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On the perception of movement vigour

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Abstract

It is common to get the impression that someone moves rather slowly or quickly in everyday life. In motor control, the natural pace of movement is captured by the concept of vigour, which is often quantified from the speed or duration of goal-directed actions. A common phenomenon, here referred to as the *vigour law*, is that preferred speed and duration idiosyncratically increase with the magnitude of the motion. According to the direct-matching hypothesis, this vigour law could thus underlie the judgment of someone else's movement vigour.

We conducted a series of three experiments (N = 80) to test whether the vigour law also exists in perception and whether it is linked to that of action. In addition to measuring participants' vigour, we also asked them to judge the quickness of stimuli representing horizontal arm reaching movements varying through amplitudes, speeds, and durations.

Results showed that speed and duration of movements perceived as neither fast nor slow (i.e., natural pace) increased with amplitude, thereby indicating that the vigour law holds when an observer judges the natural pace of others' movements. Results also revealed that this judgment was *population-based* (related to the average vigour of all participants) rather than *individual-based* (participant's own vigour).

Keywords

Movement vigour; Perception-action; Judgment; Direct-matching hypothesis; Vigour law

27 **Introduction**

28

29 Imagine that you are looking for your keys, see them on the table next to you, and grab them. You end
30 up making a reaching movement at your preferred speed, that is, with some *vigour*. You could certainly
31 have executed this movement more quickly or slowly if the circumstances had required it, but you
32 spontaneously chose a given speed. Let's now consider that you are witnessing someone else
33 performing the same task. Whether their movement is too slow or too fast could then influence your
34 own decisions (e.g., getting impatient or calming the person). But how do we judge the vigour of
35 someone's movement in the first place?

36 The mirror system, discovered three decades ago (Rizzolatti et al., 1996), allows us to postulate that
37 the perception of movement vigour may be linked to the vigour of our actions. Indeed, this system has
38 shown an activation of the same specific cortical networks when the same action is observed, imagined
39 or produced (Grafton et al., 1996; Noë, 2004; Rizzolatti et al., 1996; Rizzolatti & Craighero, 2004; Wilson
40 & Knoblich, 2005). Since then, several studies have found a genuine interest to expand an
41 interdisciplinary view claiming the systematic connection between perception, cognition, and motor
42 control mechanisms (Gentsch et al., 2016 for a review). Moreover, the motor system is more strongly
43 engaged during action observation when participants already have a specific motor representation of
44 the action they observed (see the Theory of Event Coding by Hommel et al., 2001; Calvo-Merino et al.,
45 2005; Casile & Giese, 2006; Prinz, 1997; Schütz-Bosbach & Prinz, 2007). In this vein, the so-called direct-
46 matching hypothesis holds that the kinematics of an observed movement is directly mapped onto the
47 observer's internal motor representation of this action during its observation, so that the 'motor
48 knowledge' of the observer is used to understand the observed action (Iacoboni et al., 1999; Rizzolatti
49 et al., 2001). This mechanism could thus be meaningful to enhance social and physical interaction with
50 others and, in particular, to compare the speed of an observed movement to some knowledge of
51 vigour in action.

52 A classical approach to test the direct-matching hypothesis has been to check whether the kinematic
53 laws and motor invariants that underlie human movement influence observers involved in a judgment
54 task of other's action. For instance, Viviani and Stucchi (1992) have used the two-thirds power law (i.e.,
55 during curved movements of the upper limbs, tangential hand speed is non-linearly related to the
56 trajectory's curvature) to create a dynamic visual illusion, which allowed to highlight the influence of
57 the motor system on perception. Complying with this law has also been shown to be critical to enhance
58 human-robot physical interaction (Maurice et al., 2018), and evidence for its neural representation
59 was reported (Dayan et al., 2007). In the same way, numerous studies have exploited the well-
60 characterized Fitts' law (i.e., the speed-accuracy trade-off). They tested whether Fitts' law held for
61 motor imagery (Decety & Jeannerod, 1996; Wong et al., 2013) and for perception of movements
62 produced by human and non-human agents (Chandrasekharan et al., 2012; Grosjean et al., 2007;
63 Young et al., 2009b). The results showed that the durations of the displacements imagined or perceived
64 by the participants increased linearly with the index of difficulty of the task (ID, based on the
65 distance/width ratio), thereby complying with Fitts' law. Neural correlates of Fitts' law in action
66 observation were also found (Eskenazi et al., 2012).

67 The present work builds on these previous studies and aims to extend our knowledge on the
68 involvement of motor or kinematic laws in judging the movements of others. In contrast to Fitts' law
69 that focuses on the maximal speed of movement, our work focuses on the movement vigour (i.e., the
70 preferred, self-chosen speed of movement). This notion has received a lot of attention recently and
71 was shown to link decision-making and motor control (Carland et al., 2019; Dudman & Krakauer, 2016;
72 Shadmehr et al., 2019; Shadmehr & Ahmed, 2020). In several studies, movement vigour was
73 characterized empirically by the relationships between amplitude, speed, and duration of a set of goal-
74 directed movements (Berret et al., 2018; Choi et al., 2014; Labaune et al., 2020; Reppert et al., 2018).
75 Importantly, Young and colleagues showed that Fitts' law does not hold for natural-pace movements
76 given that, for a constant ID, duration of movements linearly increases with amplitude (Young et al.,
77 2009b). Remarkably, both the speed and duration of a self-paced movement tend to monotonically

78 increase with its extent, which we refer here to as the *vigour law*. Indeed, this observation has been
 79 found to hold for all individuals and actions as varied as eye saccades, head movements, arm reaching
 80 or walking a distance (Labaune et al., 2020; Reppert et al., 2018). For instance, for self-paced arm
 81 reaching, duration D approximately increases with amplitude A according to the equation:

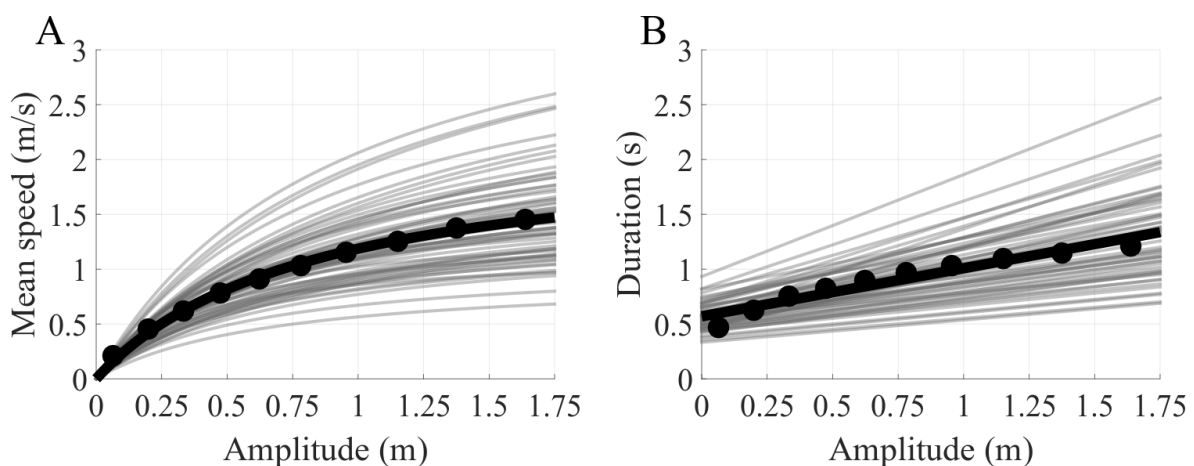
$$82 \quad D = \alpha A + \beta \quad (\text{Eq. 1})$$

83 with parameters $\alpha > 0$, $\beta > 0$ (Berret et al., 2018), and mean speed S correspondingly increases
 84 according to:

$$85 \quad S = \frac{A}{\alpha A + \beta} \quad (\text{Eq. 2})$$

86 These specific equations implement the vigour law for reaching, the parameters of which typically vary
 87 across individuals (Fig. 1).

88



89

90 **Figure 1. The vigour law for reaching movements.** Data from two previous experiments were fitted to
 91 illustrate the vigour law for horizontal arm movements (rotation around the shoulder joint; Berret et
 92 al., 2018; Labaune et al., 2020). (A) Mean speed and (B) duration of reaching movements as function
 93 of stimulus amplitude. Mean speed was fitted according to Eq. 2 and duration was fitted according to
 94 Eq. 1 for each participant separately (gray curves; $N = 58$). (A) The best-fitting parameters for mean
 95 speed were as follows: $\alpha = 0.509 \pm 0.176$; $\beta = 0.395 \pm 0.094$; mean $R^2 = .976 \pm$
 96 $.055$; R^2 range = [.579; .998]. (B) The best-fitting parameters for duration were as follows: $\alpha =$
 97 0.439 ± 0.169 ; $\beta = 0.569 \pm 0.122$; mean $R^2 = .904 \pm .042$; R^2 range = [.764; .986]. The black

98 *points represent the mean speed (or duration) averaged across all participants for each amplitude, and*
99 *the same fitting was applied respectively. Another fitting function could have been applied on duration,*
100 *as suggested by Young et al. (2009b). Indeed, they found that a combination of Fitts' law and a linear*
101 *function of amplitude best fitted their duration data ($D = a + b \times \log_2 \left(\frac{A}{W} + 1 \right) + c \times A$, with D the*
102 *movement duration, A the amplitude and W the width of the targets). However, we chose the linear fit*
103 *because the linear component is highly predominant for movements performed at natural speed.*

