, 2020](#); [Herz et al., 2022](#), [Carsten et al.,](#)  
282 [2023](#); [Saleri and Thura, 2024](#)), and the selection, preparation, and execution of movements are  
283 parameterized following the same economical rules as those which govern decisional processes  
284 ([Shadmehr et al., 2010](#); [Haith et al., 2012](#); [Choi et al., 2014](#); [Morel et al., 2017](#)).

285 On the other hand, numerous behavioral studies have now provided strong support for action-  
286 based (or embodied) models of decision-making that hypothesize that action alternatives and their  
287 associated properties, including costs, are incorporated into the choice process ([Cisek, 2007](#);  
288 [Lepora and Pezzulo, 2015](#)). These behavioral studies tested the impact of motor constraints on  
289 decision-making using different designs. Very often, a specific motor cost, itself manipulated in  
290 different ways, is associated with each option proposed to participants during each trial, and the

291 basis for choosing varies depending on the paradigm. For example, decisions may be based  
292 primarily on the motor properties of movements, with one option being costlier than the other in  
293 terms of biomechanical cost or energy expenditure on each trial (Cos et al., 2011, 2014; Morel et  
294 al., 2017), sometimes during ongoing actions (Michalski et al., 2020; Griebach et al., 2022;  
295 Canaveral et al., 2024). In other cases, the movements performed to express a choice carry different  
296 costs but the decision is primarily based on perceptual cues (Burk et al., 2014; Marcos et al., 2015;  
297 Hagura et al., 2017) or rewards (Pierrieau et al., 2021; Griebach et al., 2022) associated with each  
298 of the two possible options. In most of these scenarios, the manipulation of motor costs influences  
299 the choice of target selected by participants before or during movement execution.

300 There is, however, evidence that questions a systematic effect of motor costs on decision making,  
301 suggesting a task and/or parameter specific aspect to this phenomenon. For example, in a recent  
302 study by Manzone and Welsh, the authors demonstrate that when motor costs are clearly and  
303 explicitly felt by participants (which is not necessarily the case in other similar studies (Marcos et  
304 al., 2015; Hagura et al., 2017)), this explicit effort has a reduced or even absent impact on  
305 perceptual decision making (Manzone and Welsh, 2023). In the study of Pierrieau and colleagues,  
306 the authors report that when the rewarded target carries the highest motor cost, reaching  
307 movements executed within 350ms of reaction time are biased toward the other target, but this  
308 effect disappears if participants takes longer to react (Pierrieau et al., 2021). Finally, when  
309 comparing the effects of motor costs between a manual movement task and a walking task within  
310 the same participants, Griebach and colleagues observed that the motor costs bias on perceptual  
311 decisions only weakly transfer between tasks (Griebach et al., 2023). Together, these results point  
312 to a contextual influence of action effort and costs on perceptual decision-making.

313 In our own recent experiments, we manipulated the motor condition in which perceptual decisions  
314 were made by human or non-human subjects. Specifically, the two options offered to the  
315 participants to report their choices (based on changing visual evidence) carried broadly the same  
316 motor cost, but this cost varied in dedicated blocks of trials imposed on the subjects. In this case,  
317 whether for human subjects or for monkeys, we observed a strong impact of the motor condition  
318 on the precision and duration of the perceptual decisions taken before the arm movement was  
319 executed to express these choices (Reynaud et al., 2020; Saleri Lunazzi et al., 2021; Saleri and  
320 Thura, 2024).

321 Given the design-related contrasted results of the experiments mentioned above when each  
322 movement option carries a specific cost, we could wonder whether in our experimental condition  
323 where the two motor targets are associated with the same motor costs, the change of context,  
324 notably the voluntary choice of the subjects to execute a more or less costly movement to gain  
325 more or fewer points, and this possibly from one trial to another and not in blocks of several dozen  
326 trials, could have consequences on the consideration of these motor costs during the perceptual  
327 decision-making process. In support of action-based decision models though, we observed that not  
328 only do motor costs influence decision-making when motor constraints are voluntarily chosen by  
329 the subjects, often from one trial to another and not in blocks, but that this influence persists  
330 whatever the difficulty of the decision, suggesting a very close and robust link between motor  
331 parameters expressing a perceptual decision and the perceptual decision process.

