

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 judgement 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 judgement was *population-based* (related to the average vigour of all participants) rather than *individual-based* (participant's own vigour).

Keywords

Movement vigour; perception-action; judgement; direct-matching hypothesis; vigour law

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Introduction

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

The mirror system, discovered three decades ago (Rizzolatti et al., 1996), allows us to postulate that the perception of movement vigour may be linked to the vigour of our actions. Indeed, this system has shown an activation of the same specific cortical networks when the same action is observed, imagined, or produced (Grafton et al., 1996; Noë, 2004; Rizzolatti & Craighero, 2004; Rizzolatti et al., 1996; Wilson & Knoblich, 2005). Since then, several studies have found a genuine interest to expand an interdisciplinary view claiming the systematic connection between perception, cognition, and motor control mechanisms

(Gentsch et al., 2016 for a review). Moreover, the motor system is more strongly engaged during action observation when participants already have a specific motor representation of the action they observed (see the Theory of Event Coding by Calvo-Merino et al., 2005; Casile & Giese, 2006; Hommel et al., 2001; Prinz, 1997; Schütz-Bosbach & Prinz, 2007). In this vein, the so-called direct-matching hypothesis holds that the kinematics of an observed movement is directly mapped onto the observer's internal motor representation of this action during its observation, so that the “motor knowledge” of the observer is used to understand the observed action (Iacoboni et al., 1999; Rizzolatti et al., 2001). This mechanism could thus be meaningful to enhance social and physical interaction with others and, in particular, to compare the speed of an observed movement to some knowledge of vigour in action.

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

The present work builds on these previous studies and aims to extend our knowledge on the involvement of motor or kinematic laws in judging the movements of others. In contrast to Fitts' law that focuses on the maximal speed of movement, our work focuses on the movement vigour (i.e., the preferred, self-chosen speed of movement). This notion has received a lot of attention recently and was shown to link decision-making and motor control (Carland et al., 2019; Dudman & Krakauer, 2016; Shadmehr & Ahmed, 2020; Shadmehr et al., 2019). In several studies, movement vigour was characterised empirically by the relationships between amplitude, speed, and duration of a set of goal-directed movements (Berret et al., 2018; Choi et al., 2014; Labaune et al., 2020; Reppert et al., 2018). Importantly, Young and colleagues showed that Fitts' law does not hold for natural-pace movements given that, for a constant ID, duration of movements linearly increases with amplitude (Young et al., 2009b). Remarkably, both the speed and duration of a self-paced movement tend to monotonically increase with its extent, which we refer here to as the *vigour law*. Indeed, this observation has been found to hold for all individuals and actions as varied as eye saccades, head movements, arm reaching, or walking a distance (Labane et al., 2020; Reppert et al., 2018). For instance, for self-paced arm reaching, duration D approximately increases with amplitude A according to the equation

$$D = \alpha A + \beta \quad (1)$$

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

$$S = \frac{A}{\alpha A + \beta} \quad (2)$$

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

Large but robust inter-individual differences of vigour were found and documented in several studies which compared the vigour of movements across participants, days, or effectors (Berret et al., 2018; Choi et al., 2014; Labaune et al., 2020; Reppert et al., 2018; Shadmehr et al., 2019). Moreover, it has been shown that high boredom proneness scores (assessed by questionnaires) were significantly and positively correlated with high vigour scores during reaching movements (Berret et al., 2018). Similar yet non-significant trends were obtained between impulsivity and reaching vigour (Berret et al., 2018), and between impulsivity and eye saccade vigour (Choi et al., 2014). Although these effects are small, these results are consistent with one of the main explanatory theories of the vigour law, namely that movement vigour depends not only on biomechanical factors but also on the individual's implicit motivation and the general brain tendency to temporally discount the reward associated with task accomplishment (Shadmehr et al., 2010). Indeed, the subjective value of a reward decreases over time, at different rates among individuals (Green et al., 1994; Myerson & Green, 1995). In goal-directed movements, the mere completion of the movement triggers the acquisition of the reward through the activation of dopaminergic systems. The time of movement thus delays the acquisition of the reward and leads to its subjective devaluation. According to this view, movement vigour would result from a trade-off between a cost of movement (e.g., physical effort) and a cost of time implementing this subjective reward discounting (Berret et al., 2018; Shadmehr et al., 2010). Vigour is therefore thought to be related to cognitive decision-making processes (Shadmehr et al., 2016) and to originate from cortico-basal ganglia circuits, as exemplified by the bradykinesia observed in Parkinson's patients (Mazzoni et al., 2007).

Besides being a critical feature of one's everyday movement, vigour is also critical for interacting with others. Indeed, many social behaviours require adapting the vigour of our movement to that of the other person, e.g., when we shake someone's hand or walk next to an elderly person. In these cases, successful physical or social interaction is subjected to the compliance with the other's vigour, which thus questions the perception of vigour. According to the direct-matching hypothesis, the vigour law described above should hold in perception. To the best of our knowledge, the vigour law has not been tested in perception

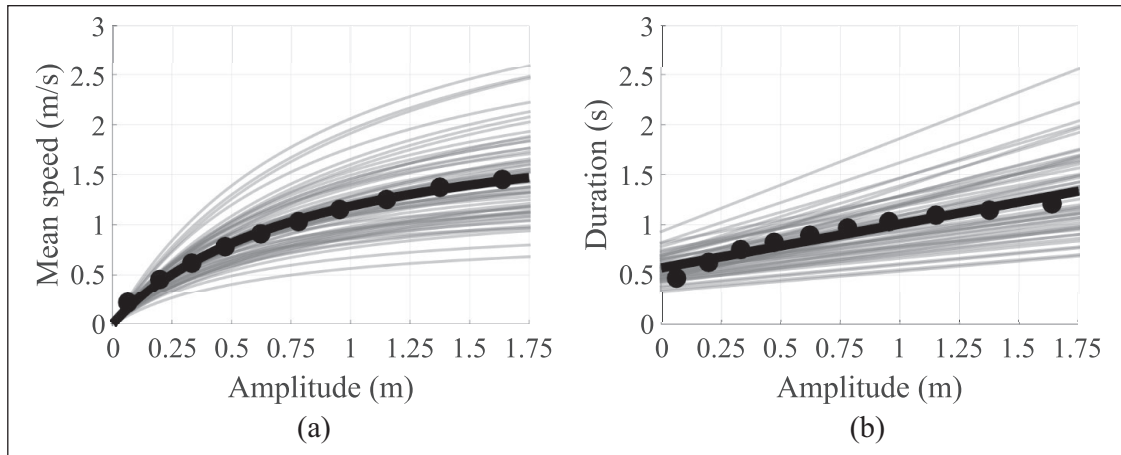


Figure 1. The vigour law for reaching movements. Data from two previous experiments were fitted to illustrate the vigour law for horizontal arm movements (rotation around the shoulder joint; Berret et al., 2018; Labaune et al., 2020). (a) Mean speed and (b) duration of reaching movements as function of stimulus amplitude. Mean speed was fitted according to Equation 2 and duration was fitted according to Equation 1 for each participant separately (grey curves; $N=58$). (a) The best-fitting parameters for mean speed were as follows: $\alpha = 0.509 \pm 0.176$; $\beta = 0.395 \pm 0.094$; mean $R^2 = .976 \pm .055$; R^2 range = [.579; .998]. (b) The best-fitting parameters for duration were as follows: $\alpha = 0.439 \pm 0.169$; $\beta = 0.569 \pm 0.122$; mean $R^2 = .904 \pm .042$; R^2 range = [.764; .986]. The black points represent the mean speed (or duration) averaged across all participants for each amplitude, and the same fitting was applied respectively. Another fitting function could have been applied on duration, as suggested by Young et al. (2009b). Indeed, they found that a combination of Fitts' law and a linear function of amplitude best fitted their duration data ($D = a + b \times \log_2((A/W) + 1) + c \times A$, with D the movement duration, A the amplitude, and W the width of the targets). However, we chose the linear fit because the linear component is highly predominant for movements performed at natural speed.