104

105 Large but robust inter-individual differences of vigour were found and documented in several studies
106 which compared the vigour of movements across participants, days, or effectors (Berret et al., 2018;
107 Choi et al., 2014; Labaune et al., 2020; Reppert et al., 2018; Shadmehr et al., 2019). Moreover, it has
108 been shown that high boredom proneness scores (assessed by questionnaires) were significantly and
109 positively correlated with high vigour scores during reaching movements (Berret et al., 2018). Similar
110 yet non-significant trends were obtained between impulsivity and reaching vigour (Berret et al., 2018),
111 and between impulsivity and eye saccade vigour (Choi et al., 2014). Although these effects are small,
112 these results are consistent with one of the main explanatory theory of the vigour law, namely that
113 movement vigour depends not only on biomechanical factors but also on the individual's implicit
114 motivation and the general brain tendency to temporally discount the reward associated with task
115 accomplishment (Shadmehr et al., 2010). Indeed, the subjective value of a reward decreases over time,
116 at different rates among individuals (Green et al., 1994; Myerson & Green, 1995). In goal-directed
117 movements, the mere completion of the movement triggers the acquisition of the reward through the
118 activation of dopaminergic systems. The time of movement thus delays the acquisition of the reward
119 and leads to its subjective devaluation. According to this view, movement vigour would result from a
120 trade-off between a cost of movement (e.g., physical effort) and a cost of time implementing this
121 subjective reward discounting (Berret et al., 2018; Shadmehr et al., 2010). Vigour is therefore thought
122 to be related to cognitive decision-making processes (Shadmehr et al., 2016) and to originate from

123 cortico-basal ganglia circuits, as exemplified by the bradykinesia observed in Parkinson's patients
124 (Mazzoni et al., 2007).

125 Besides being a critical feature of one's everyday movement, vigour is also critical for interacting with
126 others. Indeed, many social behaviors require adapting the vigour of our movement to that of the
127 other person, for example when we shake someone's hand or walk next to an elderly person. In these
128 cases, successful physical or social interaction is subjected to the compliance with the other's vigour,
129 which thus questions the perception of vigour. According to the direct-matching hypothesis, the vigour
130 law described above should hold in perception. To the best of our knowledge, the vigour law has not
131 been tested in perception although the perception of time, speed or distance has been studied in
132 previous works (Casasanto & Boroditsky, 2008; Gavazzi et al., 2013; Hayashi & Ivry, 2020; Lacquaniti
133 et al., 2014; McKee, 1981; Robbe, 2021). Furthermore, the inter-individual differences of vigour could
134 be exploited to refine our understanding of the nature of the motor knowledge that could be activated
135 in this context, i.e., individual-based or population-based (Liepelt et al., 2008). Indeed, while the direct-
136 matching hypothesis has received strong empirical support using other motor laws, most of the
137 previously mentioned studies relied on data averaged across participants (Chandrasekharan et al.,
138 2012; Grosjean et al., 2007), thereby limiting the possible conclusions about the nature of the direct
139 matching.

140 Therefore, the present article aims to determine (1) whether the vigour law described above holds in
141 general when an observer judges the quickness of someone else's movement and (2) whether this
142 judgment is related to the own observer's vigour in a similar action or to a more generic motor
143 knowledge. We addressed those questions through a series of three experiments focusing on arm
144 reaching movements.

145

146 **General materials and method**

147

148 In the first experiment, we asked participants to judge whether biological point-to-point movements
149 of a dot moving on a screen were considered as fast or not, while varying the dot's speed and amplitude
150 on each trial. The motion speed that was considered as neither fast nor slow by the participants for
151 each amplitude was estimated, which allowed us to test the analog of the vigour law in perception.
152 Comparisons with the observers' own vigour in action were also performed to assess whether the
153 vigour of performed and observed movements could be directly linked. In *Experiments 2* and *3*, we
154 used a dynamic visual illusion as Viviani and Stucchi (1992) did to investigate the link between the
155 vigour in action and perception from a complementary approach. There, the vigour law was directly
156 implemented in some of the stimuli to check whether it was harder to judge the speed of a movement
157 complying with the vigour law. To probe if this judgment is rather population-based (referring to the
158 statistics of movements observed around them as a reference, *Experiment 2*) or individual-based
159 (referring to the participants' own sensorimotor system as a reference, *Experiment 3*), we
160 implemented in each stimulus either the mean vigour law of the population (based on reaching
161 movements data of the participants of previous studies) or the participant's own vigour law as
162 measured in the same action during a companion experiment. All the stimuli were produced with
163 Matlab using Psychtoolbox (Kleiner et al., 2007), and all statistical analyses were performed with JASP
164 software. Power analyses were conducted with G*Power software when relevant to test the direct-
165 matching hypothesis. All the experimental protocols were approved by the local Ethics Committee of
166 Paris-Saclay University (CER-Paris-Saclay-2018-36-R). Written informed consent was obtained from
167 each participant in the studies as required by the Helsinki declaration.

168

169 **Experiment 1**

170

171 The goal of *Experiment 1* was to determine whether the vigour law, identified in the motor control
172 field, could also rule the perception of movement pace.

173

174 **Materials and method**

175 *Participants.* Previous studies that were the foundation of the present work and used similar
176 experimental design chose sample sizes ranging from 10 to 21 participants (Chandrasekharan et al.,
177 2012; Grosjean et al., 2007; Wong et al., 2013). To reinforce the power of our analyses, thirty young
178 adults with no known neuromuscular disease and with normal or corrected-to-normal vision
179 participated in this experiment (14 females, 28.5 ± 5.08 years old; mean \pm SD values).

180 *Experimental design and materials.* The participants stood 2-meters away from a large vertical screen,
181 and a keyboard was placed on a table in front of them. A 3-cm wide dot was displayed on the screen
182 by means of a projector located behind to represent hand's location of an individual performing
183 horizontal pointing movements with a fully-extended arm. The dot could thus move horizontally from
184 a starting point to a target point, following the biological features of point-to-point arm movement
185 (acceleration from the still starting point to the maximum speed, then deceleration to the still target
186 point as generated by the minimum jerk model; Flash & Hogan, 1985). The linear amplitudes of the
187 projected movements on the screen were computed using trigonometry:

188
$$ampl = 2 \times 0.75 \times \tan\left(\frac{\theta}{2}\right) \quad (Eq. 3)$$

189 where θ is the shoulder angular amplitude of the represented reaching movement of an individual
190 having a 0.75 m long arm. Using Eq. 3, there were thus 4 amplitudes of movements (0.26 m, 0.55 m,
191 0.87 m and 1.26 m) corresponding respectively to 4 angular amplitudes (20°, 40°, 60° and 80°). Each
192 amplitude was presented with 10 different mean speeds (ranging from 0.25 m/s to 1.45 m/s), resulting
193 in 40 different types of stimuli. Each stimulus was displayed 10 times during the experiment. Hence,
194 the participants saw 400 individual point-to-point movements in total. At the end of each movement,
195 the participants had to evaluate the quickness of the movement by answering the question "*Was the*
196 *movement fast or slow?*" by pressing "V" on the keyboard for "Slow" or "T" for "Fast" with the index
197 finger of their dominant hand. There was no time pressure to answer. Once they had given their
198 answer, the next movement was displayed. The first half of the movements was presented rightward
199 and the other half leftward (or inversely, randomized across participants). Each half of the task began

200 with an initial familiarization sequence of 40 movements to judge, then 5 blocks of 40 movements to
201 judge were gathered. Each stimulus appeared once in each block, their order of appearance being
202 randomized to prevent learning, habituation or fatigue effects from impacting the results. There were
203 short breaks between each block, as long as the participants needed (about 1 min).

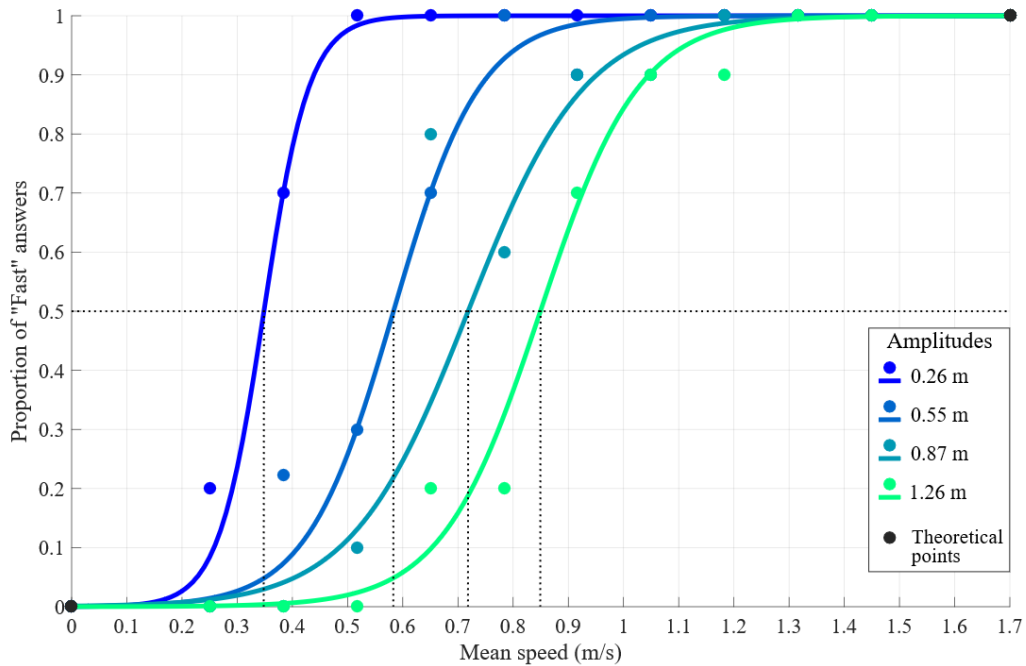
204 To investigate the link between the vigour in perception and the vigour in action, participants were
205 also evaluated on real arm reaching movements similar to those observed as described above. We
206 used the protocol and material of previous articles to do so (Berret et al., 2018; Labaune et al., 2020).
207 The total duration of the task (i.e., action plus perception, in a randomized order) was about one hour.