### 332 [Participants seek to preserve their rate of reward](#)

333 The prospect of executing a more or less demanding movement therefore strongly and  
334 systematically modulates the duration of decisions in the present experiment. But how can we  
335 explain the meaning of this modulation, namely a shortening of decisions when these are expressed  
336 by constrained movements? One might have expected to observe the opposite, i.e. slower and more  
337 precise decisions when these choices are expressed by costly movements. Indeed, an influent  
338 theory proposed that when an action is costly and requires effort, the overall motivation to behave  
339 is reduced, leading to not only slower movements, but also longer reaction times (Mazzoni et al.,  
340 2007; Shadmehr et al., 2019). Another interpretation of an identical result would be to consider  
341 that the participants sought to optimize the efforts invested in a costly behavior. Indeed, faced with  
342 a demanding movement, it is conceivable that they wanted to ensure that they made a good  
343 decision by extending the duration of the deliberation, longer deliberation being usually associated  
344 with better performance in stable coherence decision paradigms.

345 However, this is not what we observed. None of the 23 subjects had significantly longer decision  
346 times when the movements performed to express a choice were constrained (see Fig. 3, right  
347 panel). Our interpretation of the direction of this modulation is that participants sought to optimize  
348 the total duration of their response, namely the duration of the decision added to that of the  
349 movement. Indeed, in the experiment described in this report, the duration of each trial is entirely  
350 dependent on the subject's behavior, who therefore has control over this duration and over her/his



351 speed-accuracy trade-off strategy. By choosing constrained movements to potentially gain more  
352 points, participants possibly integrated that these movements requiring a higher degree of motor  
353 control would be slower, in terms of duration, than less constrained movements (Fig. 2, right panel,  
354 and see Fig. S1 for the analysis of movement parameters, including duration, between the two  
355 motor conditions as a function of decision difficulty). Consequently, subjects possibly sought to  
356 compensate for this additional time devoted to movement by shortening the duration of their  
357 perceptual decisions, regardless of the difficulty of these decisions. This allows them to maximize  
358 their success rate, that is, the number of successful trials, minus the effort associated with those  
359 trials, divided by the time required to perform those trials. As several studies have shown, success  
360 rate is a parameter that human subjects and animals seek to optimize, more than performance per  
361 se, when faced with a succession of decisions and actions (Shadlen et al., 2008; Bogacz et al.,  
362 2010; Balci et al., 2011; Carland et al., 2019; Shadmehr et al., 2019). Figure S2 illustrates the  
363 response time (decision and movement) of the subjects as a function of the difficulty of the  
364 decisions and as a function of the motor condition. Although the response time increases with the  
365 increase in the difficulty of the decisions, there is no significant effect of the motor condition on  
366 this overall response time. This result is consistent with a mechanism of compensation of motor  
367 time costs by the duration of the decisions. Interestingly, this shortening of the decisions had no  
368 impact on the precision of these decisions (Fig. 4C), which reinforces the idea that this strategy  
369 was beneficial and adaptative in terms of optimizing the success rate. This observation is also  
370 compatible with the idea that decisions are primarily based on information from a relatively short  
371 time window (Uchida et al., 2006; Yang et al., 2008; Chittka et al., 2009). For simple color  
372 discrimination, this can be as short as 30ms (Stanford et al., 2010), but even in much more difficult  
373 tasks, it appears to be on the order of 100-300ms (Kiani et al., 2008; Price and Born, 2010).