although the perception of time, speed, or distance has been studied in previous works (Casasanto & Boroditsky, 2008; Gavazzi et al., 2013; Hayashi & Ivry, 2020; Lacquaniti et al., 2014; McKee, 1981; Robbe, 2021). Furthermore, the inter-individual differences of vigour could be exploited to refine our understanding of the nature of the motor knowledge that could be activated in this context, i.e., individual-based or population-based (Liepelt et al., 2008). Indeed, while the direct-matching hypothesis has received strong empirical support using other motor laws, most of the previously mentioned studies relied on data averaged across participants (Chandrasekharan et al., 2012; Grosjean et al., 2007), thereby limiting the possible conclusions about the nature of the direct matching.

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

General materials and method

In the first experiment, we asked participants to judge whether biological point-to-point movements of a dot moving on a screen were considered as fast or not, while varying the dot's speed and amplitude on each trial. The

motion speed that was considered as neither fast nor slow by the participants for each amplitude was estimated, which allowed us to test the analog of the vigour law in perception. Comparisons with the observers' own vigour in action were also performed to assess whether the vigour of performed and observed movements could be directly linked. In *Experiments 2* and *3*, we used a dynamic visual illusion as Viviani and Stucchi (1992) did to investigate the link between the vigour in action and perception from a complementary approach. There, the vigour law was directly implemented in some of the stimuli to check whether it was harder to judge the speed of a movement complying with the vigour law. To probe if this judgement is rather population-based (referring to the statistics of movements observed around them as a reference, *Experiment 2*) or individual-based (referring to the participants' own sensorimotor system as a reference, *Experiment 3*), we implemented in each stimulus either the mean vigour law of the population (based on reaching movements data of the participants of previous studies) or the participant's own vigour law as measured in the same action during a companion experiment. All the stimuli were produced with Matlab using Psychtoolbox (Kleiner et al., 2007), and all statistical analyses were performed with JASP software. Power analyses were conducted with G*Power software when relevant to test the direct-matching hypothesis. All the experimental protocols were approved by the local Ethics Committee of Paris-Saclay University (CER-Paris-Saclay-2018-36-R). Written informed consent was

obtained from each participant in the studies as required by the Helsinki Declaration.

Experiment 1

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

Materials and method

Participants. Previous studies that were the foundation of the present work and used similar experimental designs chose sample sizes ranging from 10 to 21 participants (Chandrasekharan et al., 2012; Grosjean et al., 2007; Wong et al., 2013). To reinforce the power of our analyses, 30 young adults with no known neuromuscular disease and with normal or corrected-to-normal vision participated in this experiment (14 females, 28.5 ± 5.08 years old, $M \pm SD$ values).

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

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

where θ is the shoulder angular amplitude of the represented reaching movement of an individual having a 0.75-m-long arm. Using Equation 3, there were thus four amplitudes of movements (0.26, 0.55, 0.87, and 1.26 m) corresponding, respectively, to four angular amplitudes (20°, 40°, 60°, and 80°). Each amplitude was presented with 10 different mean speeds (ranging from 0.25 to 1.45 m/s), resulting in 40 different types of stimuli. Each stimulus was displayed 10 times during the experiment. Hence, the participants saw 400 individual point-to-point movements in total. At the end of each movement, the participants had to evaluate the quickness of the movement by answering the question "Was the movement fast or slow?" by pressing "V" on the keyboard for "Slow" or "T" for "Fast" with the index finger of their dominant hand. There

was no time pressure to answer. Once they had given their answer, the next movement was displayed. The first half of the movements was presented rightward and the other half leftward (or inversely, randomised across participants). Each half of the task began with an initial familiarisation sequence of 40 movements to judge; then, five blocks of 40 movements to judge were gathered. Each stimulus appeared once in each block, their order of appearance being randomised to prevent learning, habituation, or fatigue effects from affecting the results. There were short breaks between each block, as long as the participants needed (about 1 min).

To investigate the link between the vigour in perception and the vigour in action, participants were also evaluated on real arm reaching movements similar to those observed as described above. We used the protocol and material of previous articles to do so (Berret et al., 2018; Labaune et al., 2020). The total duration of the task (i.e., action plus perception, in a randomised order) was about 1 hr.

Data processing. Data processing was performed using custom Matlab scripts, from the recorded answers of the participants (1 for "fast" answers and 0 for "slow" answers). Proportion of "Fast" answers for each stimulus was computed for each participant. Four sigmoid curves were then fitted, one for each stimulus amplitude. Theoretical points were added at 0 for 0 m/s and 1 for 1.7 m/s and the function was initialised (minimum and maximum values set to 0 and 1, respectively) to improve fitting quality (Figure 2). The fitted function was of the form

$$f(x) = \frac{1}{1 + e^{\frac{PSE - x}{JND}}} \quad (4)$$

where *PSE* is the point of subjective equality and *JND* is the just noticeable difference. As exclusion 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), obvious to judge, had been, respectively, judged as slow and fast. It would otherwise have denoted a participant who misunderstood the task. Participants were therefore excluded from the statistical analyses if at least one of the two sigmoids fitted on their extreme stimuli was more than 10% (i.e., error on more than 1 trial) away from 1 and 0, respectively. In this experiment, all the participants ($N=30$) met the criteria, so none was excluded from statistical analyses.

The PSE (50% of "fast" answers and 50% of "slow" answers) of each curve was gathered (four per participant). Here, PSE represents the speed at which a movement of a given amplitude would appear neither fast nor slow to the participant, or in other words, the speed from which a movement of a given amplitude started to appear as fast (called "Perceived mean speed"). Durations of movements corresponding to these perceived mean speeds were