208 *Data processing.* Data processing was performed using custom Matlab scripts, from the recorded
209 answers of the participants (1 for “fast” answers and 0 for “slow” answers). Proportion of “Fast”
210 answers for each stimulus were computed for each participant. Four sigmoid curves were then fitted,
211 one for each stimulus amplitude. Theoretical points were added at 0 for 0 m/s and 1 for 1.7 m/s and
212 the function was initialized (minimum and maximum values set to 0 and 1 respectively) to improve
213 fitting quality (Fig. 2). The fitted function was of the form:

$$214 \quad f(x) = \frac{1}{1 + e^{-\frac{PSE-x}{JND}}} \quad (\text{Eq. 4a})$$

215 where *PSE* is the Point of Subjective Equality and *JND* is the Just Noticeable Difference. As exclusion
216 criteria, it was checked that the two extreme stimuli (0.25 m/s for 1.26 m and 1.45 m/s for 0.26 m),
217 obvious to judge, had been respectively judged as slow and fast. It would otherwise have denoted a
218 participant that misunderstood the task. Participants were therefore excluded from the statistical
219 analyses if at least one of the two sigmoids fitted on their extreme stimuli was more than 10% (i.e.,
220 error on more than 1 trial) away from 1 and 0 respectively. In this experiment, all the participants (N =
221 30) met the criteria so none was excluded from statistical analyses.

222



223

224 **Figure 2. Proportion of “fast” answers as function of mean speed and amplitude (for a representative**
 225 **participant).** Each curve stands for one amplitude of stimuli (0.26 m, 0.55 m, 0.87 m and 1.26 m,
 226 corresponding respectively to 4 angular amplitudes of 20°, 40°, 60° and 80°; see Eq. 3). A sigmoid
 227 function (Eq. 4a) was used to fit the data. For visualization purpose, the 0.5 proportion line and the four
 228 vertical lines indicating the corresponding PSE were displayed.

229

230 The PSE (50% of “fast” answers and 50% of “slow” answers) of each curve was gathered (four per
 231 participant). Here, PSE represents the speed at which a movement of a given amplitude would appear
 232 neither fast nor slow to the participant; or in other words, the speed from which a movement of a
 233 given amplitude started to appear as fast (called “Perceived mean speed”). Durations of movements
 234 corresponding to these perceived mean speeds were computed (duration = amplitude/PSE; called
 235 “Perceived duration”). Then, the four Perceived mean speeds were fitted according to Eq. 2 and the
 236 four Perceived durations were fitted according to Eq. 1 separately for each participant (with amplitude
 237 of regressor). Associated R^2 values and fitting parameters were gathered and averaged across
 238 participants. Following an approach similar to Choi et al. (2014), scores representing the perceived

239 vigour were computed. To do so, z-scores of the PSE for each amplitude were computed across
240 participants, then the z-scores of the four amplitudes were averaged for each participant. Data
241 processing of reaching movement and the computation of their scores representing the performed
242 vigour followed the same approach, which was already described in previous articles (on the
243 performed mean speeds to be comparable with the perceived vigour scores; Berret et al., 2018;
244 Labaune et al., 2020). Therefore, we could obtain two vigour scores per participant (perceived and
245 performed, normalized as z-scores and hence comparable). The mean speed of the performed
246 movements was also fitted according to Eq. 2, and the duration of the performed movements was also
247 fitted according to Eq. 1 separately for each participant. Data pairwise normality was verified (Shapiro-
248 Wilk test, significance threshold set at $< .05$). In this experiment, the bivariate normality was met ($p >$
249 $.05$), therefore parametric analysis was chosen. Pearson's linear correlation analysis was conducted to
250 investigate the relationship between scores of perceived and performed vigour. A Bayesian correlation
251 was also performed.

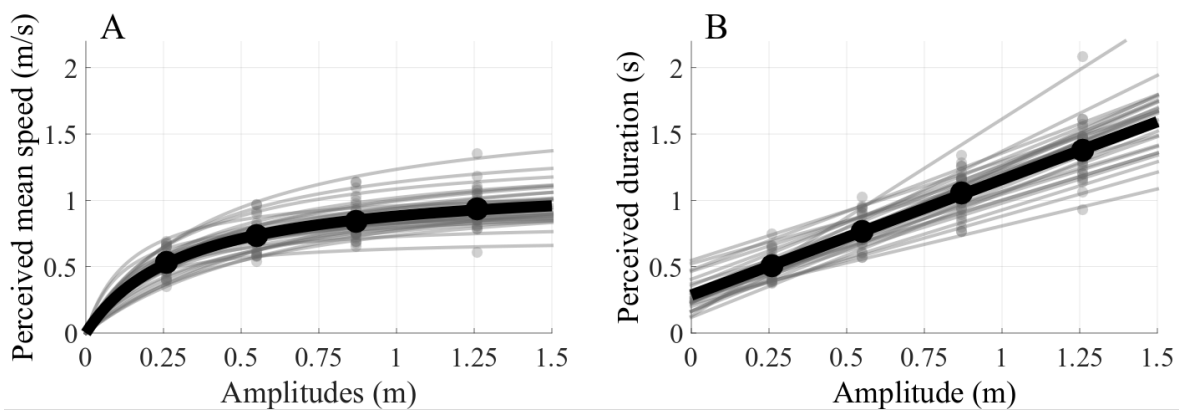
252

253 ***Results and discussion***

254 Results showed that the speed of movements perceived as neither fast nor slow (PSE) tended to
255 increase with amplitude, not only when averaged over the sample but also for each individual. The
256 wider the movement amplitude, the higher the speed perceived as neither fast nor slow (i.e., the
257 higher the speed from which the movement appears fast). The best-fitting parameters were as follows:
258 $\alpha = 0.871 \pm 0.175$; $\beta = 0.285 \pm 0.110$; $mean R^2 = .871 \pm .164$, $R^2 range = [.342; .998]$, $Q1 =$
259 $.800$ and $Q3 = .981$ (Fig. 3A). Results also showed that movements perceived as neither fast nor slow
260 have durations that tended to increase linearly with amplitude, both on average over the sample and
261 for each individual. The wider the movement amplitude, the longer the duration of the movement that
262 has been perceived as neither fast nor slow (i.e., the longer the duration from which the movement
263 appears fast). The best-fitting parameters were as follows: $\alpha = 0.872 \pm 0.183$; $\beta = 0.286 \pm$
264 0.110 ; $mean R^2 = .984 \pm .019$; $R^2 range = [.906; .999]$ (Fig. 3B). Taken together, the results on

265 perceived speed and perceived duration suggest that the vigour law also seems to rule the perception
 266 of what is a natural movement pace. The same increase of duration and speed was observed during
 267 the execution of similar reaching movements (Fig. 1; see Berret et al., 2018 for duration and Labaune
 268 et al., 2020 for the speed). These results are consistent with the direct-matching hypothesis. However,
 269 when going further in trying to relate the vigour measured in action to that measured in perception,
 270 there was no significant correlation between the computed scores of vigour ($r = .161, p = .396$). An a
 271 **posteriori power analysis** showed that $power = .136$. To go further on this result, Bayesian analysis was
 272 performed. Here, $BF_{01} = 3.125$. BF_{10} reports a Bayes Factor in favor of the alternative hypothesis – i.e.,
 273 evidence for a correlation between the participants' action and perception – and BF_{01} in favor of the
 274 null hypothesis – i.e., evidence for no correlation between the participants' action and perception. In
 275 the present result, BF_{01} is 3.125, which means that, given the data, the null hypothesis appears 3.125
 276 times more plausible than the alternative hypothesis. As $3 > BF_{01} > 10$, this evidence of no correlation
 277 is moderate. This lack of correlation could be due to a judgment based on a general vigour law derived
 278 from the population.

279



280

281 **Figure 3. Perceived mean speed and perceived duration as function of stimulus amplitude.** *In each*
 282 *subplot each gray curve stands for one participant (N = 30). Gray points represent the four mean speeds*
 283 *(PSE) or associated durations (amplitude/PSE) perceived by each participant for each stimulus*
 284 *amplitude. Mean speed was fitted according to Eq. 2 and duration was fitted according to Eq. 1 for*
 285 *each participant separately (gray curves). The black points represent the mean speed (or duration)*

286 *averaged across all participants for each amplitude, and the same fitting was applied respectively. A:*
287 *Perceived mean speed (i.e., perceived as neither too slow nor too fast). B: Perceived duration (i.e.,*
288 *perceived as neither too short nor too long).*

289

290 The vigour law thus seems to rule the perception of movement pace in agreement with the direct-
291 matching hypothesis. However the lack of relationship between the vigour scores of individuals in
292 action and perception, which suggests that the judgment of the vigour of others is not individual-
293 based, prompted us to verify that this was not a basic outcome of the chosen experimental design. We
294 therefore considered an alternative experimental design in which the vigour law was exploited to
295 create a potential uncertainty when it comes to judge whether a movement is fast or slow. Indeed,
296 movements complying with the vigour law correspond to the preferred pace in action; therefore, they
297 should be considered as neither fast nor slow in perception if the same law holds. Depending on
298 whether the implemented law is derived from the individual or from the population, one could refine
299 the nature of the direct matching.

