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# Evidence for a cost of time in the invigoration of isometric reaching movements

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## Abstract

How the brain determines the vigor of goal-directed movements is a fundamental question in neuroscience. Recent evidence has suggested that vigor results from a trade-off between a cost related to movement production (cost of movement) and a cost related to our brain's tendency to temporally discount the value of future reward (cost of time). However, whether it is critical to hypothesize a cost of time to explain the vigor of basic reaching movements with intangible reward is unclear because the cost of movement may be theoretically sufficient for this purpose. Here we directly address this issue by designing an isometric reaching task whose completion can be accurate and effortless in prefixed durations. The cost of time hypothesis predicts that participants should be prone to spend energy to save time even if the task can be accomplished at virtually no motor cost. Accordingly, we found that all participants generated substantial amounts of force to invigorate task accomplishment, especially when the prefixed duration was long enough. Remarkably, the time saved by each participant was linked to their original vigor in the task and predicted by an optimal control model balancing out movement and time costs. Taken together, these results support the existence of an idiosyncratic, cognitive cost of time that underlies the invigoration of basic isometric reaching movements.

## New and Noteworthy

Movement vigor is generally thought to result from a trade-off between time and motor costs. However, it remains unclear whether the time cost only modulates vigor around some nominal value explained by a minimal motor cost or whether it determines movement invigoration more broadly. Here, we present an original paradigm allowing to neutralize the cost of movement, and provide new evidence that a cost of time must underlie the invigoration of isometric reaching movements.

## Introduction

Understanding the principles underlying movement invigoration is an important topic in neuroscience given its potential implications for disorders such as Parkinson's disease (Mazzoni et al., 2007). Parkinsonian patients typically suffer from bradykinesia (Berardelli et al., 2001), an overall movement slowness which is related to a dysfunction of the basal ganglia (Turner and Desmurget, 2010; Dudman and Krakauer, 2016; Robbe and Dudman, 2020). Vigor generally characterizes the preferred speed of movement, which has been experimentally quantified through the idiosyncratic-increase of velocity and duration as a function of distance in simple point-to-point movements. Large differences in vigor were reported across individuals but, remarkably, these differences were

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34 consistent between/within sessions or between movement modalities (e.g. head vs hand move-  
35 ments, dominant vs non-dominant reaching or vs walking Reppert et al., 2018; Berret et al., 2018;  
36 Labaune et al., 2020). While biomechanical factors may of course play a role, inter-individual dif-  
37 ferences of vigor were primarily attributed to psycho-economical processes that reflect a trait-like  
38 feature of individuality (Shadmehr et al., 2016; Berret et al., 2018; Shadmehr et al., 2019; Carland  
39 et al., 2019; Shadmehr and Ahmed, 2020a). The main results point to a cost of time related to the  
40 brain’s tendency to discount the value of delayed rewards (Shadmehr et al., 2010; Haith et al., 2012;  
41 Rigoux and Guigon, 2012; Choi et al., 2014; Berret and Jean, 2016). Assuming that the goal of any  
42 movement is to put the system in a more rewarding state (Shadmehr, 2010), moving slowly would  
43 decrease the subjective value of reward and would thus be avoided in the control of goal-directed  
44 actions. This principle has been formalized in optimal control theory by using a cost of time that  
45 explicitly penalizes the passage of time (Hoff, 1994; Berret and Jean, 2016), thereby compensating  
46 for the inability of classical trajectory-formation models to account for the duration of self-paced  
47 movement (e.g. Flash and Hogan, 1985; Uno et al., 1989; Berret et al., 2011). Together with other  
48 model-based studies linking vigor to a global background signal representing the opportunity cost  
49 of time (average rate of reward or capture rate, Niv et al., 2007; Yoon et al., 2018), this suggests  
50 that a time cost could be the cornerstone of movement invigoration (Fig. 1A).

51 However, a cost of movement alone may be theoretically sufficient to explain our preferred speed  
52 (Fig. 1B). Objective measures of the cost of movement have shown that metabolic energy expen-  
53 diture increases at both low and fast speeds, which is a well-known result for walking that seems  
54 to be valid for arm reaching as well (Ralston, 1958; Huang and Ahmed, 2012; Shadmehr et al.,  
55 2016). Furthermore, people may be reluctant to move slowly for physiological reasons related to  
56 the properties of the underlying control system (Park et al., 2017; Guigon et al., 2019). Endpoint  
57 variance tends to increase at both fast and slow speeds due to the effects of signal-dependent and  
58 constant motor noise unless efficient feedback corrections are triggered by the central nervous sys-  
59 tem (Wang et al., 2016). Effort and variance are two fundamental features of sensorimotor control  
60 that are thought to compose the cost of movement (Todorov and Jordan, 2002; Liu and Todorov,  
61 2007; Gaveau et al., 2014, 2021; Berret and Jean, 2020). Interestingly, using a cost of movement  
62 was sufficient to explain the speed/accuracy trade-off –Fitts’ law– (Harris and Wolpert, 1998; Qian  
63 et al., 2013) and the increase of velocity and duration as a function of distance in point-to-point  
64 movements from mechanistic reasons only (van Beers, 2008; Berret et al., 2021). In this case,  
65 existing inter-individual differences of vigor would result from discrepancies in the subjective cost  
66 of movement represented by people and biomechanical factors, and the cost of time would explain  
67 changes of vigor around a certain nominal value in response to modulation of reward or urgency  
68 (Takikawa et al., 2002; Reppert et al., 2015; Manohar et al., 2015; Thura, 2020). Yet, it has been  
69 recently suggested that the cost of movement could be itself discounted over time (Shadmehr et al.,  
70 2016; Summerside et al., 2018) such that movement vigor would essentially reveals “how much we  
71 value the things we are moving toward” (Shadmehr and Ahmed, 2020a,b). Because of this uncer-  
72 tainty about the cost of movement actually represented by subjects, the role played by the cost  
73 of time in daily actions with intangible rewards remains putative. Hence, does the cost of time  
74 mainly serve to modulate vigor around some nominal value defined by a minimum movement cost,  
75 or does it broadly set movement invigoration?

76

77 The goal of the present study was to clarify this issue by neutralizing the cost of movement  
78 experimentally. To this aim, we designed an isometric pointing task whose completion could  
79 be accurate and effortless in prefixed durations. This is like an airport treadmill that carries  
80 travelers to their destination in more or less time depending on whether they stand still or walk  
81 on it. Here participants had to control a cursor on a screen via a force applied onto an isometric  
82 joystick. A baseline condition was first tested to characterize the behavior of participants in such  
83 an isometric reaching task where the reward –if any– is intangible, and estimate their original  
84 vigor. In a second condition, the cursor was moved by an external drive such that the task could  
85 be accomplished successfully in a certain duration without any participant intervention. If time  
86 matters in the control of this isometric reaching task, we predicted that the participants should  
87 exert a substantial amount of force onto the joystick to save time, especially when the drive duration

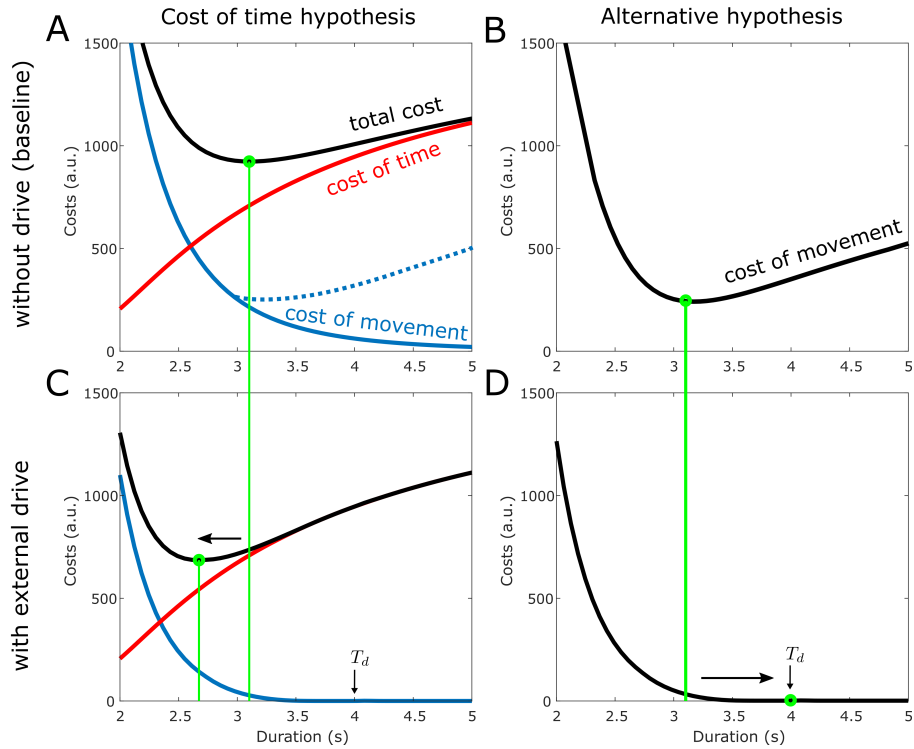


Figure 1: Vigor prediction for the different hypotheses. A. Prediction of vigor within the cost of time hypothesis. The preferred duration of a given point-to-point movement (here 3.1 s) is obtained as a trade-off between a cost of movement (blue trace) and a cost of time (red trace). Note that the cost of movement could possibly increase for longer durations (dotted blue trace). B. Prediction of vigor using the cost of movement alone (alternative hypothesis). The preferred duration is the same and the two hypotheses are indistinguishable in this baseline condition. C. Prediction of movement vigor within the cost of time hypothesis in presence of an external drive. The assisting drive (here executing the task in duration  $T_d=4$  s) reshapes the cost of movement such that the task can be accomplished with a smaller movement cost for durations shorter than the drive duration, and at no movement cost for longer durations. Due to the drive and the cost of time, the preferred duration will be shorter than the initial duration (here 2.7 s). D. Prediction of vigor using a cost of movement alone in presence of an external drive. Again, the drive reshapes the cost of movement so that the preferred duration will be that of the drive because increasing speed would result in energy expenditure anyway. In this scenario, the preferred duration will be longer than the initial duration (here 4 s). This illustrates that the two hypotheses make distinct predictions depending on whether the cost of time plays a predominant role in the invigoration of reaching actions without tangible reward.