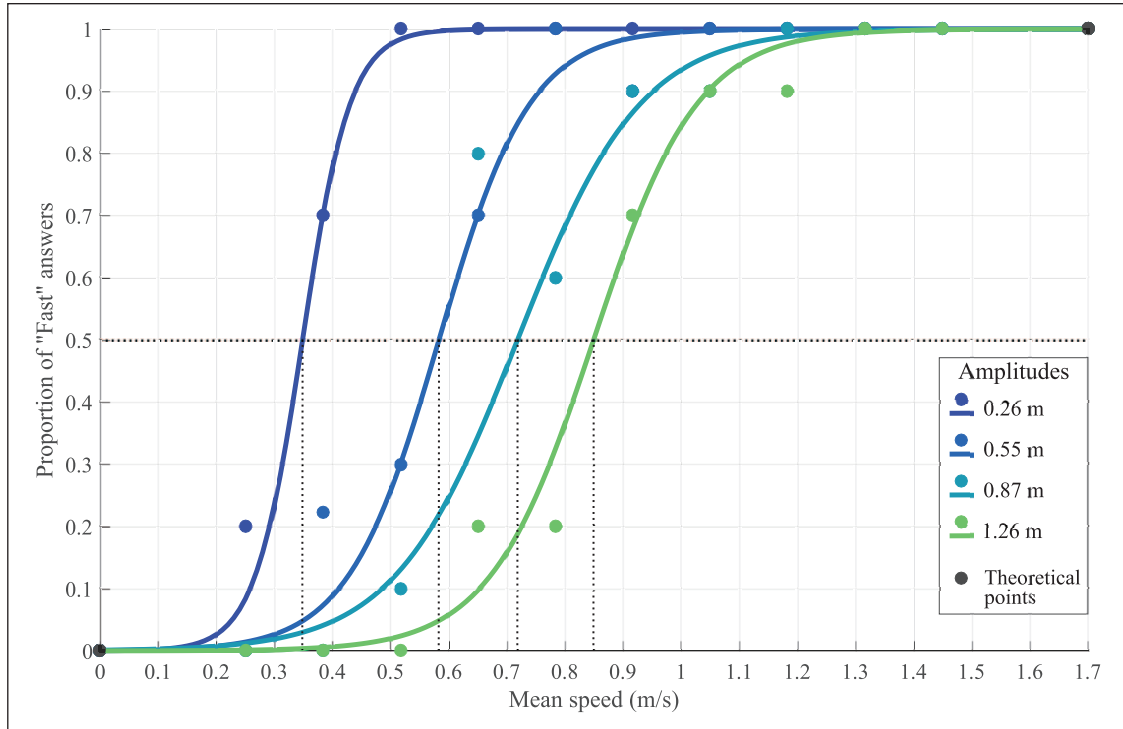


Figure 2. Proportion of “fast” answers as function of mean speed and amplitude (for a representative participant). Each curve stands for one amplitude of stimuli (0.26, 0.55, 0.87, and 1.26 m, corresponding, respectively, to four angular amplitudes of 20°, 40°, 60°, and 80°; see Equation 3). A sigmoid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

computed (duration = amplitude/PSE; called “Perceived duration”). Then, the four perceived mean speeds were fitted according to Equation 2 and the four perceived durations were fitted according to Equation 1 separately for each participant (with amplitude of regressor). Associated R^2 values and fitting parameters were gathered and averaged across participants. Following an approach similar to Choi et al. (2014), scores representing the perceived vigour were computed. To do so, z scores of the PSE for each amplitude were computed across participants, and then, the z scores of the four amplitudes were averaged for each participant. Data processing of reaching movement and the computation of their scores representing the performed vigour followed the same approach, which was already described in previous articles (on the performed mean speeds to be comparable with the perceived vigour scores; Berret et al., 2018; Labaune et al., 2020). Therefore, we could obtain two vigour scores per participant (perceived and performed, normalised as z scores and hence comparable). The mean speed of the performed movements was also fitted according to Equation 2, and the duration of the performed movements was also fitted according to Equation 1 separately for each participant. Data pairwise normality was verified (Shapiro–Wilk test, significance threshold set at $<.05$). In this experiment, the bivariate normality was met ($p > .05$); therefore, parametric analysis was chosen. Pearson’s linear correlation analysis was

conducted to investigate the relationship between scores of perceived and performed vigour. A Bayesian correlation was also performed.

Results and discussion

Results showed that the speed of movements perceived as neither fast nor slow (PSE) tended to increase with amplitude, not only when averaged over the sample but also for each individual. The wider the movement amplitude, the higher the speed perceived as neither fast nor slow (i.e., the higher the speed from which the movement appears fast). The best-fitting parameters were as follows: $\alpha = 0.871 \pm 0.175$; $\beta = 0.285 \pm 0.110$; mean $R^2 = .871 \pm .164$, R^2 range = [.342;.998], $Q1 = .800$ and $Q3 = .981$ (Figure 3a).

Results also showed that movements perceived as neither fast nor slow have durations that tended to increase linearly with amplitude, both on average over the sample and for each individual. The wider the movement amplitude, the longer the duration of the movement that has been perceived as neither fast nor slow (i.e., the longer the duration from which the movement appears fast). The best-fitting parameters were as follows: $\alpha = 0.872 \pm 0.183$; $\beta = 0.286 \pm 0.110$; mean $R^2 = .984 \pm .019$; R^2 range = [.906;.999] (Figure 3b). Taken together, the results on perceived speed and perceived duration suggest

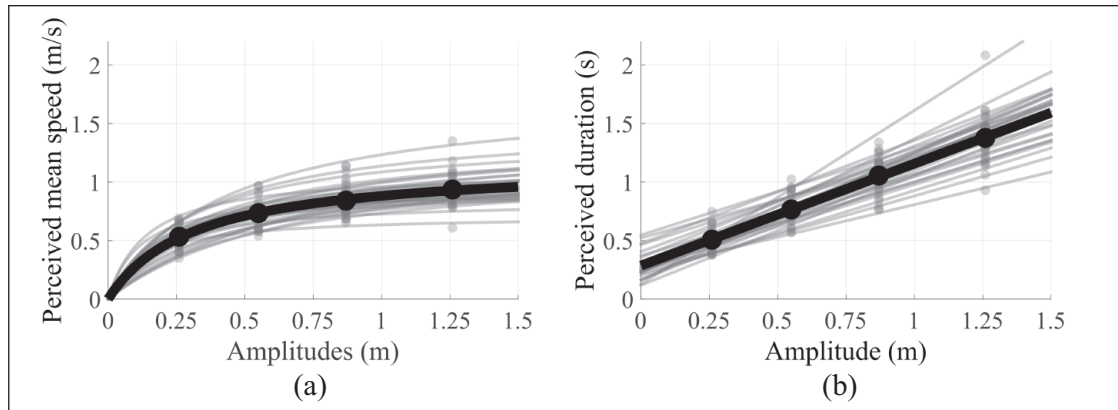


Figure 3. Perceived mean speed and perceived duration as function of stimulus amplitude. In each subplot, each grey curve stands for one participant ($N=30$). Grey points represent the four mean speeds (PSE) or associated durations (amplitude/PSE) perceived by each participant for each stimulus amplitude. Mean speed was fitted according to Equation 2 and duration was fitted according to Equation 1 for each participant separately (grey curves). The black points represent the mean speed (or duration) averaged across all participants for each amplitude, and the same fitting was applied, respectively. (a) Perceived mean speed (i.e., perceived as neither too slow nor too fast). (b) Perceived duration (i.e., perceived as neither too short nor too long).

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

The vigour law thus seems to rule the perception of movement pace in agreement with the direct-matching hypothesis. However, the lack of relationship between the vigour scores of individuals in action and perception, which suggests that the judgement of the vigour of others is not individual-based, prompted us to verify that this was not a basic outcome of the chosen experimental design. We therefore considered an alternative experimental design in which the vigour law was exploited to create a potential uncertainty when it comes to judge whether a movement is fast or slow. Indeed, movements complying with the

vigour law correspond to the preferred pace in action; therefore, they should be considered as neither fast nor slow in perception if the same law holds. Depending on whether the implemented law is derived from the individual or from the population, one could refine the nature of the direct matching.