374 This supposedly preponderant role of the cost of time on the behavior of the subjects does not  
375 mean that effort played no role. Indeed, as mentioned above, the success rate integrates the notion  
376 of effort and energy expenditure in its equation. In a recent study, we showed that just like time  
377 resources, energy resources can be transferred between decision-making and motor processes, by  
378 prioritizing the most critical process for the behavior in question (Leroy et al., 2023). But it also  
379 appears that effort does not influence decision-making as robustly as time in an experiment  
380 specifically designed to dissociate the impact of both cost types on humans decisional strategy  
381 (Saleri Lunazzi et al., 2021). This is possibly because unlike time (Myerson and Green, 1995;

382 [Shadmehr et al., 2010](#)), effort, considered in its broad definition, is not always considered as a cost  
383 (i.e. the effort paradox, [Inzlicht et al., 2018](#)). Even if many experiments of voluntary reaching have  
384 shown that when given a choice, humans tend to prefer actions that carry the least biomechanical  
385 costs over the more effortful ones ([Cos et al., 2011](#); [Marcos et al., 2015](#); [Hagura et al., 2017](#);  
386 [Pierrieau et al., 2021](#); [Canaveral et al., 2024](#)), other studies have nevertheless shown that energy  
387 optimization is not systematically sought by participants ([Kistemaker et al., 2010](#); [Morel et al.,](#)  
388 [2017](#); [Moskowitz et al., 2023](#)). So, considering that in these particular scenarios where subjects  
389 are faced with a multitude of decisions between successive (arm or eye) movements, and that the  
390 time and the number of correct trials can be optimized to complete the session as quickly as  
391 possible, a notion of success rate that seems to strongly influence behavior, it is time more than  
392 effort that most systematically influences the strategy of the participants.

### 393 [Conclusions](#)

394 Taken together, the results of the present study and our past studies indicate that human subjects  
395 are able to anticipate the consequence of a demanding movement to execute, when this  
396 supplementary cost has been deliberately chosen on a trial-by-trial basis to potentially earn more  
397 points and complete the session faster, by shortening the duration of the perceptual decisions  
398 preceding the execution of the arm movements. This consideration of motor costs in decision-  
399 making does not depend on the difficulty of the choices, and does not impact their precision. We  
400 interpret this time compensation strategy as an adaptive way to optimize their overall rate of  
401 success at the session level.

## 402 [METHODS](#)

### 403 [Participants](#)

404 Thirty-two healthy human subjects (median age  $\pm$  SD:  $25.5 \pm 4.2$ ; 26 self-identified as females, 6  
405 as males; 25 right handed) participated in this study. All subjects gave their written informed  
406 consent before starting the experiment. The ethics committee of Inserm (IRB00003888,  
407 IORG0003254, FWA00005831) approved the protocol on June 7th 2022. All methods were  
408 performed in accordance with the relevant guidelines and regulations. Each participant was asked  
409 to perform one experimental session. They received a monetary compensation (10 euros per  
410 completed session) for participating in this study. All participants also performed another version  
411 of the task described in the present report, on a different day, for a study designed to test the



412 hypothesis that the management of effort-related energy resources is shared between decision-  
413 making and motor control (Leroy et al., 2023).

#### 414 Experimental apparatus

415 The subjects sat in a comfortable armchair and made planar reaching movements using a handle  
416 held in their dominant hand. A digitizing tablet (GTCO CalComp) continuously recorded the  
417 handle horizontal and vertical positions (100 Hz with 0.013 cm accuracy). The behavioral task was  
418 implemented by means of LabVIEW 2018 (National Instruments, Austin, TX). Visual stimuli and  
419 handle position feedback (black cross) were projected by a DELL P2219H LCD monitor (60 Hz  
420 refresh rate) onto a half-silvered mirror suspended 26 cm above and parallel to the digitizer plane,  
421 creating the illusion for the participants that stimuli floated on the plane of the tablet (please see  
422 Fig. 1a in Saleri Lunazzi et al., 2023).