88 is long enough according to the cost of time hypothesis (Fig. 1C). Furthermore the time savings of  
89 each participant should be related to their original vigor in the task if it reflects how they implicitly  
90 value task accomplishment. In contrast, if time does not matter and vigor is essentially determined  
91 by a cost of movement in this task, participants should favor restful strategies even for a relatively  
92 long drive duration (Fig. 1D). Indeed, this would be the optimal behavior with respect to the  
93 minimization of any cost of movement, whether related to energy, inaccuracy or other factors.

## 94 **Materials and Methods**

### 95 **Participants**

96 The experiment included 15 participants (7 females, mean age  $\pm$  SD:  $27 \pm 7$ ). All participants were  
97 contacted through a mailing list of persons who volunteer to do experiments at the Italian Institute  
98 of Technology and were paid 10 euros for the participation. All participant were naive with respect  
99 to the goal of the experiment and signed a written informed consent. The experimental protocol  
100 was approved by the local ethical committee (C.E.R. Liguria, P.R.063REG2016).

### 101 **Experimental methods**

102 **Experimental apparatus** The experimental setup comprised an isometric joystick that mea-  
103 sured the force applied by the participant on it with a 6-dof force/torque sensor (Mini 45, ATI)  
104 and a screen (dimension 19 inch) in front of the participant (distance 65 cm). The joystick was  
105 connected to a computer via a digital acquisition card (USB-6211, National Instrument). The force  
106 was sampled at 10 kHz and filtered on-line by fitting a linear regression line to the most recent  
107 160 samples. A custom C++ program simulated the cursor dynamics at 1 kHz and updated its  
108 position on the screen at 60 Hz. The force and system state (position, velocity and external drive)  
109 were saved at 60 Hz.

110 **Task** The participant sat in front of the table with the experimental setup and grasped the  
111 joystick with the right hand and the elbow bent at 90 degree angle. The goal of the task was  
112 to move a cursor from its home position to the target displayed on the screen by pushing the  
113 isometric joystick (see Fig. 2). Importantly, participants were always instructed to move the cursor  
114 at their preferred velocity. For simplicity the cursor was restricted to move only along the  $y$ -axis  
115 (bottom-up axis on the screen).

116  
117 The experiment was divided into two sessions that were executed one after the other on the same  
118 day. The first experimental session (Session 1) served as a baseline condition from which the  
119 vigor and the cost of time of each participant were inferred. This session included four movement  
120 distances and no assistance was provided (amplitude 0.1, 0.2, 0.3 and 0.4 of screen size [height:  
121 25.5 cm]). The goal of this session was to find out the movement time corresponding to each  
122 amplitude, compute nominal vigor scores for each participant and identify the cost of time that  
123 would predict these movement times, given a cost of movement based on effort (Berret and Jean,  
124 2016). There were 20 repetitions for each amplitude, thus yielding 80 trials in this session. The  
125 order of presentation of movement amplitudes was randomized. The second session (Session 2)  
126 included two movement distances (0.2 and 0.4). Importantly in this session, an external drive that  
127 generated biological movements reaching the target in different durations ( $T_d = 1, 2, 4$  or 6 s) was  
128 added to the cursor dynamics (see next paragraph).

129 An illustration of a trial from the participant's perspective is given in Figure 2. Each trial started  
130 with the display of the target and the initial cursor's position. The participants freely initiated  
131 the force and trajectory recording, and in the second session the external drive, by pushing the  
132 space bar. They were told to avoid pushing the joystick before this event. The self-starting of the  
133 recording was necessary in the second session to start the external drive and allow strategies that  
134 did not require the participant to push the joystick at all. The motion and recording terminated  
135 when the target was reached according to position and velocity thresholds defined below. The

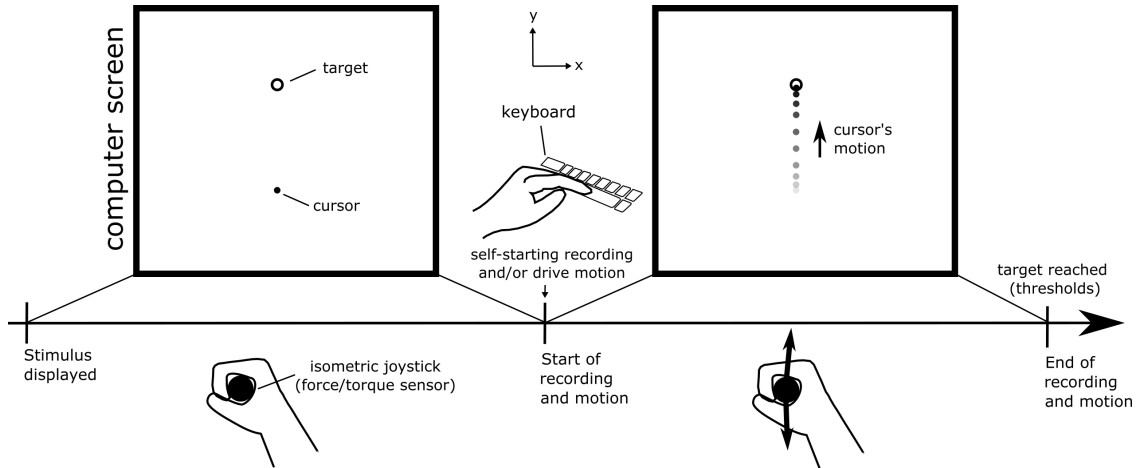


Figure 2: Trial structure from the participant’s perspective. Each trial started with the display of the target on the screen and an invariant initial cursor’s position. By pressing the space bar, the participant self-started the recording of the data and made it possible to accelerate the cursor by applying forces on the isometric joystick. In Session 2, this event also started the drive and so the cursor’s displacement. The motion and recording terminated when the target was reached. The next trial with a new target occurred after a few seconds.

136 participant could start the next trial after completing the previous movement only if 3.5 seconds  
 137 had elapsed from the beginning of the previous trial in order to limit the pace of the experiment  
 138 when there was a strong external drive which led to very short trials. In Session 2, participants  
 139 were aware of the presence and characteristics of the drive because each block started with two  
 140 trials (one per amplitude) with a message on the screen instructing them to watch the cursor being  
 141 moved to the target by the external drive in duration  $T_d$ . In this session, the participants were still  
 142 instructed to move the cursor at their preferred velocity and to avoid pushing the joystick before  
 143 pressing the space bar. There were 20 repetitions for each condition of amplitude and drive, thus  
 144 yielding a total of 160 trials in this session. The task was executed from the slowest to the fastest  
 145 drive with the amplitude randomized within each block. In Session 2, we used a block-wise design  
 146 to ensure that the participant was fully aware of the characteristics of the drive. The participants  
 147 were informed about this block-wise design without being told that the assistance will shift from  
 148 slow to fast.

149 **Cursor Dynamics** The cursor dynamics along the  $y$ -axis was as follows:

$$m\ddot{y} = f_s - v\dot{y} \quad (1)$$

150 where  $m = 25$  kg and  $v = 10$  kg/s are the simulated mass and damping of the virtual system.  
 151 These values were chosen during preliminary experiments to induce comfortable behaviors and  
 152 force levels.

153 The force  $f_s$  (measured by the force sensor on the  $y$ -axis) was the external force applied by the  
 154 participant on the cursor. Hence, the force applied by the participant directly affected the cursor  
 155 acceleration. The goal of the task in Session 1 was to move the cursor to a target (1.275 cm width,  
 156 that is, 0.05 of screen’s height),  $y_f$ , from a given home position,  $y_0$ , at the participant’s preferred  
 157 speed.

158 **Choice of external drive** When an external drive was added, the cursor’s dynamics was mod-  
 159 ified as:

$$m\ddot{y} = f_d + f_s - v\dot{y} \quad (2)$$

160 where  $f_d$  is the external action implemented by an external controller.

161 We noted in preliminary data that participants normally executed this isometric reaching task  
 162 using bell-shaped velocity profiles. Therefore, we implemented an external drive as an optimal  
 163 feedback control law that allowed to reach the target in a desired duration,  $T_d$ , with bell-shaped  
 164 velocity profiles.

165 To this aim, we considered a minimum force change model as it predicts smooth, bell-shaped  
 166 velocity profiles (Uno et al., 1989). We noted this optimal control  $u_d$  which was the solution of the  
 167 optimal control problem described hereafter. We denote by  $\mathbf{x} = (y, \dot{y}, f_d)$  the column state vector  
 168 and consider the dynamics:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + B_d u_d \quad (3)$$

169 where

$$A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & -v/m & 1/m \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad B_d = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

170 The optimal drive was chosen to move the system from an initial state  $\mathbf{x}_0 = (y_f - y_0, 0, 0)$  to a  
 171 final state  $\mathbf{x}_f = (0, 0, 0)$  in desired time  $T_d$  while minimizing the cost:

$$C(u_d) = \mathbf{x}(T_d)^\top Q_f \mathbf{x}(T_d) + \int_0^{T_d} u_d^2(t) dt \quad (4)$$

172 where  $Q_f$  is the terminal cost matrix chosen as  $Q_f = \text{diag}(6.297 \times 10^6, 6.301 \times 10^6, 10)$ . These  
 173 parameters were also determined from preliminary simulations and tests to design an optimal drive  
 174 that achieves the task reliably for all durations.

175 Solving this optimal control problem (linear-quadratic in finite horizon) yielded an optimal feedback  
 176 control of the form (e.g. Stengel, 1986):

$$u_d(t, \mathbf{x}) = K(t)\mathbf{x} \quad (5)$$

177 where  $K(t)$  is the optimal feedback gain defined from  $t = 0$  to  $t = T_d$ . For  $t \geq T_d$ , we defined  
 178  $K(t) = K(T_d)$ . Note however that this situation was assumed not to occur in practice as we did  
 179 not expect participants to move slower than the duration given by the external drive (it would  
 180 be non-optimal with respect to both the cost of movement and the cost of time). We computed  
 181 optimal control for drives with duration of  $T_d$  equal to 1 s, 2 s, 4 s and 6 s and for distances equal  
 182 to  $y_f - y_0 = 0.2$  m and 0.4 m. Note that for simplicity we mapped the distances relative to screen  
 183 size (see above) to S.I. units in the model for simulations (i.e. using the same numbers).

184 **Coupled cursor dynamics** Once the external drive is defined, we can consider the coupled  
 185 dynamics used in the experiment of Session 2. Here the state-space dynamics was as follows:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + B_d u_d + B_s f_s \quad (6)$$

186 where  $B_s = (0, 1/m, 0)^\top$ . The force input of the human participant thus affected directly the  
 187 cursor acceleration.