Experiment 2

In the previous experiment, the issue of the perception of movement quickness has been addressed and the vigour law underlying action has been found to hold in perception. However, we were not able to establish a link between the participant's own vigour in action and in perception perhaps due to our specific experimental design. The goal of *Experiment 2* was to test differently the existence of a link between the vigour in action and perception by designing an experiment in which stimuli were directly taken from the vigour law of real reaching movements. To do so, we modified the experimental paradigm by using a dynamic visual illusion in keeping with Viviani and Stucchi (1992). The participants were now provided with a first stimulus (still a dot moving horizontally for a given amplitude and with a certain speed), and they had to judge whether a second stimulus, of a different amplitude, was faster or slower than the first one they saw. The duration or speed of the second stimulus could change according to the vigour law or to alternative rules (e.g., fixed duration or fixed speed). Our premise here was that if the vigour law defines what is a neither too slow nor too fast movement as a function of amplitude, participants should be more uncertain when judging stimuli that follow the vigour law rather than when they do not. As a corollary, this experiment is also useful to test the individual- versus

population-based alternatives depending on the specific vigour law that is implemented (taken from the individual or the average of the population).

Materials and method

Participants. Based on previous similar studies that chose sample sizes ranging from 3 to 21 participants (Chandrasekharan et al., 2012; Grosjean et al., 2007; Viviani & Stucchi, 1992; Wong et al., 2013) and to reinforce the power of our analyses, 30 young adults with no known neuromuscular disease and with normal or corrected-to-normal vision participated in the experiment (15 females, 22.3 ± 3.1 years old, $M \pm SD$ values).

Experimental design and materials. The participants sat at a table in front of the same setup as in the experiments described above. Each trial began with a reference movement being displayed, followed by a test movement to judge. Therefore, the participants always saw two displacements of the dot in a row, and they had to answer the question “Compared to the reference, was the second movement faster or slower?” by means of two buttons of the response box (one button for “faster” and another for “slower”) on the table. Once they answered, the next trial was displayed. The reference movement was maintained constant throughout the experiment. Its characteristics were $A=0.7$ m, $D=0.9$ s, and $S=0.78$ m/s, based on the mean duration of 50° wide reaching movements data of the population of previous studies (Berret et al., 2018; Labaune et al., 2020). As inclusion criteria, it was verified that four extreme stimuli arbitrarily chosen were correctly estimated compared with the reference movement (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, 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 misunderstood the task. All participants ($N=30$) met the criteria so they were all included. To be as accurate as possible in the data analysis (linear fitting), we added two intermediary test amplitudes compared with the previous protocols (6 points instead of 4). Test movements thus varied across six amplitudes around the reference amplitude (0.26, 0.40, 0.55, 0.87, 1.05, and 1.26 m, corresponding to six angular amplitudes of 20° , 30° , 40° , 60° , 70° , and 80° ; see Equation 3) and four conditions: (1) test movements always had the same mean speed as the reference movement (*Fixed Speed*, denoted by FS); therefore, durations of movement varied from 0.34 s for 0.26 m to 1.61 s for 1.26 m; (2) test movements always had the same duration as the reference movement (*Fixed Duration*, denoted by FD); therefore, mean speeds of movement varied from 0.29 to 1.40 m/s; and (3 and 4) test movements had different durations and mean speeds from the reference movement but followed the vigour law (i.e., speed and duration both increase with amplitude according to the

relationships found in action for a population of participants; *Fixed Vigour*, denoted by FV). This condition was duplicated with *Fixed Duration Vigour* (denoted by FDV) and *Fixed Speed Vigour* (denoted by FSV) to cover as many possibilities of judgement as possible and have more data points to capture potential hesitations (duration-based or a speed-based; see explanations in Figure 4). In FDV, durations and speeds varied from 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 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 were 24 different stimuli (six amplitudes tested in each of the four conditions, FS, FD, FDV, and FSV). Each stimulus was displayed 10 times during the experiment. Hence, the participants had to judge 240 movements in total. The first half of the movements was presented rightward and the other half leftward (or inversely, randomised across participants). Participants were told that there was no right or wrong answer, but that only the general impression that the test movement had left them in relation to the movement of reference should be taken into account. They were given some examples of facilitating strategies that they were free to use to judge, such as imagining that someone actually performs reaching movements in front of them, imagining that they perform them themselves, or replaying in their head the dot displacements after the stimulus has ended. There was no time pressure to answer; participants were encouraged to take as much time as they needed to make their judgements. The task began with an initial familiarisation sequence of 48 movements to judge (half rightward and half leftward), and then, 24 blocks of 10 pseudo-randomised movements were gathered. There were short breaks between each block (about 1 min). Total duration of *Experiment 2* was about 45 min.

Data processing. Data processing was performed using custom Matlab scripts, from the recorded answers of the 30 participants (1 for “faster” answers and 0 for “slower” answers) and their response times (seconds between the end of the stimulus and their answer). As the duplication of the FV condition in FDV and FSV conditions did not affect the main results or conclusion of the experiment, statistical analyses were performed on the global FV condition (FDV and FSV data being averaged). Proportion of “Faster” answers for each stimulus was computed for each participant. Three affine fits were applied for each participant, one curve for each condition. Then, three affine fits were applied for the whole sample ($N=30$), one curve for each condition (on the six means of answers of the 30 participants, i.e., on 180 points). The associated R^2 , value at 0.5, and slope of each curve were gathered. Here, the value at 0.5 (50% of “faster” answers and 50% of “slower” answers) represents the amplitude for which a movement with a given speed and duration appears neither faster nor slower than the reference; in other words, the amplitude