#### 423 Behavioral task

424 Participants performed multiple trials of a multi-step decision-making task (Fig. 1). Each trial  
425 begins with a black circle (the starting circle,  $\varnothing = 3\text{cm}$ ) displayed at the bottom of the screen. To  
426 initiate a trial, the subject moves the handle in the starting circle and maintains the position for  
427 300ms. A large ( $\varnothing = 9\text{cm}$ ) circle then appears on the screen (the decision stimulus) for 300ms. It  
428 contains 100 green and blue tokens. The ratio between blue and green tokens defines the coherence  
429 of the decision stimulus. At this stage, the stimulus informs the subject about the difficulty of the  
430 perceptual decision she/he has to make later in the trial, but the dominant color among the tokens  
431 is not informative of the correct target to select at the end of the trial. The proportion of tokens of  
432 the dominant color is 77% on the first trial of the session.

433 Then the decision circle disappears and two rectangles are displayed above the starting circle,  
434 separated from each other by 10 cm. In each rectangle a text informs the subject about the difficulty  
435 of the movement that she/he has to execute in each trial to report the perceptual decision: “1” for  
436 an easy movement, executed toward a large visual target ( $\varnothing = 3.75\text{cm}$ , with a trial-to-trial  
437 variability of 2%), or “5” for a difficult movement, executed toward a small target ( $\varnothing = 1.25\text{cm}$ ,  
438 with a trial-to-trial variability of 2%). The subject has 1s to move the handle in the chosen rectangle  
439 and then must hold it for 500ms to validate this choice. She/he then returns to the starting circle  
440 and maintains the position for another 500ms to continue the trial.

441 The decision circle (filled with the 100 tokens) as well as the blue and green movement targets  
442 then appear. The movement targets are visual circles displayed 180° apart of the starting circle.  
443 Their size depends on the choice of the subject, either large ( $\emptyset = 3.75\text{cm}$ ) or small ( $\emptyset = 1.25\text{cm}$ ).  
444 The distance between the starting circle center and each movement target center was 10cm, with  
445 a trial-to-trial variability of 1.9cm. The dominant color among the tokens (with the same proportion  
446 as at the beginning of the trial) now determines the correct target to select.

447 The subject task is to determine the dominant color in the decision circle, either blue or green. To  
448 express this perceptual decision, the participant moves the handle in the lateral target whose color  
449 corresponds to her/his choice and maintains this position for 500ms. The dominant color (blue or  
450 green) as well as the position of the green and blue movement targets relative to the starting circle  
451 are randomized from trial to trial. The maximum decision duration allowed (the time between the  
452 decision circle onset and movement onset) is 1s. The maximum movement duration allowed (the  
453 time between movement onset and offset) is 750ms.

454 At the end of the trial, a visual cue informs the subject about the outcome of the trial. The chosen  
455 target was surrounded by a green circle if she/he accurately reaches the correct target, and by a red  
456 one if she/he accurately reaches the wrong target. The subject earns the number of points  
457 corresponding to the chosen difficulty of the movement to execute if the correct target was  
458 accurately reached. The goal of the subject is to earn a total of 200 points. If the subject fails to  
459 reach or stop in the chosen target (inaccurate movement, whether it is the correct target or not),  
460 the number of points chosen at the beginning of the trial is subtracted. Regardless of the movement  
461 constraint level chosen by the subject, if she/he selects the wrong target (decision error) with an  
462 accurate movement, points are not deducted. To move on to the next trial, the subject moves the  
463 handle back in the starting circle and maintains the position for 500ms.

464 In this experiment, the number of points accumulated by the subject determines the coherence of  
465 the decision stimulus. The coherence of the decision stimulus is initially set to 77% at the  
466 beginning of the session and it linearly decreases with the accumulation of points, reaching 51%  
467 at 200 points. As a consequence, the difficulty of decision progressively increases as the subject  
468 gets close to 200 points. We expected to observe with this design a mixture of choices of the  
469 difficulty of the movements to be performed to express the perceptual decisions, regardless of the

470 coherence of the decision stimulus, with a bias for the most difficult movements chosen more  
471 frequently at the beginning of the session (when perceptual decisions are easier) than at the end.