## 188 Data processing and parameters

189 **Kinematics** The force was the only user input and was filtered on-line (see Experimental Ap-  
 190 paratus). Position and velocity being integrated by the dynamic system (Eq. 6) were not filtered  
 191 further. For each trial, we identified the beginning of the movement (velocity threshold 0.005 m/s).  
 192 The trial and recording finished when the cursor position was inside the target (distance to its cen-  
 193 ter less than 0.025 m) with a velocity below 0.02 m/s. For each trial, we computed the movement  
 194 duration and the movement amplitude. We also identified if a sub-movement was present (negative  
 195 velocity) and counted the number of peaks in the force profile (each force peak corresponds to a  
 196 period when the absolute of the force is above 1 N for at least 0.1 s). We excluded from the analyses  
 197 about 13% of the trials because there was movement reversal, more than five peaks in the force  
 198 profile or the movement time differed from the condition average by more than three standard  
 199 deviation. To compute average trajectories, single trial trajectories were resampled to have the  
 200 same number of samples and average duration.

201 **Amount of force** In order to estimate the effort produced by the participant using an objective  
 202 measure, we considered the *amount of force* applied during the trial, defined as (Shadmehr et al.,  
 203 2016):

$$\int_0^{T_s} |f_s(t)| dt.$$

204 **Vigor scores** In this paper we computed vigor scores using the maximum likelihood approach  
 205 described by Reppert et al. (2018) but we used the duration of movements instead of peak velocities.

206 To this end, we first computed the grand mean duration of movements of each amplitude  $A_i \in$   
 207  $\{0.1, 0.2, 0.3, 0.4\}$  (data of all participants pooled together). These movement durations were then  
 208 used to fit the affine function

$$T_i = g(A_i) = \alpha + \beta A_i, \quad \alpha, \beta \in \mathbb{R}$$

209 Then, we expressed the movement duration for each amplitude of each participant  $j = 1, \dots, 15$  as:

$$T_{i,j} = \frac{1}{\text{vg}_j} g(A_i) + \varepsilon_j$$

210 where  $\varepsilon_j \sim \mathcal{N}(0, \sigma_j^2)$  (Gaussian variable with zero mean and variance  $\sigma_j^2$ ). The quantity  $\text{vg}_j$   
 211 will denote the vigor score of participant  $j$ . A score of vigor greater than 1 will thus indicate  
 212 a participant that is more vigorous than the average of the participants and therefore exhibits  
 213 shorter movement durations in general.

214 Considering the log-likelihood of all the data points given the model parameters  $\{\text{vg}_j, \sigma_j^2\}_{j=1, \dots, 15}$   
 215 and maximizing it with respect to  $\text{vg}_j$ , yields the following formula for each participant  $j \in$   
 216  $\{1, \dots, 15\}$ :

$$\text{vg}_j = \frac{\sum_{i=1}^4 g(A_i)^2}{\sum_{i=1}^4 T_{i,j} g(A_i)}$$

217 where  $A_i$  is the movement amplitude and  $T_{i,j}$  the individual mean movement duration for that  
 218 amplitude.

219 Note that we also tested a canonical function  $g(A_i)$  including a concave term  $g(A_i) = \alpha + \beta A_i +$   
 220  $\gamma \log_2(A_i/W + 1)$  where  $W$  is the target's width (see Berret et al., 2018; Young et al., 2009) but this  
 221 resulted in vigor scores that were highly correlated with the present ones ( $r > 0.99$ ). Furthermore,  
 222 we could have defined vigor scores from peak velocities as Reppert et al. (2018) but, again, the  
 223 vigor scores were strongly correlated with the present ones ( $r > 0.99$ ).

## 224 Statistical analyses

225 We used repeated-measure ANOVAs to analyze movement duration and average force as a function  
 226 of movement amplitude and, in Session 2, drive duration. Both factors were coded with polynomial  
 227 contrasts to conduct a trend analysis. All statistical analyses were conducted in R (R Core Team,  
 228 2019) with *afex* (Singmann et al., 2019) and *emmeans* (Lenth, 2019) packages.

## 229 Optimal control modelling

230 Here we model the behavior of participants in the second session. We extended the system state  
 231  $\mathbf{x} = (y, \dot{y}, f_d)$  to include the human contribution, as  $\tilde{\mathbf{x}} = (\mathbf{x}, f_s)$ , and considered the following  
 232 augmented dynamics:

$$\dot{\tilde{\mathbf{x}}} = \tilde{A}\tilde{\mathbf{x}} + \tilde{B}_d u_d + \tilde{B}_s u_s \quad (7)$$

233 with  $\tilde{B}_d = (0, 0, 1, 0)^\top$  and  $\tilde{B}_s = (0, 0, 0, 1)^\top$  and

$$\tilde{A} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & -v/m & 1/m & 1/m \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \quad (8)$$



234 where  $u_d$  is the optimal drive and  $u_s$  is the human motor command. In this model, the motor  
 235 command  $u_s$  is at the level of force change, which reflects the fact that human force varies smoothly  
 236 due to the low-pass filtering property of muscle contraction. The motor optimal drive  $u_d$  is also  
 237 at the level of force change and affects the cursor dynamics via  $f_d$ . In absence of participant  
 238 intervention (i.e.,  $u_s \equiv 0$ ), the system is equivalent to Eq. 3 and the cursor moves according to the  
 239 previously defined optimal drive.

240 Here, we considered the following cost function:

$$C(u_s) = \int_0^{T_s} (u_s^2(t) + h(t)) dt. \quad (9)$$

241 where  $T_s$  is the movement duration,  $h(t)$  is the cost of time of the participant, and  $u_s^2(t)$  counts  
 242 their effort input in the task. We finally added terminal constraints to capture how a trial was  
 243 terminated in the experiment. We imposed that the final velocity and position were respectively  
 244 below 0.02 m/s and 0.025 m in accordance with the experimental conditions given above.

245 The use of the optimal control model involved two steps: (1) an identification step with the data  
 246 of Session 1; and (2) a prediction step to compare with the data of Session 2.

247 In the identification step, we followed the methodology documented in Berret and Jean (2016)  
 248 and Berret et al. (2018) to identify the term  $h(t)$  for each participant using the data of Session 1  
 249 where movement duration  $T_s$  for each amplitude was obtained from linear regression (see above),  
 250 and external drive was absent ( $u_d \equiv 0$  in the above equations). The cost of time was then fitted  
 251 to a generalized sigmoid function to get an analytical formula for  $h(t)$  (see Berret et al., 2018 for  
 252 more details details about the procedure). In the prediction step, we solved an optimal control  
 253 problem in free time to predict movement duration  $T_s$  and the user’s input  $f_s$ . In this step, the  
 254 external drive  $u_d$  was as defined experimentally and the cost of time  $h(t)$  was as identified during  
 255 the identification step, all the other parameters being unchanged.

256 The procedure was repeated for each distance of Session 2 (0.2 m and 0.4 m), each  $T_d$  (1 s, 2 s, 4 s  
 257 and 6 s) and each participant (since each participant will have a different cost of time given that  
 258 their behaviors in Session 1 will differ).

259 This model predicts that participants who perform optimally will find a trade-off between a certain  
 260 physical effort and a cost related to the passage of time. In other words, if there is a cost of time,  
 261 they should spend some energy to save time even when there is an assisting drive that can achieve  
 262 the task by itself. An illustration of the balance between effort and time was provided in Fig. 1. If  
 263 there is no cost of time, participants should not intervene as it would be the optimal strategy with  
 264 respect to any cost of movement (for instance effort or accuracy here).

## 265 Results

### 266 Experimental results of Session 1 (without drive)

267 **Mean trajectories** Here we describe the average self-paced behavior of the participants in  
 268 absence of an external drive. The grand mean trajectories are reported in Figure 3 for the distances  
 269 0.2 m (Fig. 3A) and 0.4 m (Fig. 3B) respectively. Velocity profiles are approximately bell-shaped  
 270 even though the experimental protocol stopped motion according to some threshold that is visible  
 271 at the end of the velocity profiles. Force profiles resemble acceleration profiles and mainly consist of  
 272 a positive phase (to accelerate the cursor) and a negative phase to decelerate it. Small initial force  
 273 values indicate that the participants respected well the instruction of not pushing on the joystick  
 274 before pressing the space bar (initial force  $0.39 \pm 0.66$  N). The force profiles do not return to zero  
 275 because of the criterion used to detect the end of a trial (see Methods). Substantial inter-individual  
 276 differences can be noted for instance on velocity peaks or on the force used to perform the task.  
 277 Repeated-measures ANOVA confirmed that movement duration ( $F_{3,42}=85.33$ ,  $\eta_G^2=.39$ ,  $p<.001$ )  
 278 and force ( $F_{3,42}=93.93$ ,  $\eta_G^2=.36$ ,  $p<.001$ ) varied across amplitudes. A trend analysis revealed that  
 279 movement time and average force increased linearly with movement amplitude for the range of  
 280 values included in the study.

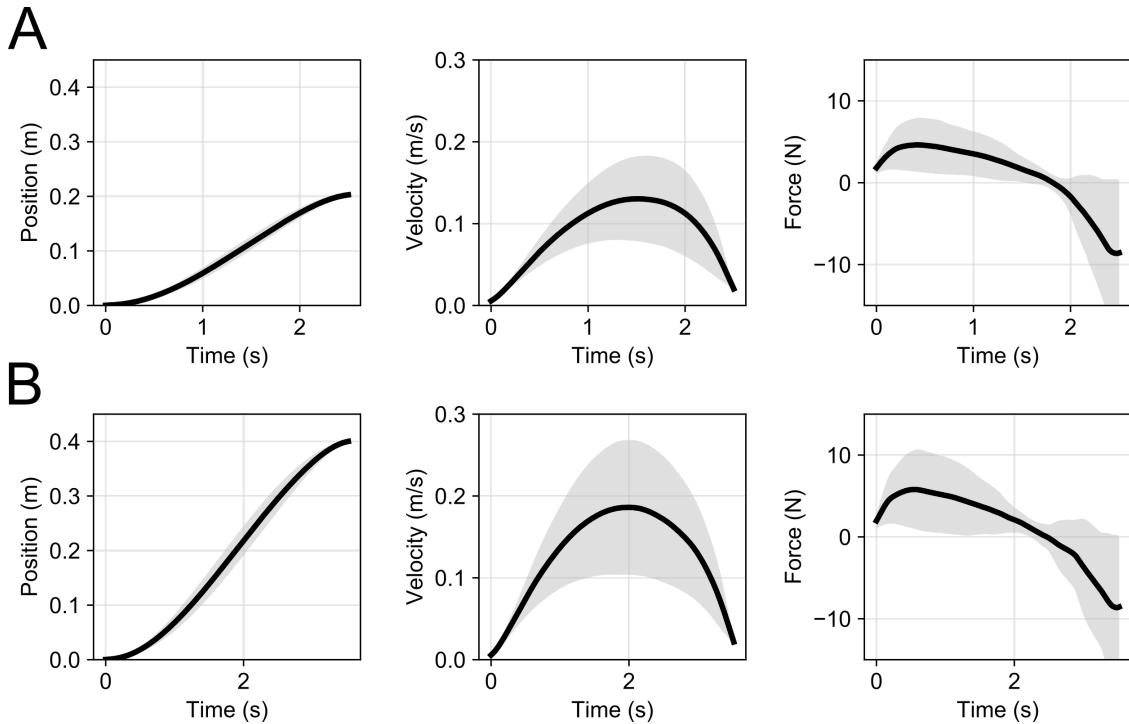


Figure 3: Grand mean trajectories in Session 1. A. Mean displacement, velocity and force for the distance 0.2 m. Thick black lines are means across participants and shaded areas are standard deviations. Trajectories were normalized temporally before computing means and deviations. B. Same information for the distance 0.4 m.