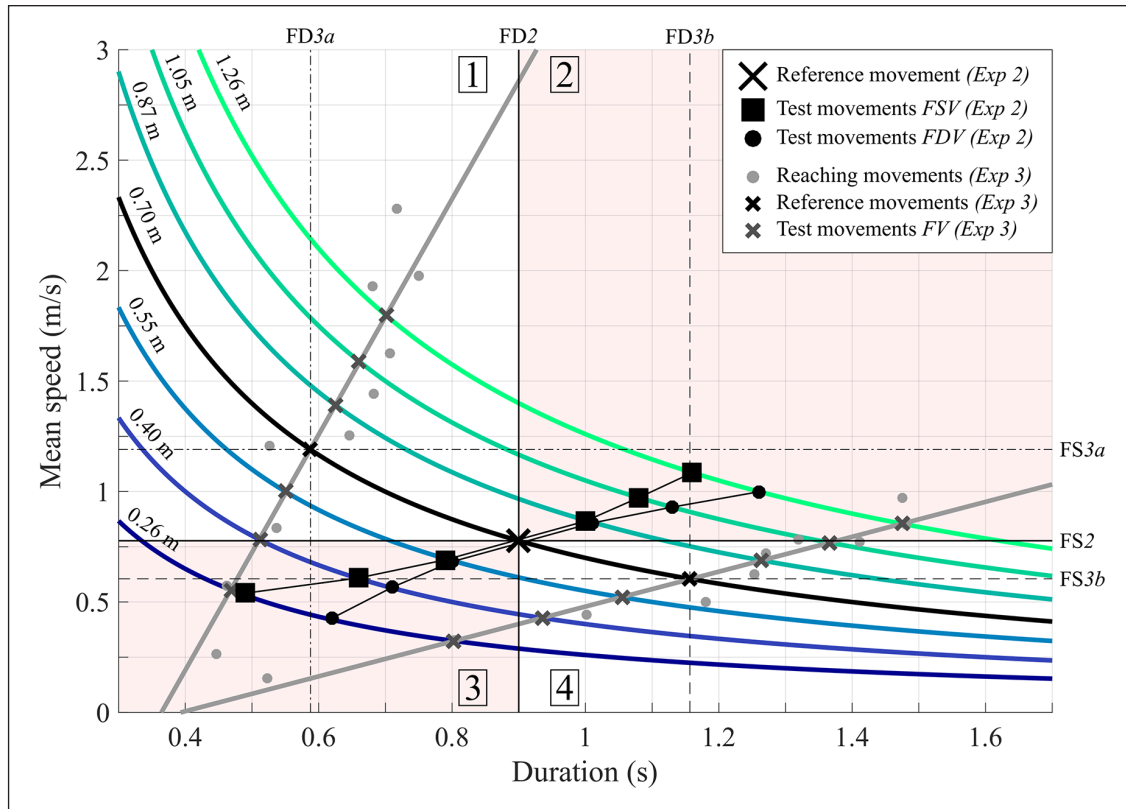


Figure 4. Mean speed as function of duration for each amplitude: theoretical determination of stimuli (Experiments 2 and 3). For a given amplitude/duration pair, the associated mean speed is depicted (computed through the equation $S=A/D$, where S , A , and D are, respectively, mean speed in metres per second, amplitude in metres, and duration in seconds). Experiment 2: Four quadrants are determined by speed and duration values of the reference movement, from which orthogonal lines indicate, respectively, stimuli of Fixed Speed (FS2) and Fixed Duration (FD2) conditions. The answers are theoretically certain in quadrants 1 (shorter duration/higher speed) and 4 (longer duration/lower speed), and they are theoretically uncertain in the 2 (longer duration/higher speed) and 3 (shorter duration/lower speed). It could lead to uncertainty if the participants use the concept of vigour to judge. To maximise the chances of testing the threshold of as many participants as possible and to take into account the possibilities of a duration-based or a speed-based judgement, centre of the quadrants 2 and 3 for each amplitude curve was computed separately on the two axes (“Duration centre” and “Mean speed centre”), resulting in the Fixed Vigour conditions (respectively, Fixed Duration Vigour [FDV] and Fixed Speed Vigour [FSV]). Here, the vigour law averaged across participants was used. Experiment 3: two representative individuals with high and low vigour (a and b, respectively) are taken as examples. Their reaching movements are depicted, from which their respective reference movement and test movements in the three conditions (FS3, FD3, and FV3) were computed.

for which a movement with a given speed and duration appears to be the same as the reference. The slope represents the uncertainty of the judgement—the smaller the slope, the higher the uncertainty. We could make the following predictions. If participants were able to precisely identify the speed of an observed movement to judge its quickness, results in the FS condition would have been close to 50% of “faster” answers, regardless of amplitude. Indeed, as in this condition, test movements always have the same speed as the reference movement, participants should always hesitate and answer “faster” and “slower” about half of the time (because it was not possible to answer “the same”). Nonetheless, if participants based their judgement on the duration of an observed movement, results in the FD condition would have been close to 50% of “faster” answers, regardless of amplitude (test

movements always having the same duration as the reference movement). However, we hypothesised that this uncertainty (systematically close to 50% of “faster” answers) would be observed more strongly in the FV condition than in the two others because this condition implements the changes of speed and duration that are expected from action for changes of amplitudes.

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

Data normality and sphericity were verified before each statistical analysis (respectively, Shapiro–Wilk and

Mauchly tests, significance thresholds set at $<.05$). If the data distribution was not normal, non-parametric analyses were performed, and if sphericity was violated, a correction was applied. Here, slopes did not follow a normal distribution. Friedman test and Conover's post hoc comparisons (Bonferroni correction) were thus performed on the slopes of all participants for the three conditions. Absolute deviation of answers from 0.5 was also computed for each participant for each stimulus. Those deviation scores were averaged for each condition (10 deviation scores or 20 for FV), resulting in three deviation scores (between 0 and 0.5) per participant. Those data followed a normal distribution but their sphericity was violated. Repeated-measures analysis of variance (ANOVA) with Greenhouse–Geisser correction and post hoc analyses (Bonferroni correction) were then performed. Means of the 10 response times for each stimulus were also computed for each participant. The grand mean was computed for each participant on all their response times, and percentage of deviation from this grand mean was computed for each stimulus. The percentage of deviation from mean response time was averaged for each condition (10 percentages or 20 for FV), resulting in three percentages per participant. Those data followed a normal distribution and their sphericity was not violated, so repeated-measures ANOVA and post hoc analyses (Bonferroni correction) were performed.

Results and discussion

Results showed that when test movements had the same speed as the reference movement (FS condition), participants judged them faster for smaller amplitudes (corresponding to shorter durations) and slower for larger amplitudes (corresponding to longer durations; Figure 5a). This suggests that participants could base their judgement on movement duration. However, the exact reverse trend was observed when test movements had the same duration as the reference movement (FD condition). Participants judged test movements slower for smaller amplitudes (corresponding to lower speeds) and faster for larger amplitudes (corresponding to higher speeds; Figure 5b). Taken together, those two conclusions suggest that participants do not always base their judgement only on movement speed or only on movement duration, but are able to use the relevant cue depending on the condition. In contrast, when the vigour law was directly implemented in the stimuli (FV condition), results showed that participants were significantly more uncertain and tended to judge the test movements as neither faster nor slower than the reference, regardless of amplitude. In this condition, test movements had always different speeds and durations than the reference (Figure 5c). This suggests that participants could base their judgement on the vigour law. As expected, results of the Friedman test showed a significant effect of condition on the slopes, $\chi^2(2)=60.000$, $p<.001$, $W=1.000$.

Conover's post hoc comparisons showed that slopes in the FS and FD conditions are significantly different from slopes in the FV condition ($p_{\text{bonf}} <.001$ for both). Surprisingly, they are also different from one another ($p_{\text{bonf}} <.001$). Furthermore, the repeated-measures ANOVA (with Greenhouse–Geisser correction) on the deviation scores from 0.5 was significant, $F(1.269, 36.808)=62.966$, $p<.001$, $\eta^2=.685$. The results of the post hoc analysis showed that FS and FD conditions were significantly different from FV condition ($p_{\text{bonf}} <.001$ for both). Surprisingly, FS and FD were also significantly different ($p_{\text{bonf}} <.001$; Figure 6a). Response time is another indicator—the higher the response time, the higher the uncertainty—that seems to corroborate these results. As expected, the repeated-measures ANOVA on the percentage of deviation from mean response time was significant, $F(2, 58)=39.079$, $p<.001$, $\eta^2=.574$. The results of the post hoc analysis showed that FS and FD conditions were significantly different from FV condition (respectively, $p_{\text{bonf}} <.05$ and $p_{\text{bonf}} <.001$). Once again, FS and FD were significantly different ($p_{\text{bonf}} <.001$; Figure 6c). Participants took globally less time to answer in the FS and FD conditions than in the FV condition, which suggests a harder judgement when the test movements were closer to the reference movement. Overall, these findings suggest that the judgement of movement quickness is not simply based on global thresholds on physical quantities such as speed or duration but rather on an analog of the vigour law.

While participants hesitated more in the FV condition, we wondered whether they would have hesitated even more if the stimuli were generated from their own vigour in similar movements. The goal was to test differently the nature of the direct matching and confirm whether the motor representations used in this judgement task appear to be more population-based than individual-based. Previous work indeed showed that perception of duration or speed of movement of others can be influenced by body states and by current or recent experience of motion (Chandrasekharan et al., 2012; Hamilton et al., 2004; Jacobs & Shiffrar, 2005). Furthermore, in the study of Knoblich and Prinz (2001), participants were able to recognise their own drawing movements among different movements patterns. We thus conducted *Experiment 3*.