300

301 **Experiment 2**

302

303 In the previous experiment, the issue of the perception of movement quickness has been addressed
304 and the vigour law underlying action has been found to hold in perception. However, we were not able
305 to establish a link between the participant's own vigour in action and in perception perhaps due to our
306 specific experimental design. The goal of *Experiment 2* was to test differently the existence of a link
307 between the vigour in action and perception by designing an experiment in which stimuli were directly
308 taken from the vigour law of real reaching movements. To do so, we modified the experimental
309 paradigm by using a dynamic visual illusion in keeping with Viviani and Stucchi (1992). The participants
310 were now provided with a first stimulus (still a dot moving horizontally for a given amplitude and with
311 a certain speed), and they had to judge whether a second stimulus, of a different amplitude, was faster

312 or slower than the first one they saw. The duration or speed of the second stimulus could change
313 according to the vigour law or to alternative rules (e.g., fixed duration or fixed speed). Our premise
314 here was that if the vigour law defines what is a neither too slow nor too fast movement as a function
315 of amplitude, participants should be more uncertain when judging stimuli that follow the vigour law
316 rather than when they do not. As a corollary, this experiment is also useful to test the individual- versus
317 population-based alternatives depending on the specific vigour law that is implemented (taken from
318 the individual or the average of the population).

319

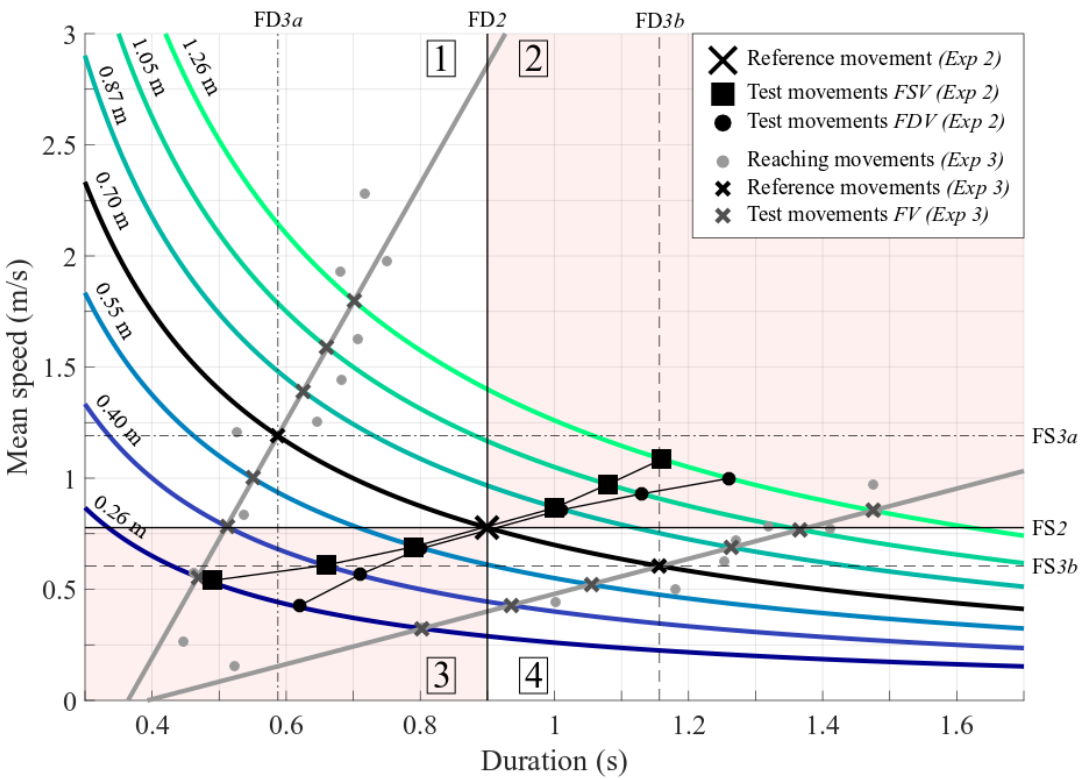
320 ***Materials and method***

321 *Participants.* Based on previous similar studies that chose sample sizes ranging from 3 to 21
322 participants (Chandrasekharan et al., 2012; Grosjean et al., 2007; Viviani & Stucchi, 1992; Wong et al.,
323 2013) and to reinforce the power of our analyses, thirty young adults with no known neuromuscular
324 disease and with normal or corrected-to-normal vision participated in the experiment (15 females,
325 22.3 ± 3.1 years old; mean \pm SD values).

326 *Experimental design and materials.* The participants sat at a table in front of the same setup as in the
327 experiments described above. Each trial began with a reference movement being displayed, followed
328 by a test movement to judge. Therefore, the participants always saw two displacements of the dot in
329 a row, and they had to answer the question “*Compared to the reference, was the second movement*
330 *faster or slower?*” by means of two buttons of the response box (one button for “faster” and another
331 for “slower”) on the table. Once they answered, the next trial was displayed. The reference movement
332 was maintained constant throughout the experiment. Its characteristics were $A = 0.7$ m, $D = 0.9$ s and
333 $S = 0.78$ m/s, based on the mean duration of 50° wide reaching movements data of the population of
334 previous studies (Berret et al., 2018; Labaune et al., 2020). As inclusion criteria, it was verified that four
335 extreme stimuli arbitrarily chosen were correctly estimated compared to the reference movement
336 (clearly faster for 0.26 m, 0.25 s, 1.06 m/s and for 1.26 m, 0.50 s, 2.52 m/s; clearly slower for 0.26 m,
337 1.50 s, 0.18 m/s and for 1.26 m, 3.50 s, 0.36 m/s). It would otherwise have denoted a participant that

338 misunderstood the task. All participants (N = 30) met the criteria so they were all included. In order to
339 be as accurate as possible in the data analysis (linear fitting), we added two intermediary test
340 amplitudes compared to the previous protocols (6 points instead of 4). Test movements thus varied
341 across 6 amplitudes around the reference amplitude (0.26 m, 0.40 m, 0.55 m, 0.87 m, 1.05 and 1.26
342 m, corresponding to 6 angular amplitudes of 20°, 30°, 40°, 60°, 70° and 80°; see Eq. 3) and four
343 conditions: (i) test movements always had the same mean speed as the reference movement (*Fixed*
344 *Speed*, denoted by FS), therefore, durations of movement varied from 0.34 s for 0.26 m to 1.61 s for
345 1.26 m; (ii) test movements always had the same duration as the reference movement (*Fixed Duration*,
346 denoted by FD), therefore, mean speeds of movement varied from 0.29 m/s to 1.40 m/s; (iii and iv)
347 test movements had different durations and mean speeds from the reference movement but followed
348 the vigour law (i.e., speed and duration both increase with amplitude according the relationships found
349 in action for a population of participants; *Fixed Vigour*, denoted by FV). This condition was duplicated
350 with *Fixed Duration Vigour* (denoted by FDV) and *Fixed Speed Vigour* (denoted by FSV) to cover as
351 many possibilities of judgment as possible and have more data points to capture potential hesitations
352 (duration-based or a speed-based; see explanations in Fig. 4). In FDV, durations and speeds varied from
353 0.62 s and 0.43 m/s for the 0.26 m wide movement to 1.26 s and 1.00 m/s for the 1.26 m wide
354 movement, and in FSV they varied from 0.49 s and 0.54 m/s to 1.16 s and 1.09 m/s. Therefore, there
355 were 24 different stimuli (6 amplitudes tested in each of the 4 conditions, FS, FD, FDV and FSV). Each
356 stimulus was displayed 10 times during the experiment. Hence, the participants had to judge 240
357 movements in total. The first half of the movements was presented rightward and the other half
358 leftward (or inversely, randomized across participants). Participants were told that there was no right
359 or wrong answer, but that only the general impression that the test movement had left them in relation
360 to the movement of reference should be taken into account. They were given some examples of
361 facilitating strategies that they were free to use to judge, such as imagining that someone actually
362 performs reaching movements in front of them, imagining that they perform them themselves, or
363 replaying in their head the dot displacements after the stimulus has ended. There was no time pressure

364 to answer; participants were encouraged to take as much time as they needed to make their
 365 judgments. The task began with an initial familiarization sequence of 48 movements to judge (half
 366 rightward and half leftward), then 24 blocks of 10 pseudo-randomized movements were gathered.
 367 There were short breaks between each block (about 1 min). Total duration of *Experiment 2* was about
 368 45 minutes.
 369



370
 371 **Figure 4. Mean speed as function of duration for each amplitude: theoretical determination of**
 372 **stimuli (Experiments 2 and 3).** For a given amplitude/duration pair, the associated mean speed is
 373 depicted (computed through the equation $S = A/D$, where S , A and D are respectively mean speed in
 374 meters per second, amplitude in meters and duration in seconds). Experiment 2: Four quadrants are
 375 determined by speed and duration values of the reference movement, from which orthogonal lines
 376 indicate respectively stimuli of Fixed Speed (FS2) and Fixed Duration (FD2) conditions. The answers are
 377 theoretically certain in quadrants 1 (shorter duration/higher speed) and 4 (longer duration/lower
 378 speed), and they are theoretically uncertain in the 2 (longer duration/higher speed) and 3 (shorter