281

282 **Amplitude-duration and amplitude-force relationships** The overall behavior of partici-  
 283 pants in terms of movement duration and amount of force are shown in Figure 4 (black filled  
 284 circles). As in real point-to-point arm reaching experiments, the duration of movement was found  
 285 to increase with amplitude almost linearly, as confirmed by trend analysis (linear:  $t_{42}=15.88$ ,  
 286  $p<.001$ ; quadratic:  $t_{42}=-1.95$ ,  $p=.06$ ). Movements of distance corresponding to 0.2 m and 0.4 m  
 287 were performed in about 2.5 s and 3.5 s respectively. The amount of force also increased with  
 288 amplitude in a similar way (linear:  $t_{42}=16.76$ ,  $p<.001$ ; quadratic:  $t_{42}=-0.92$ ,  $p=0.36$ ). The grand  
 289 mean amount of force was about 7 N for the distance 0.2 m and 11 N for the distance 0.4 m. Again,  
 290 a relatively large inter-individual variability was visible here and we thus focus on some individual  
 291 performance scores in the following.

292

293 **Individual movement vigor scores and costs of time** The relationship between amplitude  
 294 and duration for each individual is reported in Figure 5A. A color code is used to track each indi-  
 295 vidual throughout the study. Linear regressions confirmed that duration increased with movement  
 296 amplitude in an approximately affine way for every participant ( $r^2 = 0.95 \pm 0.06$ , mean  $\pm$  std across  
 297 participants). Using a fitting function including a  $\log_2$  term, we got a slightly improved goodness of  
 298 fit but with one additional parameter ( $r^2 = 0.97 \pm 0.06$ ). From these relationships, it was possible  
 299 to compute vigor scores and sort individuals according to these scores (Fig. 5B) (see Methods).

300

301 Furthermore, the same relationships allowed us to identify the cost of time for each participant  
 302 (see also Methods). The resultant costs of time are depicted in Figure 5C. As expected since  
 303 both measures are derived from the same data, there is a strong correlation between the vigor of

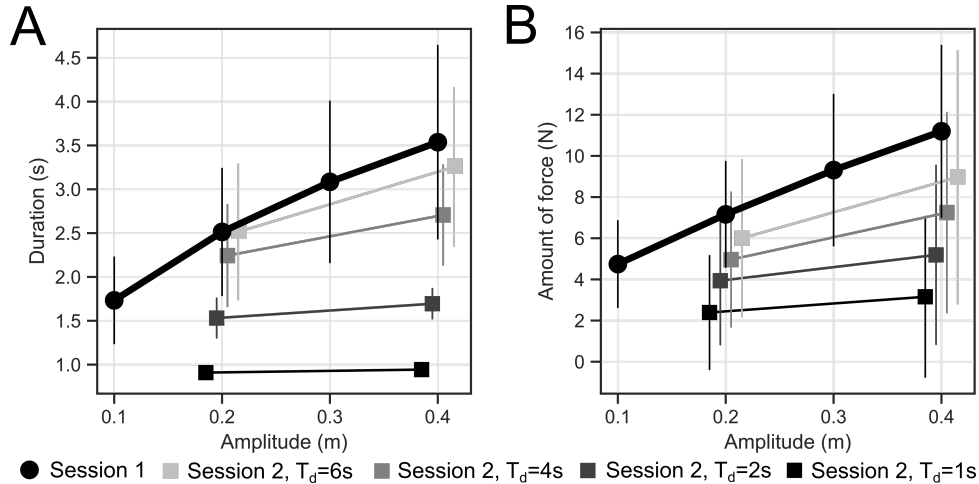


Figure 4: Mean behavior across participants as a function of distance. A. Amplitude-duration relationships in Sessions 1 and 2. Filled circles are data from Session 1 for the 4 tested amplitudes. Grey-colored filled squares are data from Session 2 for the 4 drives and the 2 amplitudes tested. Vertical bars represent standard deviations in all cases. B. Same information for the amplitude-amount of force relationships.

304 participants and the magnitude of their cost of time (Fig. 5D). Typically, the faster participants in  
 305 Session 1 (i.e. with larger vigor scores) penalized time more steeply (i.e. increased more quickly,  
 306 and to a higher asymptotic value, their time costs).

### 307 Experimental and simulation results of Session 2 (with drive)

308 We now consider the experimental data of Session 2 where the external drive allows, in theory,  
 309 the participant to complete the task without any muscular force. Figure 6 depicts the grand mean  
 310 behavior across participants for two different drives (2 s and 6 s) and the two distances tested in  
 311 this Session (0.2 m in panels A-C and 0.4 m in panels D-F). These two distances were illustrated for  
 312 Session 1 in Fig. 3 for comparison. Black/grey traces show the experimental data and red/purple  
 313 traces show the simulated data. The simulations relied on the costs of time identified from the  
 314 data of Session 1 (one cost of time per participant) and the free-time optimal control simulations  
 315 minimizing a trade-off between the cost of movement and the individual-based cost of time (which  
 316 explains why simulated data also vary across participants). Velocity profiles are bell-shaped as in  
 317 the first Session. Force profiles appear more irregular but they still present a positive and negative  
 318 peaks that corresponds to an acceleration and deceleration of the cursor, even though the presence  
 319 of the drive may both accelerate and decelerate the cursor on its own. The figure shows that  
 320 participants used some force to save time, thus achieving the task in less than 3.5 s when the drive  
 321 corresponded to a 6 s movement duration for example. Noticeably, participants still used some  
 322 force on average even when the drive was stronger and would lead to a 2 s long movement on its  
 323 own.

324 Mean movement duration and amounts of force across participants are reported in Figure 4 (filled  
 325 squares). As expected, the performance became closer to that of Session 1 as the drive duration  
 326 increased. Average movement duration increased with drive duration ( $F_{3,42} = 69.25$ ,  $\eta_G^2 = .68$ ,  
 327  $p < .001$ ) and amplitude ( $F_{1,14} = 393.36$ ,  $\eta_G^2 = .10$ ,  $p < .001$ ). The statistically significant interaction  
 328 ( $F_{3,42} = 63.47$ ,  $\eta_G^2 = .065$ ,  $p < .001$ ) reflected a steeper increase of the movement duration with drive  
 329 duration for large movement than for small movements (contrast between linear trends:  $t_{42} = 16.62$ ,  
 330  $p < .001$ ). A similar analysis of average force revealed the same trends. Average amount of force  
 331 also increased with drive duration ( $F_{3,42} = 17.27$ ,  $\eta_G^2 = 0.15$ ,  $p < .001$ ) and amplitude ( $F_{1,14} = 19.56$ ,  
 332  $p < 0.001$ ). The statistically significant interaction ( $F_{3,42} = 21.33$ ,  $\eta_G^2 = 0.01$ ,  $p < .001$ ) reflected a  
 333 steeper increase of the average force with drive duration for large movement than for small move-  
 334 ments (contrast between linear trends:  $t_{42} = 6.02$ ,  $p < .001$ ).

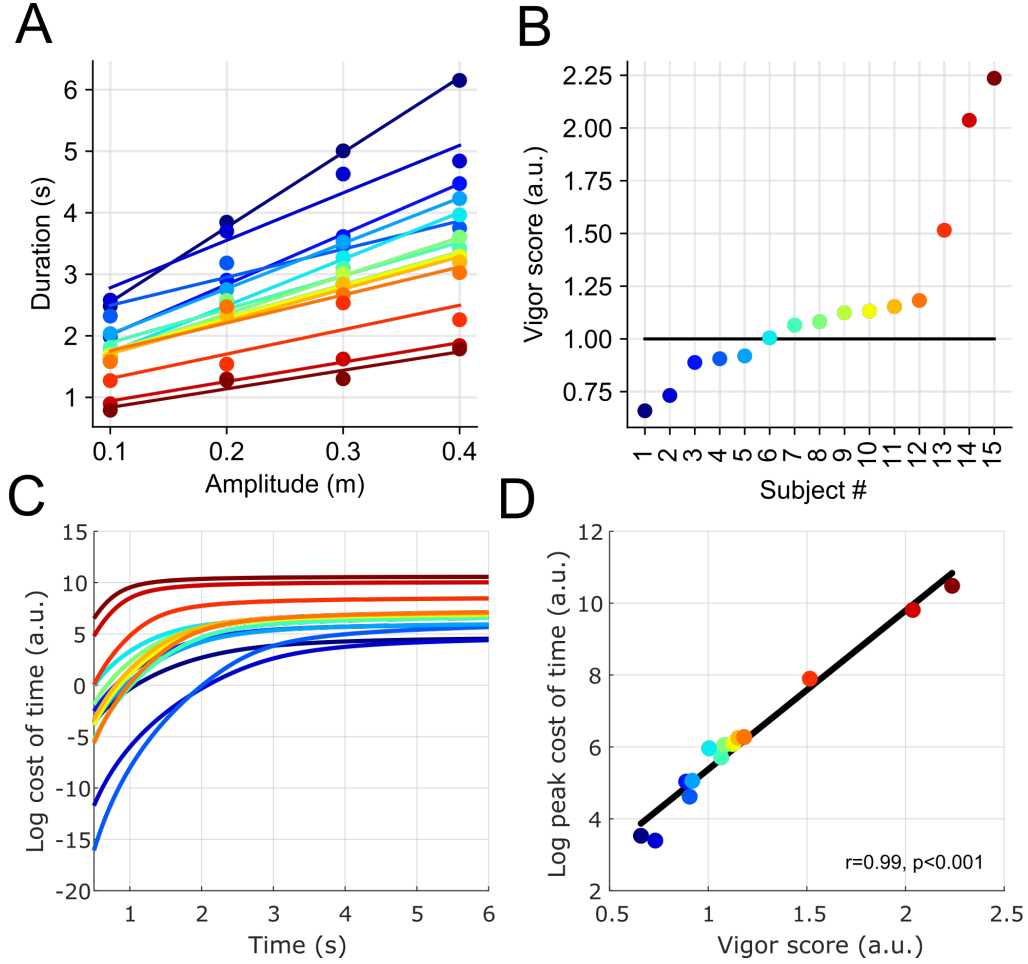


Figure 5: Individual vigor scores. A. Amplitude-duration relationships in Session 1. Each color is the data of one participant. Linear regression lines are displayed. The cost of time was inferred from these individual-level relationships. B. Corresponding vigor scores allowing to sort individuals from the slowest to the fastest in the isometric reaching task of Session 1. The horizontal black line corresponds to a reference vigor score of 1. C. Logarithm of the costs of time identified for each participant, i.e.  $\log(\int_0^T h(t)dt)$ . The x-axis in this plot refers to the movement duration  $T$ . D. Correlation between the vigor scores and the logarithm of the peak derivative of the costs of time (i.e. maximal value of  $h(t)$ ).