Experiment 3

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

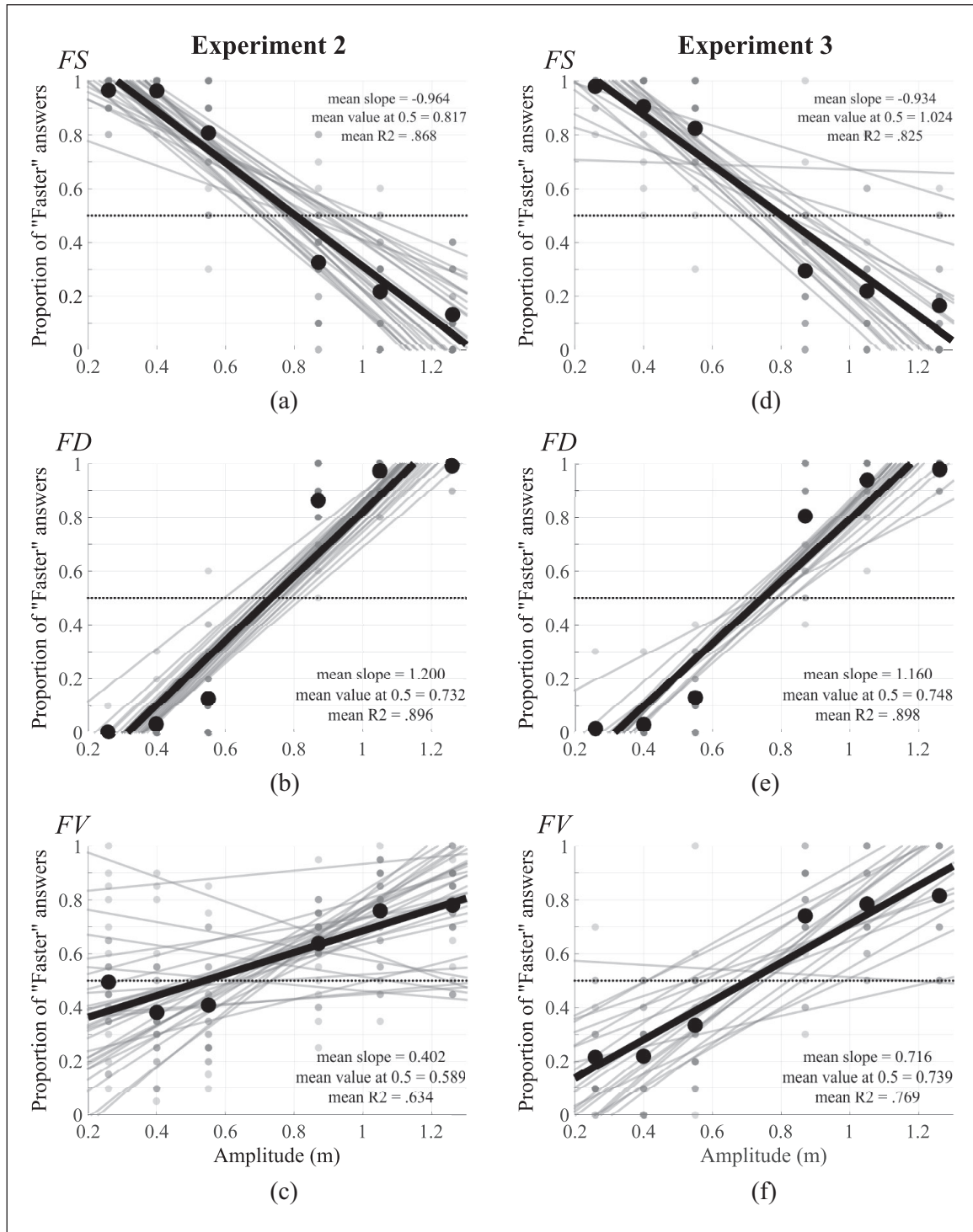


Figure 5. Proportion of “Faster” answers as function of stimulus amplitude and condition (all participants of Experiments 2 and 3). Each subplot stands for one condition of one experiment. For visualisation purpose, the 0.5 proportion lines were displayed. Grey points represent the proportion of “faster” answers given by each participant for each stimulus amplitude. Affine fits were applied for each participant separately (grey curves). The black points represent the mean proportion of “faster” answers averaged across all participants for each amplitude. An affine fit was then applied in each subplot. Mean slope, mean value at 0.5, and mean R^2 across the sample are depicted for each subplot. Experiment 2: (a) Fixed Speed (FS), (b) Fixed Duration (FD), (c) Fixed Vigour (FV). Experiment 3: (d) Fixed Speed (FS), (e) Fixed Duration (FD), (f) Fixed Vigour (FV).