379 *duration/lower speed). It could lead to uncertainty if the participants use the concept of vigour to judge.*
380 *In order to maximize the chances of testing the threshold of as many participants as possible and to*
381 *take into account the possibilities of a duration-based or a speed-based judgment, center of the*
382 *quadrants 2 and 3 for each amplitude curve was computed separately on the two axes (“Duration*
383 *center” and “Mean speed center”), resulting in the Fixed Vigour conditions (respectively Fixed Duration*
384 *Vigour (FDV) and Fixed Speed Vigour (FSV)). Here the vigour law averaged across participants was used.*
385 *Experiment 3: two representative individuals with high and low vigour (a and b respectively) are taken*
386 *as examples. Their reaching movements are depicted, from which their respective reference movement*
387 *and test movements in the 3 conditions (FS3, FD3 and FV3) were computed.*

388
389 *Data processing.* Data processing was performed using custom Matlab scripts, from the recorded
390 answers of the thirty participants (1 for “faster” answers and 0 for “slower” answers) and their
391 response times (seconds between the end of the stimulus and their answer). As the duplication of the
392 FV condition in FDV and FSV conditions did not impact the main results nor conclusion of the
393 experiment, statistical analyses were performed on the global FV condition (FDV and FSV data being
394 averaged). Proportion of “Faster” answers for each stimulus were computed for each participant.
395 Three affine fits were applied for each participant, one curve for each condition. Then, three affine fits
396 were applied for the whole sample (N = 30), one curve for each condition (on the 6 means of answers
397 of the 30 participants, i.e., on 180 points). The associated R^2 , value at 0.5 and slope of each curve were
398 gathered. Here, the value at 0.5 (50% of “faster” answers and 50% of “slower” answers) represents
399 the amplitude for which a movement with a given speed and duration appears neither faster nor
400 slower than the reference; in other words, the amplitude for which a movement with a given speed
401 and duration appears to be the same as the reference. The slope represents the uncertainty of the
402 judgment – the smaller the slope the higher the uncertainty. We could make the following predictions.
403 If participants were able to precisely identify the speed of an observed movement to judge its
404 quickness, results in the FS condition would have been close to 50% of “faster” answers regardless of

405 amplitude. Indeed, as in this condition test movements always have the same speed as the reference
406 movement, participants should always hesitate and answer “faster” and “slower” about half of the
407 time (because it was not possible to answer “the same”). Nonetheless, if participants based their
408 judgment on the duration of an observed movement, results in the FD condition would have been
409 close to 50% of “faster” answers regardless of amplitude (test movements always having the same
410 duration as the reference movement). However, we hypothesized that this uncertainty (systematically
411 close to 50% of “faster” answers) would be observed more strongly in the FV condition than in the two
412 others because this condition implements the changes of speed and duration that are expected from
413 action for changes of amplitudes.

414 It should be noted that although a sigmoidal fit initially appeared to be appropriate (especially for the
415 FS and FD conditions), the linear fit was finally chosen because of its superior robustness in the FV
416 condition (sigmoidal fit of the FV condition: $mean R^2 = .575 \pm .357$; $R^2 range =$
417 $[.000; .982]$; linear fit of the FV condition: $mean R^2 = .634 \pm .294$; $R^2 range = [.042; .947]$).

418 Data normality and sphericity were verified before each statistical analysis (respectively Shapiro-Wilk
419 and Mauchly tests, significance thresholds set at $< .05$). If the data distribution was not normal, non-
420 parametric analyses were performed and if sphericity was violated, a correction was applied. Here,
421 slopes did not follow a normal distribution. Friedman test and Conover’s post-hoc comparisons
422 (Bonferroni correction) were thus performed on the slopes of all participants for the three conditions.
423 Absolute deviation of answers from 0.5 was also computed for each participant for each stimulus.
424 Those deviation scores were averaged for each condition (10 deviation scores or 20 for FV), resulting
425 in three deviation scores (between 0 and 0.5) per participant. Those data followed a normal
426 distribution but their sphericity was violated. Repeated measures ANOVA with Greenhouse-Geisser
427 correction and post-hoc analyses (Bonferroni correction) were then performed. Means of the ten
428 response times for each stimulus were also computed for each participant. The grand mean was
429 computed for each participant on all their response times, and percentage of deviation from this grand
430 mean were computed for each stimulus. Those percentage of deviation from mean response time

431 were averaged for each condition (10 percentages or 20 for FV), resulting in three percentages per
432 participant. Those data followed a normal distribution and their sphericity was not violated, so
433 repeated measures ANOVA and post-hoc analyses (Bonferroni correction) were performed.

434

435 **Results and discussion**

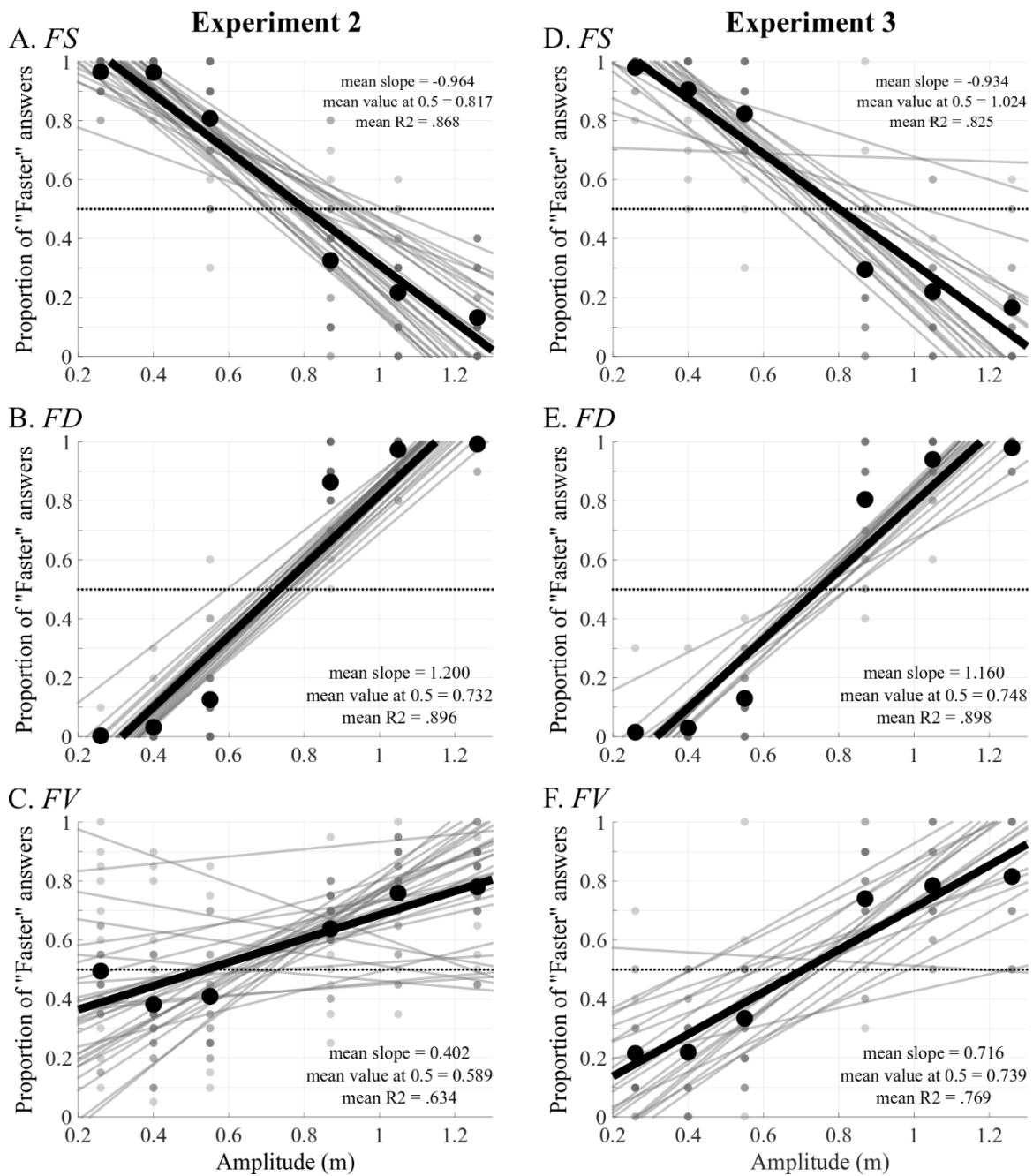
436 Results showed that when test movements had the same speed as the reference movement (FS
437 condition), participants judged them faster for smaller amplitudes (corresponding to shorter
438 durations) and slower for larger amplitudes (corresponding to longer durations; Fig. 5A). This suggests
439 that participants could base their judgment on movement duration. However, the exact reverse trend
440 was observed when test movements had the same duration as the reference movement (FD
441 condition). Participants judged test movements slower for smaller amplitudes (corresponding to lower
442 speeds) and faster for larger amplitudes (corresponding to higher speeds; Fig. 5B). Taken together,
443 those two conclusions suggest that participants do not always base their judgment only on movement
444 speed nor only on movement duration, but are able to use the relevant cue depending on the
445 condition. In contrast, when the vigour law was directly implemented in the stimuli (FV condition),
446 results showed that participants were significantly more uncertain and tended to judge the test
447 movements as neither faster nor slower than the reference regardless of amplitude. In this condition,
448 test movements had always different speeds and durations than the reference (Fig. 5C). This suggests
449 that participants could base their judgment on the vigour law. As expected, results of the Friedman
450 test showed a significant effect of condition on the slopes ($\chi^2(2) = 60.000, p < .001, W = 1.000$).
451 Conover's post-hoc comparisons showed that slopes in the FS and FD conditions are significantly
452 different from slopes in the FV condition ($p_{bonf} < .001$ for both). Surprisingly, they are also different
453 from one another ($p_{bonf} < .001$). Furthermore, the repeated measures ANOVA (with Greenhouse-
454 Geisser correction) on the deviation scores from 0.5 was significant ($F(1.269,36.808) = 62.966, p < .001,$
455 $\eta^2 = .685$). The results of the post-hoc analysis showed that FS and FD conditions were significantly
456 different from FV condition ($p_{bonf} < .001$ for both). Surprisingly, FS and FD were also significantly