#### 472 [Instructions provided to the subjects](#)

473 To familiarize each participant with the task and with the manipulation of the handle on the tablet,  
474 a training phase was proposed prior to the experimental phase per se. During this training phase,  
475 subjects performed about 20 training trials where they could choose the difficulty of the movement  
476 to make (easy or difficult) and report moderately difficult (63% coherence) perceptual decisions  
477 by executing reaching movements to those targets. The training phase was prolonged if subjects  
478 required so. During the experimentation phase, each subject was instructed to perform the task  
479 described above and they were informed that they needed to earn a total of 200 points to complete  
480 the session. Importantly, the 32 subjects who performed the task were not told about the decreasing  
481 coherence of the decision stimulus indexed to the accumulation of points. They were also not told  
482 about their number of points accumulated after each trial. We informed the subjects that there  
483 would be no scheduled breaks during the session, except in case of discomfort or real fatigue. No  
484 subject requested a break during their session.

#### 485 [Data analysis and statistics](#)

486 Data were collected by means of LabVIEW 2018 (National Instruments, Austin, TX), stored in a  
487 database (Microsoft SQL Server 2005, Redmond, WA), and analyzed off-line with custom-written  
488 MATLAB scripts (MathWorks, Natick, MA).

489 Arm movement characteristics were assessed using the subjects' movement kinematics.  
490 Horizontal and vertical arm position data (collected from the handle on the digitizing tablet) were  
491 first filtered using a tenth-degree polynomial filter and then differentiated to obtain a velocity  
492 profile. Onset and offset of movements were determined using a 3.75 cm/s velocity threshold. Peak  
493 velocity and amplitude was determined as the maximum value and the Euclidian distance between  
494 movement onset and offset, respectively.

495 An accurate movement is defined as a movement that reached a target (whether it is the correct  
496 target or not) and stayed in it for 500ms. In this report we only refer to movements executed to  
497 report the perceptual decisions (not those executed to select the difficulty of the movement to  
498 perform to report the perceptual decisions). Decision duration is defined as the time between the  
499 onset of the stimulus providing the visual evidence to the subject (the decision circle containing

500 the 100 tokens) to the onset of the movement executed to report the decision. A decision is defined  
501 as correct if the correct target is chosen, regardless of the accuracy of the movement.

502 Chi-squared tests for independence were used to assess the effect of movement difficulty  
503 (constrained or less constrained) on individual subjects' movement and decision accuracy.  
504 Wilcoxon rank sum tests were used to assess the effect of movement constraint level on individual  
505 subjects' decision and movement duration. Chi-squared tests for independence were used to test  
506 the effect of decision difficulty, evaluated by chronologically grouping trials in 10 quantiles, on  
507 individual subjects' proportion of constrained movement choices. At the population level, Kruskal-  
508 Wallis tests were used to test the effect of decision difficulty on the proportion of constrained  
509 movement choices. Analyses of covariance (ANCOVAs) were used to assess the effect of decision  
510 difficulty, motor constraint level and their interaction on decision accuracy and duration. The  
511 significance level of all statistical tests was set at 0.05, and highest levels of significance are  
512 reported when appropriate.

## 513 AUTHORS' CONTRIBUTION

514 EL, EK and DT designed the experiment

515 EK coded the task

516 EL collected the data

517 EL and DT conducted the analyses and prepared the figures

518 DT wrote the draft of the manuscript

519 EL, EK and DT revised the draft and approved the final version of the manuscript

## 520 CONFLICT OF INTEREST STATEMENT

521 The authors declare no competing financial interests.

## 522 DATA AVAILABILITY STATEMENT

523 The datasets used and/or analyzed during the current study are available from the corresponding  
524 author on reasonable request.

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