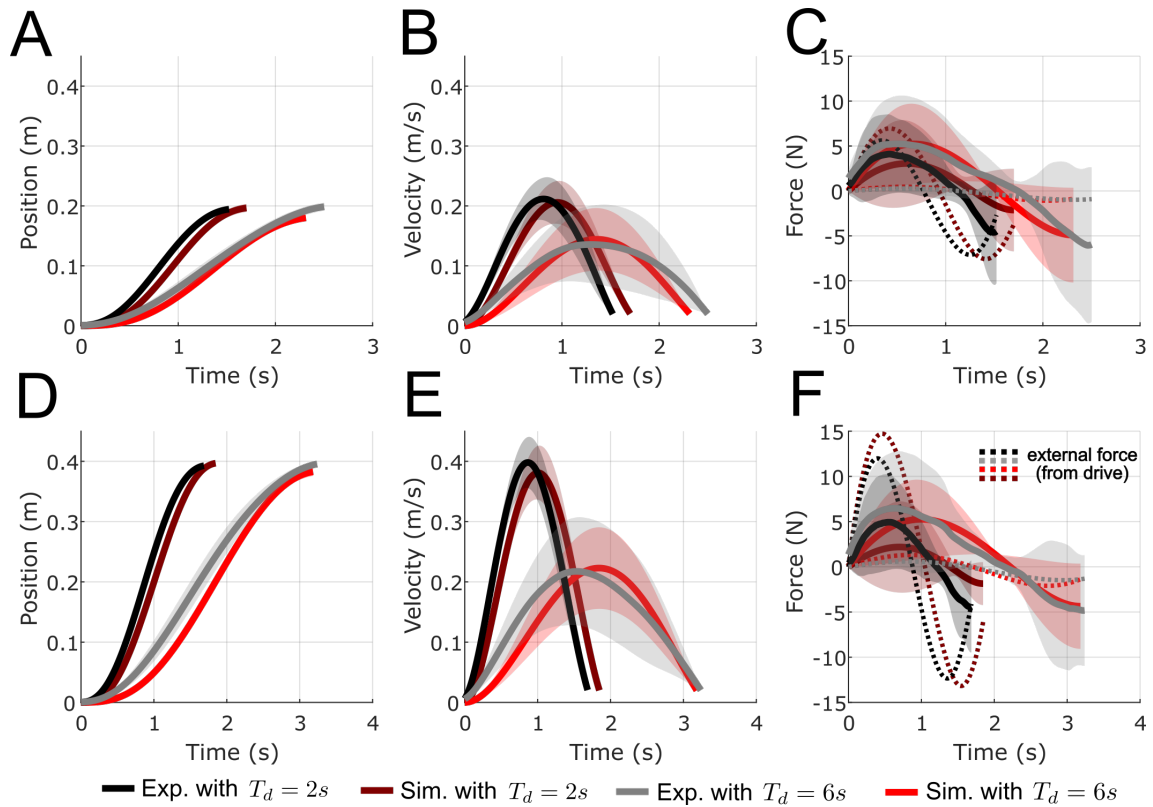


Figure 6: Experimental and simulated trajectories in presence of the drive. A. Cursor displacements in the experiments (black/grey) and simulations (purple/red), for two different drive durations (2s and 6s), for the distance 0.2m. Mean trajectories across participants are reported with standard deviations as shaded areas. B. Same information for the velocity. C. Same information for the force. In solid line, the input force  $f_s$  is depicted. In dotted line, the external force coming from the drive is also reported. D-F. Same information but for the distance 0.4 m.

336 In Figure 7, we depict mean movement durations chosen by participants in Session 2 and compare  
337 them to drive durations (black identity line –indicating the optimal duration if only a cost of  
338 movement is minimized–) and model predictions (red trace and shaded area). The overall behavior  
339 was as follows: movement duration increased with the duration of the drive and tended to plateau  
340 near the movement duration obtained in Session 1 for slow drives. Indeed, the movement duration  
341 of participants for a drive of 6 s was closed to the duration obtained in Session 1 (dotted line in  
342 Fig. 7). Noticeably, the model replicated quite well this average behavior. An optimal trade-off  
343 between movement and time costs thus leads to this evolution of movement duration with respect  
344 to drive duration for each distance.

345

346 Next, we analyzed the force that participants were prone to exert to save a given amount of time.  
347 We thus focused on the relationship between the gain of time and the amount of force used by  
348 the participants to complete the task, the gain of time being defined as the drive duration minus  
349 the actual duration. We found that all the participants tended to increase the amount of force to  
350 save more time across conditions (Fig. 8). The model replicated this trend quite well on average,  
351 especially for the longer drive durations. Important inter-individual differences could also be noted.  
352 For instance, to save one second, participants could use quite different amounts of force. In Fig. 8C  
353 for instance, participant #1 (least vigorous) used less than 5 N to save 1 second while participant  
354 #15 (most vigorous) used more than 10 N to save the same amount of time. It is worth noting that  
355 they saved the same amount of time for different drive durations ( $T_d=4$  s for participant #1 and  
356  $T_d=2$  s for participant #15). Our model captured these main inter-individual differences thanks  
357 to the subjective costs of time identified from the data of Session 1.

358

359 Finally, we investigated if there was any relationship between the vigor of participants in Session 1  
360 and their behavior in Session 2 (Fig. 9). Remarkably, we found that the more vigorous participants  
361 in Session 1 were indeed the ones saving more time in Session 2 (high correlations with  $r>0.90$  for  
362 both tested distances,  $N=15$  participants). These participants were also the ones using a greater  
363 amount of force (correlation coefficients between vigor and average amount of force  $r>0.90$  –not  
364 depicted–). In summary, vigorous participants spent more energy to save more time.

365

## 366 Discussion

367 Recent studies have suggested that the vigor of movement results from a trade-off between a cost  
368 related to movement production and a cost related to the passage of time. However, whether a cost  
369 of time underlies the vigor of simple reaching movements remains unclear as a cost of movement  
370 could be theoretically sufficient to explain our preferred speed on average. This cost of time could  
371 mainly serve to modulate our speed around a reference value according to the urgency or reward  
372 of the task. To disambiguate this question, we designed an isometric pointing task that makes  
373 distinct predictions depending on whether a cost of movement or a cost of time is prevalent. In  
374 some conditions, an external drive moved the cursor to the target with a certain duration such  
375 that the task could be accomplished accurately and effortlessly with no participant intervention.  
376 Despite this self-completion of the task, the participants exerted all the more force the slower the  
377 movement of the cursor was and the higher their original vigor in the task was, in agreement  
378 with optimal control simulations assuming a trade-off between time and effort. These findings are  
379 compatible with the existence of an idiosyncratic, cognitive cost of time underlying the invigoration  
380 of basic isometric reaching movements.

381 Producing a movement inevitably entails a motor cost that can be translated into tangible variables  
382 such as metabolic energy, effort, smoothness, error or variance. The identification of the cost that  
383 best reproduces human trajectories has attracted a lot of attention in optimal control theory  
384 (see Engelbrecht, 2001; Todorov, 2004; Berret et al., 2019 for reviews) but it has proven difficult to