457 different ($p_{bonf} < .001$; Fig. 6A). Response time is another indicator – the higher the response time the
458 higher the uncertainty – that seems to corroborate these results. As expected, the repeated measures
459 ANOVA on the percentage of deviation from mean response time was significant ($F(2,58) = 39.079$, p
460 $< .001$, $\eta^2 = .574$). The results of the post-hoc analysis showed that FS and FD conditions were
461 significantly different from FV condition (respectively $p_{bonf} < .05$ and $p_{bonf} < .001$). Once again FS and FD
462 were significantly different ($p_{bonf} < .001$; Fig. 6C). Participants took globally less time to answer in the
463 FS and FD conditions than in the FV condition, which suggests a harder judgment when the test
464 movements were closer to the reference movement. Overall, these findings suggest that the judgment
465 of movement quickness is not simply based on global thresholds on physical quantities such as speed
466 or duration but rather on an analog of the vigour law.

467 While participants hesitated more in the FV condition, we wondered whether they would have
468 hesitated even more if the stimuli were generated from their own vigour in similar movements. The
469 goal was to test differently the nature of the direct matching and confirm whether the motor
470 representations used in this judgment task appear to be more population-based than individual-based.

471 Previous work indeed showed that perception of duration or speed of movement of others can be
472 influenced by body states and by current or recent experience of motion (Chandrasekharan et al.,
473 2012; Hamilton et al., 2004; Jacobs & Shiffrar, 2005). Furthermore, in the study of Knoblich and Prinz
474 (2001) participants were able to recognize their own drawing movements among different movements
475 patterns. We thus conducted *Experiment 3*.

476



477

478 **Figure 5. Proportion of “Faster” answers as function of stimulus amplitude and condition (all**

479 **participants of Experiments 2 and 3). Each subplot stands for one condition of one experiment. For**

480 **visualization purpose, the 0.5 proportion lines were displayed. Gray points represent the proportion of**

481 **“faster” answers given by each participant for each stimulus amplitude. Affine fits were applied for**

482 **each participant separately (gray curves). The black points represent the mean proportion of “faster”**

483 **answers averaged across all participants for each amplitude. An affine fit was then applied in each**

484 **subplot. Mean slope, mean value at 0.5 and mean R^2 across the sample are depicted for each subplot.**

485 Experiment 2: A: Fixed Speed (FS). B: Fixed Duration (FD). C: Fixed Duration Vigour (FV). Experiment 3:
486 D: Fixed Speed (FS). E: Fixed Duration (FD). F: Fixed Duration Vigour (FV).

487

488 **Experiment 3**

489

490 The goal of this last experiment was to assess whether the judgment of movement quickness was more
491 “individual-based” or “population-based”. Indeed, the perception of movement quickness could refer
492 to the vigour law of the participant in action instead of a generic vigour law derived from the statistics
493 of the population. In this experiment, and differently from the previous experiment, the stimuli
494 (reference and test movements) were thus adapted to each participant, i.e., based on their measured
495 vigour law in action.

496

497 ***Materials and method***

498 *Participants.* Based on previous similar studies that chose sample sizes ranging from 3 to 21
499 participants (Chandrasekharan et al., 2012; Grosjean et al., 2007; Viviani & Stucchi, 1992; Wong et al.,
500 2013), twenty young adults with no known neuromuscular disease and with normal or corrected-to-
501 normal vision participated in the experiment (10 females, 24.4 ± 4.7 years old; mean \pm SD values).

502 *Experimental design and materials.* Inclusion criteria were the same as in *Experiment 2*. In this
503 experiment, all participants (N = 20) met the criteria so they were all included. Reaching movements
504 were assessed following the protocol described in previous articles (Berret et al., 2018; Labaune et al.,
505 2020). Also following the same data processing than in Labaune et al. (2020), mean speed and duration
506 of each reaching movement were gathered and then clustered and averaged by amplitudes. Affine fits
507 were applied on the ten averaged mean speeds as function of the averaged durations of movement.
508 Standard linear regressions were used because they performed well on the data. Associated linear
509 equations were gathered, representing the vigour law of each participant (example of two
510 representative participants Fig. 4). The characteristics (mean speed and duration) of the reference

511 movement (0.7 m) and of the six test movements of the *Fixed Vigour* condition (FV; 0.26 m, 0.40 m,
512 0.55 m, 0.87 m, 1.05 and 1.26 m) were computed directly from the vigour law of the participant. They
513 were then implemented in the custom Matlab scripts used to run the “perception” part of the
514 experiment. Mean speed and duration of the reference movement thus determined the characteristics
515 of the stimuli in the *Fixed Speed* (FS) and the *Fixed Duration* (FD) conditions. The participants sat at a
516 table in front of the same setup as described in *Experiment 2*. The experimental design was also similar,
517 the participants had to answer the question “*Compared to the reference, was the second movement*
518 *faster or slower?*” with the response box. There were 18 different stimuli (6 amplitudes tested in each
519 of the 3 conditions), each one being displayed 10 times during the experiment. Hence, the participants
520 had to judge 180 movements in total. The first half of the movements was presented rightward and
521 the other half leftward (or inversely, randomized across participants). The task began with an initial
522 familiarization sequence of 36 movements to judge (half rightward and half leftward), then 18 blocks
523 of 10 pseudo-randomized movements were gathered. There were short breaks between each block.
524 Total duration of *Experiment 3* was about 1h15. Participants were unaware that the stimuli were based
525 on their own reaching movements. When asked after the entire protocol was completed, none of them
526 had guessed.

527 *Data processing.* Data processing was the same as in *Experiment 2*. Sphericity was never violated. None
528 of the data followed a normal distribution, so non-parametric statistical analyses were performed.
529 Mann-Whitney tests were then performed on the slopes in the FS, FD and FV conditions of *Experiment*
530 *2* and *Experiment 3* (not normally distributed) to compare the uncertainty of the judgment in each
531 condition across the two experiments (“population-based” versus “individual-based”). A Bayesian
532 correlation was also performed.