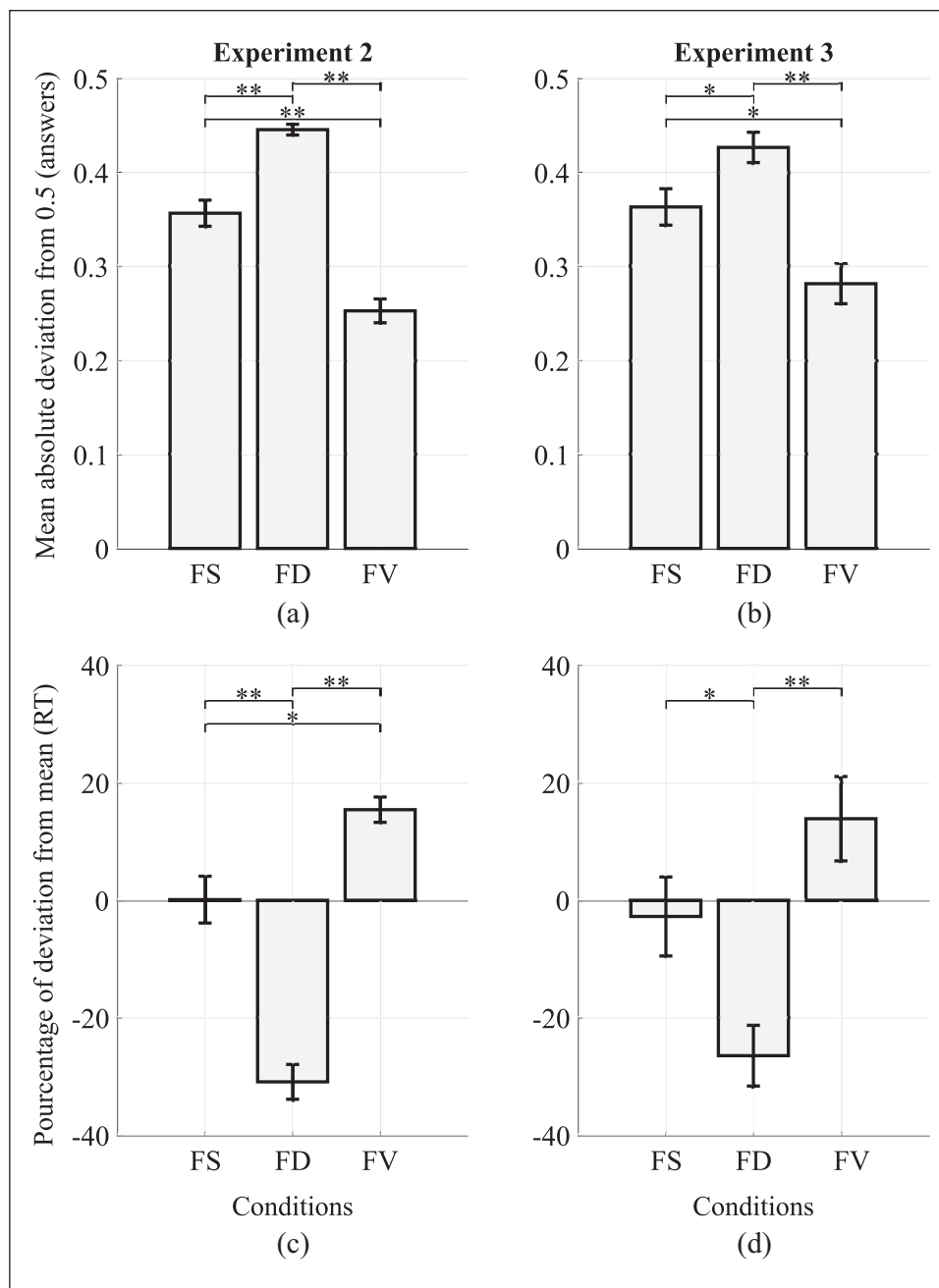


Figure 6. Deviation scores from 0.5 and percentage of deviation from mean response time (all participants of Experiments 2 and 3). The three conditions are represented in each subplot: Fixed Speed (FS), Fixed Duration (FD), and Fixed Vigour (FV). Bars show standard error arising from variability across 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.

Materials and method

Participants. Based on previous similar studies that chose sample sizes ranging from 3 to 21 participants (Chandrasekharan et al., 2012; Grosjean et al., 2007; Viviani & Stucchi, 1992; Wong et al., 2013), 20 young adults with no known neuromuscular disease and with normal or

corrected-to-normal vision participated in the experiment (10 females, 24.4 ± 4.7 years old, $M \pm SD$ values).

Experimental design and materials. Inclusion criteria were the same as in *Experiment 2*. In this experiment, all participants ($N=20$) met the criteria so they were all included. Reaching movements were assessed following the

protocol described in previous articles (Berret et al., 2018; Labaune et al., 2020). Also following the same data processing than in Labaune et al. (2020), mean speed and duration of each reaching movement were gathered and then clustered and averaged by amplitudes. Affine fits were applied on the 10 averaged mean speeds as function of the averaged durations of movement. Standard linear regressions were used because they performed well on the data. Associated linear equations were gathered, representing the vigour law of each participant (example of two representative participants, Figure 4). The characteristics (mean speed and duration) of the reference movement (0.7 m) and of the six test movements of the *Fixed Vigour* condition (FV; 0.26, 0.40, 0.55, 0.87, 1.05, and 1.26 m) were computed directly from the vigour law of the participant. They were then implemented in the custom Matlab scripts used to run the “perception” part of the experiment. Mean speed and duration of the reference movement thus determined the characteristics of the stimuli in the *Fixed Speed* (FS) and the *Fixed Duration* (FD) conditions. The participants sat at a table in front of the same setup as described in *Experiment 2*. The experimental design was also similar; the participants had to answer the question “Compared to the reference, was the second movement faster or slower?” with the response box. There were 18 different stimuli (six amplitudes tested in each of the three conditions), each one being displayed 10 times during the experiment. Hence, the participants had to judge 180 movements in total. The first half of the movements was presented rightward and the other half leftward (or inversely, randomised across participants). The task began with an initial familiarisation sequence of 36 movements to judge (half rightward and half leftward), and then, 18 blocks of 10 pseudo-randomised movements were gathered. There were short breaks between each block. Total duration of *Experiment 3* was about 1 hr and 15 min. Participants were unaware that the stimuli were based on their own reaching movements. When asked after the entire protocol was completed, none of them had guessed.

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

Results and discussion

Results in the FS and FD conditions were the same as in *Experiment 2* (respectively, Figure 5d and e). Results in

the FV condition were also similar, more uncertain than in the FS and FD conditions (Figure 5f). Once again as expected, results of the Friedman test showed a significant main effect of condition on the slopes, $\chi^2(2)=40.000$, $p < .001$, $W=1.000$. Conover’s post hoc comparisons showed that slopes in the FS and FD conditions are significantly different from slopes in the FV condition ($p_{\text{bonf}} < .01$), and surprisingly, they are still different from one another ($p_{\text{bonf}} < .001$). As expected, the Friedman test on the deviation scores from 0.5 was significant, $\chi^2(2)=29.641$, $p < .001$, $W=0.741$. The Conover’s post hoc comparisons showed that FS and FD conditions were significantly different from FV condition (respectively, $p_{\text{bonf}} < .05$ and $p_{\text{bonf}} < .001$). FS and FD were again significantly different ($p_{\text{bonf}} < .05$; Figure 6b). The Friedman test showed a significant main effect of condition on the percentage of deviation from mean response time, $\chi^2(2)=18.900$, $p < .001$, $W=0.472$. Conover’s post hoc comparisons showed that FD condition was significantly different from FV condition ($p_{\text{bonf}} < .001$). No significant difference was found between FS and FV ($p_{\text{bonf}} = .489$) but once again between FS and FD ($p_{\text{bonf}} < .05$; Figure 6d).

Results of the Mann–Whitney tests between slopes in *Experiments 2* and *3* in FS and FD conditions were not significant (respectively, $Mdn_{\text{FS4}} = -1.005$ and $Mdn_{\text{FS5}} = -1.103$, $W=317$, $p = .744$ and $Mdn_{\text{FD4}} = 1.212$ and $Mdn_{\text{FD5}} = 1.210$, $W=315$, $p = .774$; Figure 5a/d and 5b/e). However, the Mann–Whitney test in the FV condition showed that slopes in *Experiment 2* were significantly smaller ($Mdn_{\text{FV4}} = 0.403$) than those in *Experiment 3* ($Mdn_{\text{FV5}} = 0.774$), $W=142$, $p < .01$, $r_{\text{rb}} = -.527$; Figure 5c and f). An a posteriori power analysis showed that $\text{power} = .850$. Given that a smaller slope denotes a greater uncertainty, the population-based protocol induced greater uncertainty in judgement than the individual-based protocol. The Bayesian analysis ($\text{BF}_{10} = 7.763$) confirms this result ($3 > \text{BF}_{10} > 10$; i.e., moderate effect), which reaffirms that the nature of the motor representations used in the direct matching could be population-based.

General discussion

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

someone else's movement. These contributions are discussed in more detail below.

The vigour law underlies both action and perception of movement

Experiments 1–3 consistently showed that judging the quickness of others' movements across amplitude is not based only on duration or only on speed but on a specific increase of these quantities with respect to amplitude, according to the vigour law.

In *Experiment 1*, the vigour of performed movements of each participant and the vigour they judged while observing others' movements were recorded separately. Results showed the existence of an analog of the vigour law in the judgement task, as both the speed and duration of an observed movement perceived as naturally paced increased with amplitude. This result holds both for the average data of the samples studied and for nearly all participants individually. Importantly, if the participants had used a global duration threshold to judge if a movement is slow or fast regardless of its amplitude, then the duration of movements perceived as neither fast nor slow would have been stable experimentally (and the associated speed would have increased across amplitudes). Alternatively, if they had used a duration threshold for each amplitude (e.g., the average of stimuli durations for each amplitude, which is equivalent to a global speed threshold here), then the speed perceived as neither fast nor slow would have been stable (and the associated duration would have increased). The concurrent increase of perceived duration and of perceived speed across amplitudes rules out the hypothesis of a judgement based on a global threshold strategy for duration or speed. In other words, in *Experiment 1*, how amplitude influenced the judgement reflected the vigour law in perception. To verify that this finding was not induced by the experimental design itself, we used a different paradigm in *Experiments 2* and *3*. The idea was that movements following the vigour law should be perceived as having equivalent quickness, regardless of the amplitude. We indeed found that participants were more uncertain in the fixed-vigour condition than in the other conditions (fixed duration and fixed speed). In other words, in *Experiments 2* and *3*, the condition in which amplitude influenced judgement, the less reflected the vigour law in perception. These results corroborate the fact that the judgement is not based on a simple threshold strategy on either duration or speed, and again corroborate the influence of the vigour law on such judgements. This supports the direct-matching hypothesis and extends the results of studies of Viviani and Stucchi (1992) and Grosjean et al. (2007), which showed that kinematic laws (respectively, the two-thirds power law and Fitts' law) drive judgement, especially in an ambiguous situation.