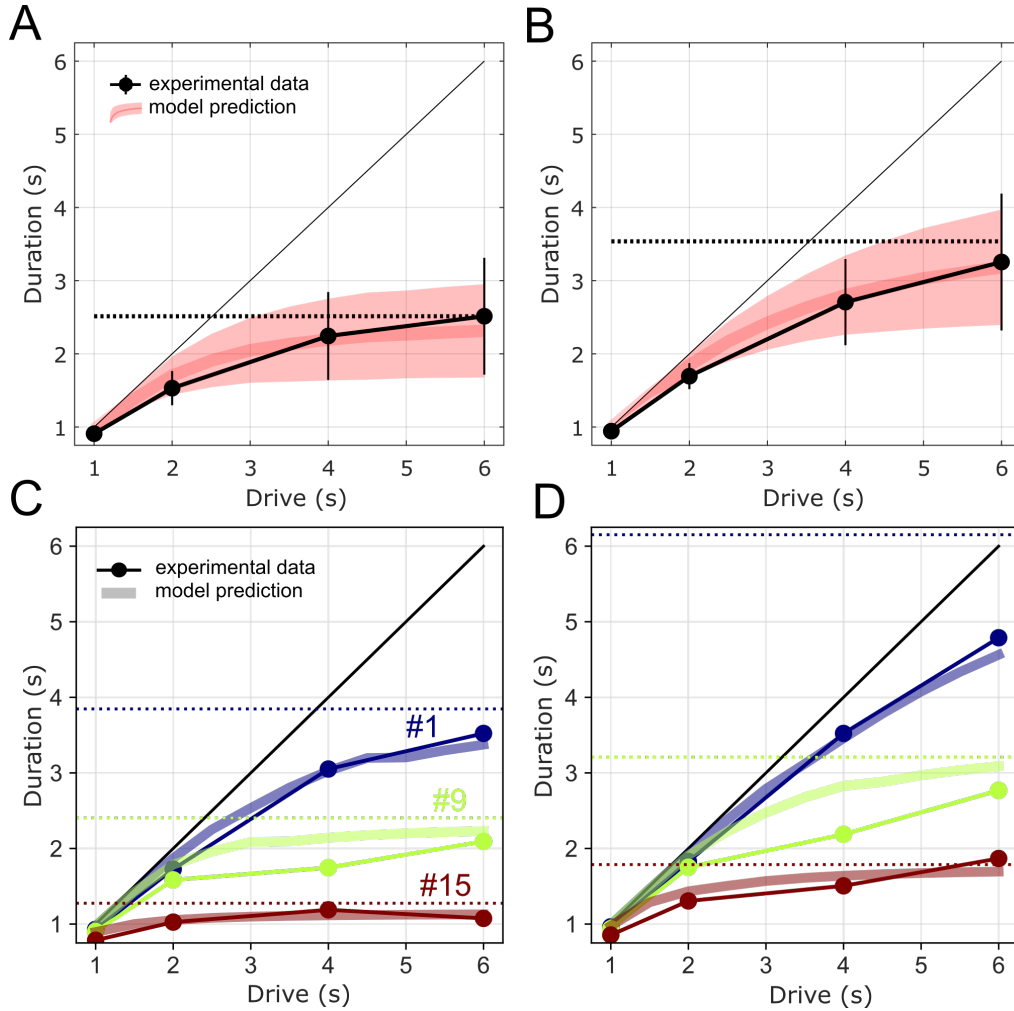


Figure 7: Movement duration with respect to drive duration in Session 2. A. Mean experimental and simulated data for distance 0.2m. Black markers and traces are experimental data. Mean and standard deviations across participants are reported. Red traces and shaded areas are model predictions (also mean and standard deviations across participants). The horizontal dotted line correspond to the mean duration measured in Session 1 for that distance. The identity line corresponds to the drive duration, which would be the optimal duration if only a cost of movement is minimized. B. Same information for distance 0.4 m. C-D. Same information for three participants with high, medium and low vigor respectively.

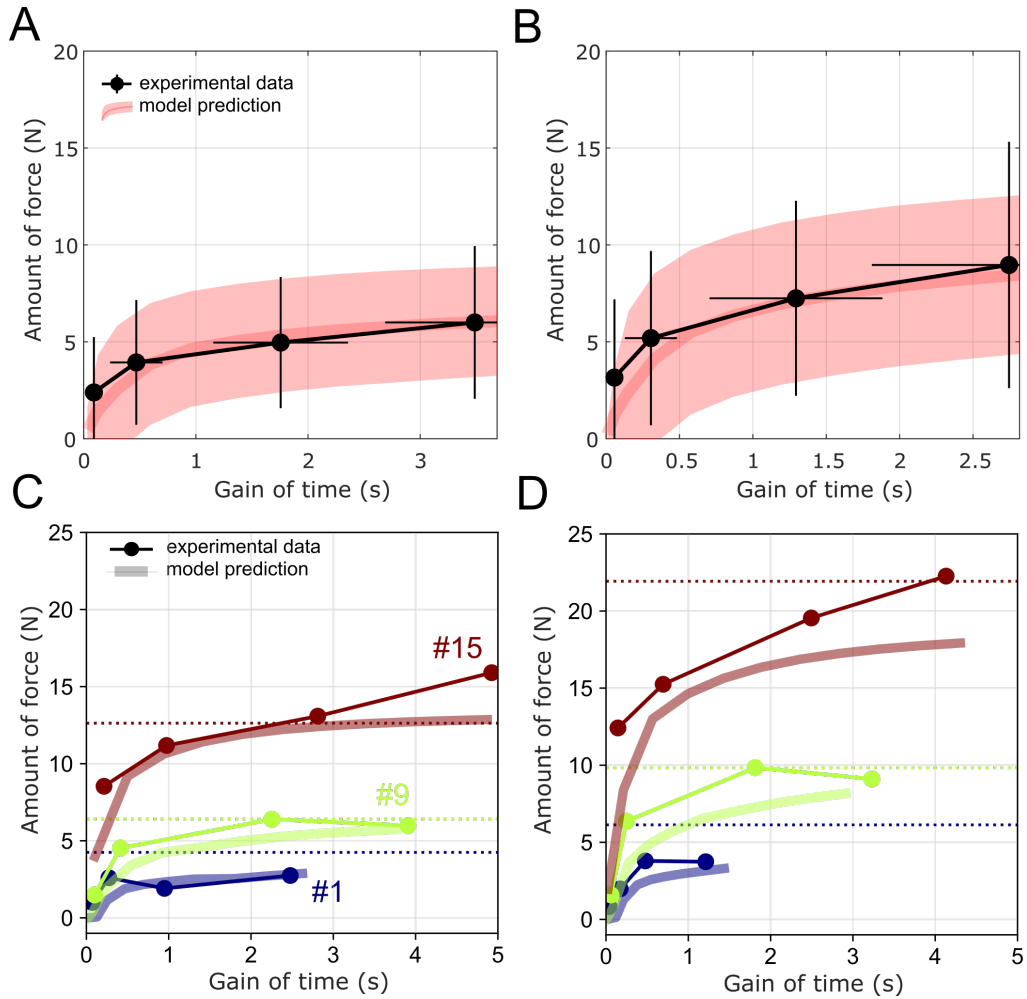


Figure 8: Relationship between gains of time and amount of forces used in Session 2. A. Mean experimental and simulated data for distance 0.2m. Black markers and traces are experimental data. The black filled circles correspond to the drives in the following order from left to right: 1 s, 2 s, 4 s and 6 s, respectively. Mean and standard deviations were calculated across participants. Red traces and shaded areas are model predictions (also mean and standard deviations across participants). The horizontal dotted line correspond to the mean amount of force measured in Session 1 for that distance. B. Same information for distance 0.4m. C-D. Same information for three participants with high, medium and low vigor respectively.



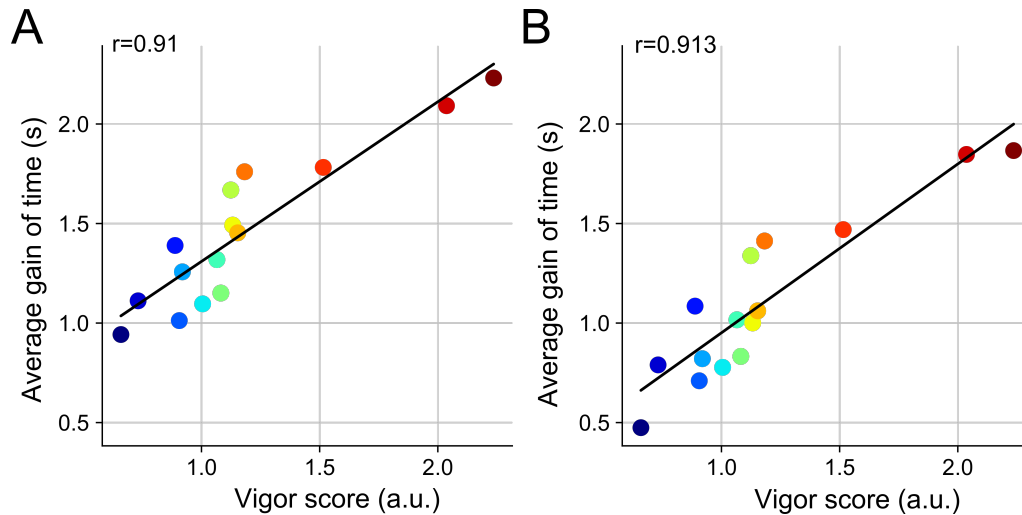


Figure 9: Relationship between vigor scores as measured in Session 1 and average gains of time in Session 2. Same color code than in Figure 5. Each dot is a participant. A. Distance 0.2 m. B. Distance 0.4 m.

385 unequivocally identify the cost of movement because of its potential compositeness and subjectivity  
 386 (Berret et al., 2011; Summerside and Ahmed, 2021). The design of our task circumvents this issue  
 387 by creating a condition in which the task accomplishes by itself, thereby neutralizing the cost of  
 388 movement for specific motion durations. Despite this opportunity, our participants systematically  
 389 exerted some force onto the joystick to achieve the task more quickly. They clearly favored saving  
 390 time over saving energy in this task. Yet, when the drive was present, it was always optimal to  
 391 remain inactive with respect to any cost of movement. This suggests that slow movements are  
 392 generally avoided (van der Wel et al., 2010), not specifically because they may incur a large cost  
 393 related to movement execution but mostly because they last long. This predominance of movement  
 394 duration over energy expenditure was also found in a perceptual decision-making task at movement  
 395 initiation (Lunazzi et al., 2021). Morel et al. (2017) have shown that duration is indeed a key factor  
 396 that makes people judge a reaching movement as “effortful”, and that this judgement does not  
 397 seem to be based on objective measures such as metabolic energy. Here, it was clear that our  
 398 participants did not minimize isometric force production alone, which suggests that the passage of  
 399 time may contribute to action selection *per se* and perhaps to a subjective representation of effort.  
 400 It has been proposed that the cost of time mainly expresses a subjective temporal discounting of  
 401 reward within the brain, which could explain why the participant achieved the task more quickly  
 402 than what is prescribed by the drive. This cost of time has been reviewed in several recent articles  
 403 (Shadmehr et al., 2019; Carland et al., 2019) and a monograph (Shadmehr and Ahmed, 2020a),  
 404 and might even reflect general personality traits (Choi et al., 2014; Berret et al., 2018). Hence  
 405 the most vigorous participants should be the steepest temporal discounters and/or the ones who  
 406 attribute the greatest subjective value to task accomplishment (Reppert et al., 2015; Yoon et al.,  
 407 2020; Shadmehr and Ahmed, 2020a). This prediction agreed well with our findings that the most  
 408 vigorous participants (as sorted from a baseline experiment) were the ones spending more energy  
 409 to save a given amount of time. In our case, the cost of time may also capture an attentional cost  
 410 related to the fact that participants were observing the motion of the cursor on the screen even  
 411 when exerting no force, or just that they were engaged in the task. Since these higher-level costs  
 412 are not strictly related to movement production processes, they are excluded from our definition  
 413 of the cost of movement but can be integrated into a cognitive cost of time.

414 Although we mainly interpreted our results within the cost of time theory, it could be argued  
 415 that participants just preferred to be active in the task. In this case, participants would also have  
 416 preferred to move the cursor by themselves rather than to passively look at it. Assessing passivity  
 417 from an amount of force lower than 0.15 N, a total of 3, 2, 1 and 0 participants passively executed  
 418 the task for the drive durations 1 s, 2 s, 4 s and 6 s respectively (post-analysis for both distances).