533

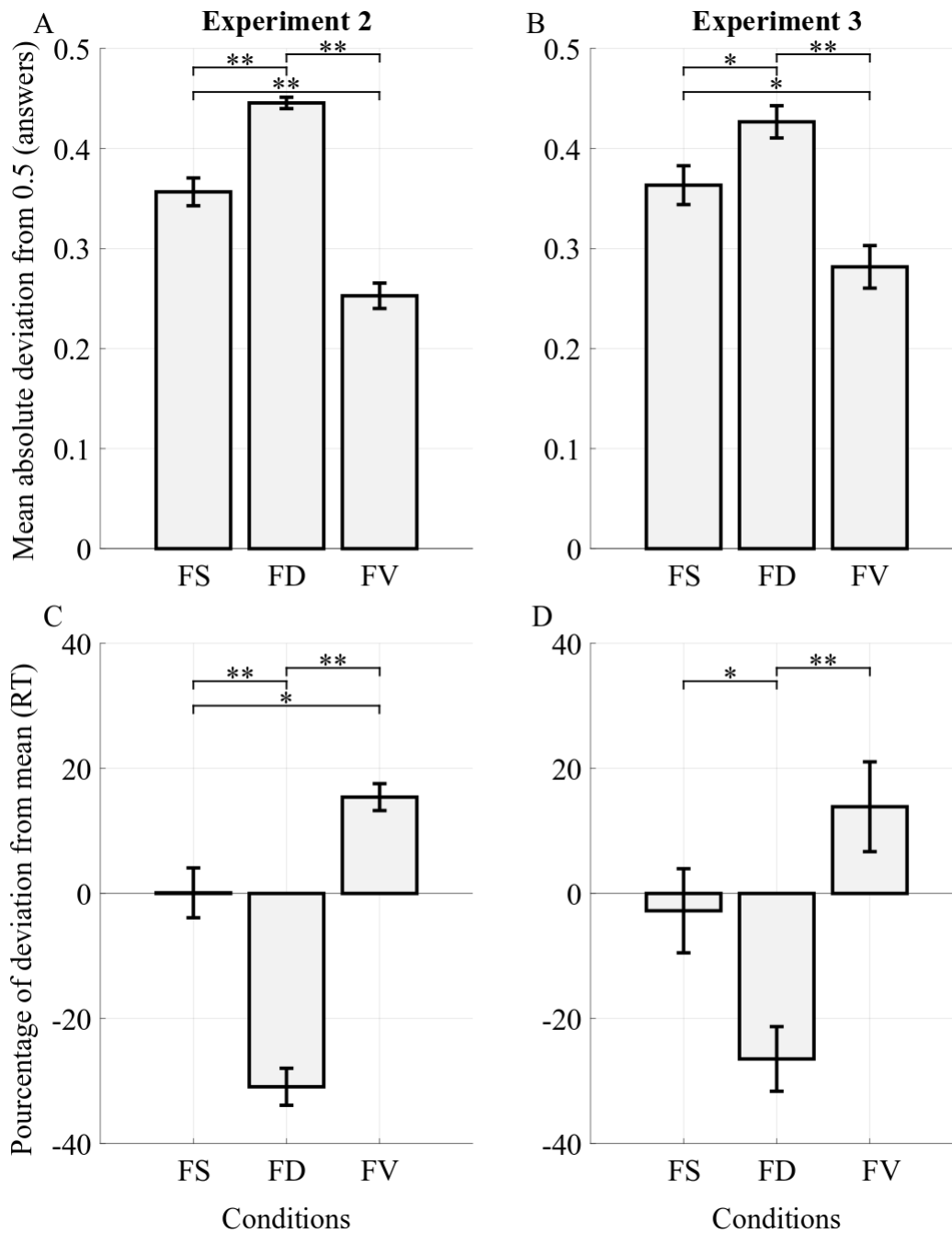
534 ***Results and discussion***

535 Results in the FS and FD conditions were the same as in *Experiment 2* (respectively Fig. 5D and 5E).

536 Results in the FV condition were also similar, more uncertain than in the FS and FD conditions (Fig. 5F).

537 Once again as expected, results of the Friedman test showed a significant main effect of condition on
538 the slopes ($\chi^2(2) = 40.000, p < .001, W = 1.000$). Conover's post-hoc comparisons showed that slopes
539 in the FS and FD conditions are significantly different from slopes in the FV condition ($p_{bonf} < .01$), and
540 surprisingly they are still different from one another ($p_{bonf} < .001$). As expected, the Friedman test on
541 the deviation scores from 0.5 was significant ($\chi^2(2) = 29.641, p < .001, W = .741$). The Conover's post-
542 hoc comparisons showed that FS and FD conditions were significantly different from FV condition
543 (respectively $p_{bonf} < .05$ and $p_{bonf} < .001$). FS and FD were again significantly different ($p_{bonf} < .05$; Fig.
544 6B). The Friedman test showed a significant main effect of condition on the percentage of deviation
545 from mean response time ($\chi^2(2) = 18.900, p < .001, W = .472$). Conover's post-hoc comparisons showed
546 that FD condition was significantly different from FV condition ($p_{bonf} < .001$). No significant difference
547 was found between FS and FV ($p_{bonf} = .489$), but once again between FS and FD ($p_{bonf} < .05$; Fig. 6D).

548 Results of the Mann-Whitney tests between slopes in *Experiment 2* and *Experiment 3* in FS and FD
549 conditions were not significant (respectively $Mdn_{FS4} = -1.005$ and $Mdn_{FS5} = -1.103, W = 317, p = .744$
550 and $Mdn_{FD4} = 1.212$ and $Mdn_{FD5} = 1.210, W = 315, p = .774$; Fig. 5A/5D and 5B/5E). However, the Mann-
551 Whitney test in the FV condition showed that slopes in *Experiment 2* were significantly smaller (Mdn_{FV4}
552 = 0.403) than in *Experiment 3* ($Mdn_{FV5} = 0.774$), $W = 142, p < .01, r_{rb} = -.527$; Fig. 5C and 5F). An a
553 **posteriori power analysis** showed that $power = .850$. Given that a smaller slope denotes a greater
554 uncertainty, the population-based protocol induced greater uncertainty in judgment than the
555 individual-based protocol. The Bayesian analysis ($BF_{10} = 7.763$) confirm this result ($3 > BF_{10} > 10$; i.e.,
556 moderate effect), which reaffirms that the nature of the motor representations used in the direct
557 matching could be population-based.



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Figure 6. Deviation scores from 0.5 and percentage of deviation from mean response time (all participants of Experiments 2 and 3). The three conditions are represented in each subplot: Fixed Speed (FS), Fixed Duration (FD) and Fixed Vigour (FV). Bars show standard error arising from variability across participants. Significance thresholds: * $p < .05$; ** $p < .001$. Experiment 2: A: Mean absolute deviation of the answers from 0.5. B: Mean percentage of deviation from the mean responses time. Experiment 3: C: Mean absolute deviation of the answers from 0.5. D: Mean percentage of deviation from the mean responses time.

566

567 **General discussion**

568

569 Overall, two main conclusions can be drawn from this series of three experiments on the perception
570 of movement vigour. First, the vigour law underlying action also holds in perception in general. This
571 means that a specific combination of mean speed, duration and/or amplitude is considered by people
572 when judging the quickness of observed movements. Second, the vigour law in perception would be
573 population-based rather than individual-based, meaning that people seem to use an average vigour
574 law derived from the observation of others' actions. These results support the direct-matching
575 hypothesis and suggest that this matching would mainly activate motor representations related to the
576 population statistics for judging the vigour of someone else's movement. These contributions are
577 discussed in more details below.

578

579 *The vigour law underlies both action and perception of movement.*

580 *Experiments 1 to 3* consistently showed that judging the quickness of others' movements across
581 amplitude is not based only on duration nor only on speed but on a specific increase of these quantities
582 with respect to amplitude, according to the vigour law.

583 In *Experiment 1*, the vigour of performed movements of each participant and the vigour they judged
584 while observing others' movements were recorded separately. Results showed the existence of an
585 analog of the vigour law in the judgment task, as both the speed and duration of an observed
586 movement perceived as naturally paced increased with amplitude. This result holds both for the
587 average data of the samples studied and for nearly all participants individually. Importantly, if the
588 participants had used a global duration threshold to judge if a movement is slow or fast regardless of
589 its amplitude, then the duration of movements perceived as neither fast nor slow would have been
590 stable experimentally (and the associated speed would have increased across amplitudes).
591 Alternatively, if they had used a duration threshold for each amplitude (e.g., the average of stimuli

592 durations for each amplitude, which is equivalent to a global speed threshold here), then the speed
593 perceived as neither fast nor slow would have been stable (and the associated duration would have
594 increased). The concurrent increase of perceived duration and of perceived speed across amplitudes
595 rules out the hypothesis of a judgment based on a global threshold strategy for duration or speed. In
596 other words, in *Experiment 1*, how amplitude influenced the judgment reflected the vigour law in
597 perception. To verify that this finding was not induced by the experimental design itself, we used a
598 different paradigm in *Experiments 2* and *3*. The idea was that movements following the vigour law
599 should be perceived as having equivalent quickness, regardless of the amplitude. We indeed found
600 that participants were more uncertain in the fixed-vigour condition than in the other conditions (fixed
601 duration and fixed speed). In other words, in *Experiments 2* and *3* the condition in which amplitude
602 influenced judgment the less reflected the vigour law in perception. These results corroborate the fact
603 that the judgment is not based on a simple threshold strategy on either duration or speed, and again
604 corroborate the influence of the vigour law on such judgments. This supports the direct-matching
605 hypothesis and extends the results of studies as Viviani and Stucchi (1992) and Grosjean et al. (2007),
606 which showed that kinematic laws (respectively the two-thirds power law and Fitts' law) drive
607 judgment, especially in an ambiguous situation.

608 In ambiguous situations, people may use heuristics – i.e., “a strategy that ignores part of the
609 information, with the goal of making decisions more quickly, frugally, and/or accurately than more
610 complex methods” (Gigerenzer & Gaissmaier, 2011) – or similar process to judge or make a decision.
611 The work of Bhatia (2017) suggests that in a situation where only one answer corresponding to a
612 heuristic is available, the participants easily respond in accordance with that heuristic. Here, it could
613 correspond to the two “obvious” conditions, *Fixed Speed* and *Fixed Duration*. For example, it seemed
614 obvious to the participants that a movement larger and longer than the reference was slower – even
615 if the average speed was the same (which corresponds to one heuristic, only one shortcut based on
616 duration and amplitude available). However, when multiple answers corresponding to heuristics are
617 available (shortcuts based on speed, duration, amplitude or combinations of these parameters), the

618 conflict created generates less automatic, more thoughtful answers. This corresponds to the hard-to-
619 judge condition, *Fixed Vigour*. This explanation is consistent with the longer response time in this
620 condition.

621 Interestingly, this first result – existence of an analog of the vigour law in perception – add to the
622 conclusions of researchers that already studied separately the perception of duration, speed or
623 amplitude of movements. Casasanto and Boroditsky (2008) studied the perception of duration and
624 amplitude, and how one affected the other. Participants were shown displacements of growing lines
625 or of a dot varying through 9 amplitudes and 9 durations, and had to replicate either the perceived
626 amplitude (by clicking at two locations accordingly distant) or the perceived duration (by clicking two
627 times accordingly delayed) after each trial. Results showed that they were biased by the amplitude of
628 a displacement to replicate their duration (under-estimation of duration of stimuli for small amplitudes
629 and over-estimation for large amplitudes), but the converse was not found.

630 Beside this main result, two unexpected results were obtained. Results of *Experiments 2* and *3* showed
631 an unexpected but robust significant difference between the *Fixed Speed* and the *Fixed Duration*
632 conditions. Early, McKee (1981) studied the construction of a judgment framework separately for
633 speed and duration. In her study, a short vertical line was displayed on an oscilloscope, moving with 7
634 different mean speeds. The amplitude of the oscilloscope screen displaying the line was increased
635 proportionally with the increasing of mean speed so that mean duration remained constant.
636 Participants were asked to judge whether the speed of each trial was faster or slower than the mean
637 speed of all stimuli (without any standard stimulus ever being displayed). The same protocol was used
638 to study duration perception, with stationary lines being displayed with 7 different durations.
639 Interestingly, results showed that it was easier to distinguish differences in speed (i.e., corresponding
640 to the *Fixed Duration* condition here) than in duration (i.e., corresponding to the *Fixed Speed* condition
641 here). Her results are thus consistent with the difference we observed between the *Fixed Speed* and
642 the *Fixed Duration* conditions.