In ambiguous situations, people may use heuristics—i.e., “a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods” (Gigerenzer & Gaissmaier, 2011)—or similar process to judge or make a decision. The work of Bhatia (2017) suggests that in a situation where only one answer corresponding to a heuristic is available, the participants easily respond in accordance with that heuristic. Here, it could correspond to the two “obvious” conditions, Fixed Speed and Fixed Duration. For example, it seemed obvious to the participants that a movement larger and longer than the reference was slower—even if the average speed was the same (which corresponds to one heuristic, only one shortcut based on duration and amplitude available). However, when multiple answers corresponding to heuristics are available (shortcuts based on speed, duration, amplitude, or combinations of these parameters), the conflict created generates less automatic, more thoughtful answers. This corresponds to the hard-to-judge condition, Fixed Vigour. This explanation is consistent with the longer response time in this condition.

Interestingly, this first result—existence of an analog of the vigour law in perception—adds to the conclusions of researchers that already studied separately the perception of duration, speed, or amplitude of movements. Casasanto and Boroditsky (2008) studied the perception of duration and amplitude and how one affected the other. Participants were shown displacements of growing lines or of a dot varying through nine amplitudes and nine durations, and had to replicate either the perceived amplitude (by clicking at two locations accordingly distant) or the perceived duration (by clicking 2 times accordingly delayed) after each trial. Results showed that they were biased by the amplitude of a displacement to replicate their duration (under-estimation of duration of stimuli for small amplitudes and over-estimation for large amplitudes), but the converse was not found.

Beside this main result, two unexpected results were obtained. Results of *Experiments 2* and *3* showed an unexpected but robust significant difference between the *Fixed Speed* and the *Fixed Duration* conditions. Early, McKee (1981) studied the construction of a judgement framework separately for speed and duration. In her study, a short vertical line was displayed on an oscilloscope, moving with seven different mean speeds. The amplitude of the oscilloscope screen displaying the line was increased proportionally with the increasing of mean speed so that mean duration remained constant. Participants were asked to judge whether the speed of each trial was faster or slower than the mean speed of all stimuli (without any standard stimulus ever being displayed). The same protocol was used to study duration perception, with stationary lines being displayed with seven different durations. Interestingly, results showed that it was easier to distinguish differences in speed (i.e.,

corresponding to the *Fixed Duration* condition here) than in duration (i.e., corresponding to the *Fixed Speed* condition here). Her results are thus consistent with the difference we observed between the *Fixed Speed* and the *Fixed Duration* conditions.

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

More globally on the fact that vigour law underlies both action and perception of movement, other studies investigated similar relationships between duration and amplitude of movement through other practice modalities. Beaudoin et al. (2020) tested participants performing a motor imagery task of walking in virtual reality. Results showed that the duration reported for the imagined movement increased with the amplitude, but no information was given about the mean speed or on the lengths of the amplitudes, which makes impossible to study the vigour law per se. In the same vein, Decety et al. (1989) tested the same participants on actual walking and on a motor imagery task of walking. In both tasks, the duration (and respectively imagined duration) increased with amplitude (5, 10, and 15 m) but again no information was given about the speed. Results obtained in these tasks provide a perspective for studying vigour law during walking and in motor imagery.

The judgement of others’ vigour seems “population-based”

Comparing the results of the *Fixed Vigour* condition in *Experiments 2* and *3*, it appeared that the population-based

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

A study of Beaudoin et al. (2020) may support this population-based reference result. They tested participants performing a motor imagery task in virtual reality. Participants were asked to imagine themselves walking down a hallway towards a chair placed at different distances from their starting point (which was always the same). Results showed that the duration reported for the imagined movement increased with the amplitude. Moreover, each participant successively embodied a “young” and an “elderly” avatar (both present in the scene anyway, and with a random order of embodiment). Results showed that for all amplitudes, participants took longer to complete the motor imagery task when embodying the older avatar than when embodying the younger avatar. Thus, it appeared that the age of the embodied avatar had an impact on their reported vigour, reinforcing the hypothesis of a link between the perception and some representation of biological movement, but not necessarily one’s own. Indeed, the movement duration of the same participants was modulated according to the stereotypical social characteristics of the avatar they embodied. This phenomenon is called the Proteus effect, and it indicates that an altered self-representation shapes an individual’s behaviour accordingly (Yee & Bailenson, 2007). Interestingly, the Proteus effect appears to persist briefly over time even after the embodiment stopped. Indeed, embodiment of elderly avatars slowed the actual walking speed of participants afterwards (Reinhard et al., 2020).

Conclusion and perspectives

One of the main contributions of this study was to show that the vigour law found in action systematically holds in perception, not only when averaged across the samples studied but also for nearly all participants individually. The study of vigour in action was motivated by a better understanding of human movement and pathological adaptation. The origin of the vigour law was explained in motor control by the existence of a cost of time and cognitive processes related to the temporal discounting of reward (Berret et al., 2018; Choi et al., 2014; Shadmehr, 2010; Shadmehr et al., 2010). The results of this article showed that for a set of movements to be perceived as of natural pace, the three fundamental parameters of mean speed, duration, and amplitude must all evolve in the same direction. When one of the three parameters is fixed while the other two are changing, the judgement can switch from fast to slow or conversely. In that case, the set of movements no longer follows the vigour law; if a given speed appears natural for a given amplitude/duration pair, this same speed will appear slow for a larger/longer pair and fast for a smaller/shorter pair. Interestingly, the same phenomenon is observed when duration is the fixed parameter. Overall, it seems that the vigour law is robust in both action and perception and that the judgement of the vigour of others is based on an external frame of reference, i.e., requiring a prior representation of the vigour of others' movements (e.g., population-based). In the light of these results, it would be interesting to further explore some of the research and application perspectives arising from each of the main contributions detailed above.

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

Second, interesting in a clinical context, in Parkinson's disease (PD), patients' vigour in voluntary movements is impaired (harder to initiate, fewer, slower, and smaller movements; Mazzoni et al., 2007). The basal ganglia are known to be the disrupted neural structure in PD. Because they are also the neural area considered to be a common centre for regulating the vigour of various limb

movements, it seems possible that they also regulate the perception of vigour. A study of Harrington et al. (1998) reinforces this idea. They studied motor timing tasks (paced finger-tapping task) and time perception tasks (judgement of the relative duration of two-tone pairs) performed by patients with PD and by age-matched healthy controls. Their results showed that the PD group performances were altered in both the action and the perception tasks compared with the control group. This view is also supported by a functional magnetic resonance imaging (fMRI) study that showed the major involvement of the basal ganglia in formulating representations of time during tasks involving the perception of the time interval between two tones (Rao et al., 2001).

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

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

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