419 For instance, one participant (#6) remained passive for drive durations  $\leq 4$  s but suddenly became  
420 active when the drive lasted 6 s. However, participants were generally active even for the smaller  
421 drive durations. The critical observation is that participants did not exert forces onto the joystick  
422 arbitrarily or just by habituation (e.g. using a fixed amount of force or fixed time in the task). In  
423 contrast, they saved time and exerted force in an idiosyncratic manner that was closely linked to  
424 their the original vigor in the task and that depended on the drive duration as predicted by an  
425 optimal control model based on their identified cost of time (which were obtained before the drive  
426 was introduced). Accordingly, highly vigorous participants were highly active in most conditions  
427 even for the 1 s or 2 s drives. These participants were clearly prone to spend a substantial effort to  
428 save a small amount of time. This may seem surprising (and it was not captured accurately by our  
429 model) but it fits well with the theory of vigor (Shadmehr and Ahmed, 2020a) and a putative link  
430 with personality traits like impulsivity or boredom proneness (Choi et al., 2014; Berret et al., 2018).  
431 Weakly vigorous participants were also active in most conditions but produced much lower amounts  
432 of force in the task, that is, they were also inclined to save time but much less than participants  
433 with high vigor scores. These observations show that participants did not simply prefer to be active  
434 with arbitrary levels of force and durations, nor did they try to replicate their baseline behaviour  
435 regardless of the duration of the drive. Instead, they energize the movement according to both  
436 their own vigor (or implicit motivation, Mazzoni et al., 2007) and the characteristics of the drive  
437 in agreement with an optimality principle minimizing a trade-off between a cost of movement and  
438 a cost of time. Another argument may be that the passage of time is subjectively faster when  
439 one is actively moving. The literature indeed suggests that the perception of time could be itself  
440 modulated by our ongoing voluntary actions (Eagleman, 2008; Merchant and Yarrow, 2016). For  
441 instance, saccadic eye movements seems to produce a time compression (Morrone et al., 2005), an  
442 observation which has been generalized to hand reaching movement and isometric force production  
443 (Tomassini et al., 2014). In the latter study, participants had to judge the time interval between  
444 tactile taps and time intervals defined by tactile stimuli were perceived as shorter when hand  
445 movements were prepared and executed. This psychophysical phenomenon is not incompatible  
446 with the hypothesis of a cognitive cost of time. Indeed, to either save true time or its subjective  
447 perception, it would have been worthwhile for the participants to energize task’s achievement.  
448 Interestingly, the link between impulsivity and the sense of time have been reviewed in (Wittmann  
449 and Paulus, 2008) and it was suggested that “[impulsive] individuals are more likely to experience  
450 a slowing down of time during situations in which they are not able to act on their impulsive urges,  
451 for example when one has to wait for a delayed reward and is confronted with the passage of time”.

452 To draw the present conclusions we relied on an isometric reaching task. The advantage of this  
453 task is that it allows resolving a number of issues that would occur with real movements. First,  
454 it removes the problem of dealing with participant-dependent or poorly known biomechanical  
455 limb parameters for different participants (inertia, centers of mass etc.). This lack of knowledge is  
456 typically problematic when estimating an objective cost of movement using musculoskeletal models.  
457 Here every participant controlled the same virtual point mass. Therefore, only the endpoint force  
458 was used to move the cursor, which allowed for a simpler definition of the movement cost in this  
459 task even though different choices were still possible. Here we used the amount of force as in  
460 (Shadmehr et al., 2016) (i.e. force-time integral) to estimate energy expenditure as objectively  
461 as possible from our experimental data. One limitation could be that we did not consider the  
462 metabolic cost of sitting with the arm still on the handle. However, this constant cost is unlikely  
463 to explain the motor decisions of the participants in our task as it is not related to movement  
464 but posture (see also Summerside and Ahmed, 2021 for a similar conclusion in a study estimating  
465 metabolic cost using expired gas analysis). Another limitation could be that we restricted our  
466 analysis to the force component on the y-axis. Additional principal component analyses however  
467 revealed that the horizontal force components linearly co-varied and that working with the norm  
468 of the force would only increase our estimation of effort by 1.3% on average, with idiosyncratic  
469 differences probably related to the specific posture of the participant in the task. Differences in  
470 vigor between participants could still arise from differences in their force production capacities,  
471 although this would not disprove the evidence for a cost of time in this task because the cost  
472 of movement was potentially neutralized in any case with the drive. Second, isometric reaching  
473 simplifies the implementation of the drive because there is no physical interaction between the

474 moving cursor and the participant. It should be possible to create similar experimental tasks with  
475 real movements. For instance, generalization of this task could involve a long treadmill for walking  
476 or an exoskeleton/manipulandum for providing participants with assistive control laws at different  
477 speeds. An additional limitation of our study could be the choice to shift from the slowest to the  
478 fastest drives, but it was made to remove a potential confound. Indeed, practicing with a fast drive  
479 could have habituated the participant to execute the task more quickly than usual (Mazzoni et al.,  
480 2012). Consequently, the finding that a participant moved faster than their preferred speed in a  
481 slow-drive block (i.e. our premise) after having practiced extensively with a fast drive could have  
482 been attributed to some habituation effect and not to a cost of time. It is likely that this confound  
483 could be mitigated by considering many trials per block and analyzing the asymptotic behavior of  
484 the participant. Here we limited the number of trials per block to reduce other side-effects such  
485 as fatigue. Accordingly, we chose to start with slow-drive blocks to attribute any time saving to a  
486 cost of time and not to a strategy biased by previous practice with a quick drive. Yet, we did not  
487 test a fully randomized block-wise design and whether it would significantly change the behavior  
488 of the participants cannot be asserted. Finally, one could argue that an isometric reaching task is  
489 not ecological. Yet, isometric reaching tasks have been used successfully in the past to explore the  
490 neural control of movement, in particular trajectory planning, motor adaptation, muscle synergies  
491 and optimal control (Ghez et al., 1997; de Ruyg et al., 2012, 2013; Berger et al., 2013; Rotella  
492 et al., 2013). Hence, it has proven to be an interesting paradigm that can provide relevant insights  
493 about the control of goal-directed actions. Choosing between time and effort is indeed a commonly  
494 encountered situation in daily life (e.g. the airport's treadmill example) and it is possible that  
495 the principles of such in-lab experiments will generalize to more ecological tasks such as choosing  
496 between taking the car or go by foot, take an escalator or climb the stairs, use his/her slow neuro-  
497 prosthetic arm or healthy arm and so on. Future work will aim at using a motorized upper-limb  
498 exoskeleton to assist the movements of participants and test whether similar principles apply when  
499 muscles produce work and a real movement of the limb occurs.

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## References

- 504  
505 Berardelli, A., Rothwell, J. C., Thompson, P. D., and Hallett, M. (2001). Pathophysiology of  
506 bradykinesia in parkinson’s disease. *Brain*, 124(Pt 11):2131–2146.
- 507 Berger, D. J., Gentner, R., Edmunds, T., Pai, D. K., and d’Avella, A. (2013). Differences in  
508 adaptation rates after virtual surgeries provide direct evidence for modularity. *The Journal of*  
509 *neuroscience : the official journal of the Society for Neuroscience*, 33:12384–12394.
- 510 Berret, B., Castanier, C., Bastide, S., and Deroche, T. (2018). Vigour of self-paced reaching  
511 movement: cost of time and individual traits. *Sci. Rep.*, 8(1):1.
- 512 Berret, B., Chiovetto, E., Nori, F., and Pozzo, T. (2011). Evidence for composite cost func-  
513 tions in arm movement planning: an inverse optimal control approach. *PLoS Comput. Biol.*,  
514 7(10):e1002183.
- 515 Berret, B., Conessa, A., Schweighofer, N., and Burdet, E. (2021). Stochastic optimal feedforward-  
516 feedback control determines timing and variability of arm movements with or without vision.  
517 *PLoS Computational Biology*, 17(6):e1009047.
- 518 Berret, B., Delis, I., Gaveau, J., and Jean, F. (2019). *Optimality and Modularity in Human*  
519 *Movement: From Optimal Control to Muscle Synergies*, pages 105–133. Springer International  
520 Publishing, Cham.
- 521 Berret, B. and Jean, F. (2016). Why don’t we move slower? the value of time in the neural control  
522 of action. *J. Neurosci.*, 36(4):1056–1070.
- 523 Berret, B. and Jean, F. (2020). Stochastic optimal open-loop control as a theory of force and  
524 impedance planning via muscle co-contraction. *PLoS computational biology*, 16:e1007414.
- 525 Carland, M. A., Thura, D., and Cisek, P. (2019). The urge to decide and act: Implications for  
526 brain function and dysfunction. *The Neuroscientist*, 25(5):491–511.
- 527 Choi, J. E. S., Vaswani, P. A., and Shadmehr, R. (2014). Vigor of movements and the cost of  
528 time in decision making. *The Journal of neuroscience : the official journal of the Society for*  
529 *Neuroscience*, 34:1212–1223.
- 530 de Ruyg, A., Loeb, G. E., and Carroll, T. J. (2012). Muscle coordination is habitual rather than  
531 optimal. *The Journal of neuroscience : the official journal of the Society for Neuroscience*,  
532 32:7384–7391.
- 533 de Ruyg, A., Loeb, G. E., and Carroll, T. J. (2013). Are muscle synergies useful for neural control?  
534 *Frontiers in computational neuroscience*, 7:19.
- 535 Dudman, J. T. and Krakauer, J. W. (2016). The basal ganglia: from motor commands to the  
536 control of vigor. *Curr. Opin. Neurobiol.*, 37:158–166.
- 537 Eagleman, D. M. (2008). Human time perception and its illusions. *Current opinion in neurobiology*,  
538 18:131–136.
- 539 Engelbrecht, S. (2001). Minimum principles in motor control. *J. Math. Psychol.*, 45(3):497–542.
- 540 Flash, T. and Hogan, N. (1985). The coordination of arm movements: an experimentally confirmed  
541 mathematical model. *J. Neurosci.*, 5(7):1688–1703.
- 542 Gaveau, J., Berret, B., Demougeot, L., Fadiga, L., Pozzo, T., and Papaxanthis, C. (2014). Energy-  
543 related optimal control accounts for gravitational load: comparing shoulder, elbow, and wrist  
544 rotations. *J. Neurophysiol.*, 111(1):4–16.
- 545 Gaveau, J., Grospretre, S., Berret, B., Angelaki, D. E., and Papaxanthis, C. (2021). A cross-species  
546 neural integration of gravity for motor optimization. *Science Advances*, 7(15).