643 Results of *Experiment 3* also unexpectedly showed that there was no difference in response time
644 between the *Fixed Speed* and the *Fixed Vigour* conditions. When participants are asked to judge the
645 quickness of a movement, their response can be based on either the speed or the duration of the
646 stimulus depending on their interpretation. It can thus be hypothesized that certain results of the
647 present study may have been influenced by the instructions given to participants (*"Compared to the*
648 *reference, was the second movement faster or slower?"*). It is important to note that in the French
649 language there is some ambiguity in the words "fast" and "slow". Indeed, they could refer to the speed
650 of the movement (it was fast if the speed was high, and slow if it was low) as well as they could refer
651 to their duration (it was fast if the duration was short, and slow if it was long). It was decided to take
652 advantage of this French polysemy to maintain this ambiguity and leave the participants free to choose
653 to judge on whether the speed or the duration of the movement they were shown. However, despite
654 the polysemy and even if the experimenter deliberately did not use the words "speed" or "duration"
655 in order to avoid a response orientation, the words "fast" and "slow" remain more connoted with the
656 notion of speed than with that of time. These elements could explain the absence of statistical
657 difference between response time in the *Fixed Speed* and the *Fixed Vigour* conditions in *Experiment 3*.
658 Other instructions could be considered for further studies.

659 More globally on the fact that vigour law underlies both action and perception of movement, other
660 studies investigated similar relationships between duration and amplitude of movement through other
661 practice modalities. Beaudoin et al. (2020) tested participants performing a motor imagery task of
662 walking in virtual reality. Results showed that the duration reported for the imagined movement
663 increased with the amplitude, but no information was given about the mean speed nor on the lengths
664 of the amplitudes, which makes impossible to study the vigour law per se. In the same vein, Decety et
665 al. (1989) tested the same participants on actual walking and on a motor imagery task of walking. In
666 both tasks, the duration (and respectively imagined duration) increased with amplitude (5m, 10m and
667 15m) but again no information was given about the speed. Results obtained in these tasks provide a
668 perspective for studying vigour law during walking and in motor imagery.

669

670 *The judgment of others' vigour seems "population-based".*

671 Comparing the results of the *Fixed Vigour* condition in *Experiments 2* and *3*, it appeared that the
672 population-based reference (e.g., a statistical representation of the vigour of movements observed in
673 the population) seemed to be privileged over an individual-based reference (from the participant's
674 own sensorimotor system). Even if an analog of the vigour law in action was found in perception, the
675 fact that the participants' perceived vigour was never linked with their performed vigour suggests that
676 the expressions of the vigour law in action and perception could be different from each other for the
677 same individual. In other words, how vigorous an individual is when performing movements could be
678 unrelated to how vigorous he judges movements of others (or how vigorous he imagines himself
679 moving), which suggests that direct matching does not specifically rely on the own motor repertoire
680 of the individual but on a broader motor knowledge derived from social interactions. For the vigour
681 law, the direct matching likely activates higher-level representations of the vigour law (and its
682 associated kinematics) obtained from the observation of similar movements in the surrounding
683 environment. Studies showed that human time perception is linked with some mechanisms used in
684 motor control (Chandrasekharan et al., 2012; Grosjean et al., 2007; Wong et al., 2013; Young et al.,
685 2009a), but they linked perception to one's representation of biological motion and not necessarily to
686 one's own movements (Gavazzi et al., 2013; Lacquaniti et al., 2014).

687 A study of Beaudoin et al. (2020) may support this population-based reference result. They tested
688 participants performing a motor imagery task in virtual reality. Participants were asked to imagine
689 themselves walking down a hallway toward a chair placed at different distances from their starting
690 point (which was always the same). Results showed that the duration reported for the imagined
691 movement increased with the amplitude. Moreover, each participant successively embodied a
692 "young" and an "elderly" avatar (both present in the scene anyway, and with a random order of
693 embodiment). Results showed that for all amplitudes participants took longer to complete the motor
694 imagery task when embodying the older avatar than when embodying the younger avatar. Thus, it

695 appeared that the age of the embodied avatar had an impact on their reported vigour, reinforcing the
696 hypothesis of a link between the perception and some representation of biological movement, but not
697 necessarily one's own. Indeed, the movement duration of the same participants was modulated
698 according to the stereotypical social characteristics of the avatar they embodied. This phenomenon is
699 called the Proteus effect, and it indicates that an altered self-representation shapes an individual's
700 behavior accordingly (Yee & Bailenson, 2007). Interestingly, the Proteus effect appears to persist
701 briefly over time even after the embodiment stopped. Indeed, embodiment of elderly avatars slowed
702 the actual walking speed of participants afterwards (Reinhard et al., 2020).

703

704 **Conclusion and perspectives**

705

706 One of the main contributions of this study was to show that the vigour law found in action
707 systematically holds in perception, not only when averaged across the samples studied but also for
708 nearly all participants individually. The study of vigour in action was motivated by a better
709 understanding of human movement and pathological adaptation. The origin of the vigour law was
710 explained in motor control by the existence of a cost of time and cognitive processes related to the
711 temporal discounting of reward (Berret et al., 2018; Choi et al., 2014; Shadmehr, 2010; Shadmehr et
712 al., 2010). The results of the present paper showed that for a set of movements to be perceived as of
713 natural pace, the three fundamental parameters of mean speed, duration and amplitude must all
714 evolve in the same direction. When one of the three parameters is fixed while the other two are
715 changing, the judgment can switch from fast to slow or conversely. In that case, the set of movements
716 no longer follows the vigour law; if a given speed appears natural for a given amplitude/duration pair,
717 this same speed will appear slow for a larger/longer pair, and fast for a smaller/shorter pair.
718 Interestingly, the same phenomenon is observed when duration is the fixed parameter. Overall, it
719 seems that the vigour law is robust in both action and perception, and that the judgment of the vigour
720 of others is based on an external frame of reference, i.e., requiring a prior representation of the vigour

721 of others' movements (e.g., population-based). In the light of these results, it would be interesting to
722 further explore some of the research and application perspectives arising from each of the main
723 contributions detailed above.

724

725 First, together with the previous evidence, all these elements seem to corroborate the presence of the
726 vigour law in action, perception and possibly motor imagery, although through diverse expressions.
727 Thus, the vigour law could not be limited to action and could be considered as a more general principle,
728 valid across these multiple modalities (Gentsch et al., 2016). The vigour law could represent a
729 fundamental concept for understanding human decisions in physical and social interactions. This
730 knowledge could be usefully applied, for example, to human-robot interaction. In an industrial context,
731 this interaction could be optimized by implementing the vigour of an individual to the robot with which
732 he is working in a collaborative task. Thus, the robot would be perceived neither as too fast nor too
733 slow by the user, which could enhance the interaction just like it was shown with the two thirds power
734 law (Maurice et al., 2018).

735

736 Second, interesting in a clinical context, in Parkinson's disease (PD) patients' vigour in voluntary
737 movements is impaired (harder to initiate, fewer, slower and smaller movements; Mazzoni et al.,
738 2007). The basal ganglia are known to be the disrupted neural structure in PD. Since they are also the
739 neural area considered to be a common center for regulating the vigour of various limb movements,
740 it seems possible that they also regulate the perception of vigour. A study of Harrington et al. (1998)
741 reinforces this idea. They studied motor timing tasks (paced finger-tapping task) and time perception
742 tasks (judgment of the relative duration of two-tone pairs) performed by patients with PD and by age-
743 matched healthy controls. Their results showed that the PD group performances were altered in both
744 the action and the perception tasks compared to the control group. This view is also supported by an
745 fMRI study that showed the major involvement of the basal ganglia in formulating representations of
746 time during tasks involving the perception of the time interval between two tones (Rao et al., 2001).

747

748 Third, besides these potential applications, it must be noted that experimental choices were made in
749 the protocols presented in this paper. For example, it would be interesting to replace the dot used
750 here as stimulus by virtual characters performing the movements to judge. In keeping with the results
751 of Calvo-Merino et al. (2005), observing human characters rather than a moving dot could engage
752 more strongly the motor system in the brain and then be a more ecological experimental design.
753 Moreover, social attributes of virtual characters can easily be manipulated (e.g., age, gender, ethnic
754 origin). This could be exploited to strengthen the result of this paper about the population-based
755 judgment of vigour. If the reference of the judgment is indeed based on the population, then the
756 activation of a social stereotype implying a vigour component should influence the judgment of the
757 vigour of others (the same movement would be judged more or less vigorous depending on the
758 associated stereotypical representation of vigour). For example, as the age-related stereotype carries
759 the stereotypical view that elderly are slow, it would be interesting to test the influence of the age of
760 an avatar on the perception participants have of their vigour.

761 Future work could also try to exploit these results in a clinical perspective, e.g., with Parkinson's
762 patients. We can hypothesize that by being stimulated by an immersive virtual environment and by
763 the embodiment of a young virtual character (activation of the stereotype of high vigour associated
764 with youth via the Proteus effect), patients would be able to train and progress on the characteristics
765 of the production of their voluntary movements, and that the benefits could be maintained outside
766 the simulation at least temporarily (Reinhard et al., 2020).

767

768 **References**

769

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