- 547 Ghez, C., Favilla, M., Ghilardi, M. F., Gordon, J., Bermejo, R., and Pullman, S. (1997). Discrete  
548 and continuous planning of hand movements and isometric force trajectories. *Experimental brain*  
549 *research*, 115:217–233.
- 550 Guigon, E., Chafik, O., Jarrassé, N., and Roby-Brami, A. (2019). Experimental and theoretical  
551 study of velocity fluctuations during slow movements in humans. *Journal of neurophysiology*,  
552 121:715–727.
- 553 Haith, A. M., Reppert, T. R., and Shadmehr, R. (2012). Evidence for hyperbolic temporal dis-  
554 counting of reward in control of movements. *J. Neurosci.*, 32(34):11727–11736.
- 555 Harris, C. M. and Wolpert, D. M. (1998). Signal-dependent noise determines motor planning.  
556 *Nature*, 394(6695):780–784.
- 557 Hoff, B. (1994). A model of duration in normal and perturbed reaching movement. *Biol. Cybern.*,  
558 pages 481–488.
- 559 Huang, H. J. and Ahmed, A. A. (2012). Is there a reaching speed that minimizes metabolic cost?  
560 In *Proceedings of the Translational and Computational Motor Control 2012*, New Orleans, LA.
- 561 Labaune, O., Deroche, T., Teulier, C., and Berret, B. (2020). Vigor of reaching, walking, and  
562 gazing movements: on the consistency of interindividual differences. *Journal of neurophysiology*,  
563 123:234–242.
- 564 Lenth, R. (2019). *emmeans: Estimated Marginal Means, aka Least-Squares Means*. R package  
565 version 1.4.2.
- 566 Liu, D. and Todorov, E. (2007). Evidence for the flexible sensorimotor strategies predicted by  
567 optimal feedback control. *J. Neurosci.*, 27(35):9354–9368.
- 568 Lunazzi, C. S., Reynaud, A. J., and Thura, D. (2021). Dissociating the impact of movement time  
569 and energy costs on decision-making and action initiation in humans.
- 570 Manohar, S. G., Chong, T. T.-J., Apps, M. A. J., Batla, A., Stamelou, M., Jarman, P. R., Bhatia,  
571 K. P., and Husain, M. (2015). Reward pays the cost of noise reduction in motor and cognitive  
572 control. *Current biology : CB*, 25:1707–1716.
- 573 Mazzoni, P., Hristova, A., and Krakauer, J. W. (2007). Why don’t we move faster? parkinson’s  
574 disease, movement vigor, and implicit motivation. *J. Neurosci.*, 27(27):7105–7116.
- 575 Mazzoni, P., Shabbott, B., and Cortés, J. C. (2012). Motor control abnormalities in parkinson’s  
576 disease. *Cold Spring Harbor perspectives in medicine*, 2(6):a009282.
- 577 Merchant, H. and Yarrow, K. (2016). How the motor system both encodes and influences our sense  
578 of time. *Current Opinion in Behavioral Sciences*, 8:22–27.
- 579 Morel, P., Ulbrich, P., and Gail, A. (2017). What makes a reach movement effortful? physical effort  
580 discounting supports common minimization principles in decision making and motor control.  
581 *PLoS Biol.*, 15(6):e2001323.
- 582 Morrone, M. C., Ross, J., and Burr, D. (2005). Saccadic eye movements cause compression of time  
583 as well as space. *Nature neuroscience*, 8:950–954.
- 584 Niv, Y., Daw, N. D., Joel, D., and Dayan, P. (2007). Tonic dopamine: opportunity costs and the  
585 control of response vigor. *Psychopharmacology (Berl)*, 191(3):507–520.
- 586 Park, S.-W., Marino, H., Charles, S. K., Sternad, D., and Hogan, N. (2017). Moving slowly is hard  
587 for humans: Limitations of dynamic primitives. *J. Neurophysiol.*, page jn.00643.2016.
- 588 Qian, N., Jiang, Y., Jiang, Z.-P., and Mazzoni, P. (2013). Movement duration, fitts’s law, and an  
589 infinite-horizon optimal feedback control model for biological motor systems. *Neural Comput.*,  
590 25(3):697–724.

- 591 R Core Team (2019). *R: A Language and Environment for Statistical Computing*. R Foundation  
592 for Statistical Computing, Vienna, Austria.
- 593 Ralston, H. J. (1958). Energy-speed relation and optimal speed during level walking. *Int. Z.*  
594 *Angew. Physiol.*, 17(4):277–283.
- 595 Reppert, T. R., Lempert, K. M., Glimcher, P. W., and Shadmehr, R. (2015). Modulation of saccade  
596 vigor during value-based decision making. *The Journal of neuroscience : the official journal of*  
597 *the Society for Neuroscience*, 35:15369–15378.
- 598 Reppert, T. R., Rigas, I., Herzfeld, D. J., Sedaghat-Nejad, E., Komogortsev, O., and Shadmehr, R.  
599 (2018). Movement vigor as a traitlike attribute of individuality. *J Neurophysiol*, 120(2):741–757.
- 600 Rigoux, L. and Guigon, E. (2012). A model of reward- and effort-based optimal decision making  
601 and motor control. *PLoS Comput. Biol.*, 8(10):e1002716.
- 602 Robbe, D. and Dudman, J. T. (2020). *The Cognitive Neurosciences*, chapter The Basal Ganglia  
603 Invigorate Actions and Decisions, pages 527–539. The Massachusetts Institute of Technology.
- 604 Rotella, M. F., Koehler, M., Nisky, I., Bastian, A. J., and Okamura, A. M. (2013). Adapta-  
605 tion to visuomotor rotation in isometric reaching is similar to movement adaptation. *IEEE ...*  
606 *International Conference on Rehabilitation Robotics : [proceedings]*, 2013:6650431.
- 607 Shadmehr, R. (2010). Control of movements and temporal discounting of reward. *Curr. Opin.*  
608 *Neurobiol.*, 20(6):726–730.
- 609 Shadmehr, R. and Ahmed, A. (2020a). *Vigor: Neuroeconomics of Movement Control*. MIT Press.
- 610 Shadmehr, R. and Ahmed, A. A. (2020b). Precis of vigor: Neuroeconomics of movement control.  
611 *The Behavioral and Brain Sciences*, pages 1–10.
- 612 Shadmehr, R., Huang, H. J., and Ahmed, A. A. (2016). A representation of effort in decision-  
613 making and motor control. *Current biology : CB*, 26:1929–1934.
- 614 Shadmehr, R., Orban de Xivry, J. J., Xu-Wilson, M., and Shih, T.-Y. (2010). Temporal discounting  
615 of reward and the cost of time in motor control. *J. Neurosci.*, 30(31):10507–10516.
- 616 Shadmehr, R., Reppert, T. R., Summerside, E. M., Yoon, T., and Ahmed, A. A. (2019). Movement  
617 vigor as a reflection of subjective economic utility. *Trends in neurosciences*, 42:323–336.
- 618 Singmann, H., Bolker, B., Westfall, J., Aust, F., and Ben-Shachar, M. S. (2019). *afex: Analysis of*  
619 *Factorial Experiments*. R package version 0.25-1.
- 620 Stengel, R. (1986). *Optimal Control and Estimation*. Dover books on advanced mathematics.  
621 Dover Publications.
- 622 Summerside, E., Shadmehr, R., and Ahmed, A. A. (2018). Vigor of reaching movements: reward  
623 discounts the cost of effort. *J. Neurophysiol.*
- 624 Summerside, E. M. and Ahmed, A. A. (2021). Using metabolic energy to quantify the subjective  
625 value of physical effort. *Journal of The Royal Society Interface*, 18(180):20210387.
- 626 Takikawa, Y., Kawagoe, R., Itoh, H., Nakahara, H., and Hikosaka, O. (2002). Modulation of  
627 saccadic eye movements by predicted reward outcome. *Exp. Brain Res.*, 142:284–291.
- 628 Thura, D. (2020). Decision urgency invigorates movement in humans. *Behavioural Brain Research*,  
629 382:112477.
- 630 Todorov, E. (2004). Optimality principles in sensorimotor control. *Nat. Neurosci.*, 7(9):907–915.
- 631 Todorov, E. and Jordan, M. I. (2002). Optimal feedback control as a theory of motor coordination.  
632 *Nat. Neurosci.*, 5(11):1226–1235.

- 633 Tomassini, A., Gori, M., Baud-Bovy, G., Sandini, G., and Morrone, M. C. (2014). Motor commands  
634 induce time compression for tactile stimuli. *Journal of Neuroscience*, 34(27):9164–9172.
- 635 Turner, R. S. and Desmurget, M. (2010). Basal ganglia contributions to motor control: a vigorous  
636 tutor. *Curr. Opin. Neurobiol.*, 20(6):704–716.
- 637 Uno, Y., Kawato, M., and Suzuki, R. (1989). Formation and control of optimal trajectory in  
638 human multijoint arm movement. minimum torque-change model. *Biol. Cybern.*, 61(2):89–101.
- 639 van Beers, R. J. (2008). Saccadic eye movements minimize the consequences of motor noise. *PLoS*  
640 *One*, 3(4):e2070.
- 641 van der Wel, R. P. R. D., Sternad, D., and Rosenbaum, D. A. (2010). Moving the arm at different  
642 rates: slow movements are avoided. *Journal of motor behavior*, 42:29–36.
- 643 Wang, C., Xiao, Y., Burdet, E., Gordon, J., and Schweighofer, N. (2016). The duration of reaching  
644 movement is longer than predicted by minimum variance. *J. Neurophysiol.*, 116(5):2342–2345.
- 645 Wittmann, M. and Paulus, M. P. (2008). Decision making, impulsivity and time perception. *Trends*  
646 *in cognitive sciences*, 12(1):7–12.
- 647 Yoon, T., Geary, R. B., Ahmed, A. A., and Shadmehr, R. (2018). Control of movement vigor and  
648 decision making during foraging. *Proceedings of the National Academy of Sciences of the United*  
649 *States of America*, 115:E10476–E10485.
- 650 Yoon, T., Jaleel, A., Ahmed, A. A., and Shadmehr, R. (2020). Saccade vigor and the subjective  
651 economic value of visual stimuli. *Journal of neurophysiology*, 123:2161–2172.
- 652 Young, S. J., Pratt, J., and Chau, T. (2009). Target-directed movements at a comfortable pace:  
653 movement duration and fitts’s law. *J Mot Behav*, 41(4):339–346.