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1 The vigor law as a kinematic invariant at work in perceptual-cognitive processes 2 Comment on "Motor invariants in action execution and perception" 3 by Francesco Torricelli et al. 4 Ombeline Labaune¹ and Bastien Berret^{2,3} 5 1. Laboratory of Visuomotor Control and Gravitational Physiology, IRCCS Fondazione Santa Lucia, 6 00179 Rome, Italy 7 2. CIAMS, Université Paris-Saclay, Orsay, France 8 3. CIAMS, Université d'Orléans, Orléans, France 9 10 In their target article, Torricelli and colleagues present a comprehensive overview of the kinematic

11 motor invariants consolidated in the literature to date (1). As stated by the authors, "because 12 kinematic invariants are (by definition) the most stable traits of our movements, they should be also 13 the most stable information that we are able to perceive and decode during action observation". This 14 reasoning leads the authors to propose that those fundamental motor invariants may offer a unified 15 framework "for the investigation of higher-order phenomena such as interpersonal coordination, 16 sensorimotor communication, action perception or intention decoding". Interestingly, the authors 17 begin their argument about motor cognition by reviewing the celebrated Fitts' law, a robust 18 mathematical description of the (affine) increase of movement duration with the index of difficulty 19 (ID) of a task (2). In a Fitts' task, participants are incentivized to move as fast as possible and to be as 20 accurate as possible. Arguably, this only represents a small proportion of our daily movements as 21 humans (or animals) do not always move at their maximal speed for a given accuracy demand. Hence 22 investigating the underpinnings of social interaction from motor invariants must also involve the 23 consideration of less constrained behaviors. In our commentary, we will thus focus on the motor 24 invariants underlying the spontaneous (or natural/self-chosen) speed of movement in goal-directed 25 behaviors, that is, the vigor of movement. As we shall see, movement vigor is subjected to 26 mathematical laws that are reminiscent of Fitts' law, but with a potentially broader impact as far as we 27 are concerned with the role of the motor system in social interaction. Furthermore, the stable traits 28 referred to by Torricelli and colleagues are also very relevant to the notion of movement vigor because 29 it generally exhibits large yet consistent inter-individual variations. These idiosyncrasies can 30 conceivably drive many of our decisions in a social environment where our own vigor is confronted 31 with that of others. In this commentary, we will therefore complement the authors' view by focusing 32 on an additional set of motor invariants that has been somewhat overlooked until recently.

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34 A closer examination of Fitts' law suggests that movement duration must be constant when ID is 35 constant. This leads to a form of isochrony principle, which has long been considered as another 36 kinematic motor invariant (3). Viviani and Flash observed that average speed tends to increase with 37 distance so that the duration of movement remains nearly constant. However, the elegant work of 38 Young and colleagues showed that isochrony is only observed for goal-directed movements performed 39 at maximum velocity; there was no isochrony for movements performed at a natural or quick velocity 40 (4). Therefore, Fitts' law appears as a limit case that is not representative of everyday movements. For 41 reaching movements at sub-maximal velocity, not only average speed but also duration increase with 42 distance. For eye saccades, a similar relationship was described decades ago and is well known as the 43 main sequence (5). Numerous studies on arm and eye movements have actually reported such a 44 concomitant increase of velocity and duration with movement amplitude (6–10). This phenomenon 45 has also been observed when walking different distances (10,11). The speed spontaneously chosen by 46 an individual when performing a goal-directed action has been subsumed under the term vigor in the 47 literature (12–14), so that we used the term vigor law to refer to this class of motor invariants that 48 pertain to self-paced movements (15). The remaining part of our commentary will focus on the 49 implications of that law and its underpinnings, from action to perception. 50

51 The first question to ask may be about the origin of the vigor law, which is only descriptive as it stands: 52 why would humans increase both the speed and duration of their movements with distance? Seminal 53 works explained the emergence of a preferred speed from movement energetics. For any distance, 54 there seems to be an optimal speed that minimizes the metabolic energy rate (11,16). However, 55 departures from an energetic minimum have been observed in several works and additional subjective 56 factors like comfort and reward seem to play a role (17-19). Recent accounts of movement vigor 57 hypothesize that it may also be linked to the general tendency of our brain to discount the value of 58 future reward (14,20). In this vein, Shadmehr (14) proposed a neuro-economic theory of vigor, based 59 on behavioral studies in psycho-economics showing a subjective devaluation of (monetary) reward 60 over time (21). This theory, sometimes referred to as the cost of time theory in motor control, states 61 that the passage of time entails a cost that the brain would seek to balance against effort or inaccuracy. 62 On the one hand, this theory readily explains why movements cannot be too slow if duration is viewed 63 as a delay that separates the individual from the achievement of the action's goal and its associated 64 reward (whether it be explicit or implicit). On the other hand, movements cannot be too fast for 65 energetic and accuracy reasons. Interestingly, optimal control models based on this theory predict this 66 concomitant increase of speed and duration as a function of movement amplitude. Evidence for such 67 a cognitive cost of time has been reported in several works (22–25). By extension, this theory links 68 vigor to decision-making processes related to neural circuits of reward (26). Movement vigor has been 69 shown to depend on the motivation in the task at hand and an increased sensitivity to effort (12,18,27). 70 Hence vigor may depend on the associated brain circuits, starting with the basal ganglia structures 71 responsible for dopamine production (12,13,28). It is worth noting that a reduced sensitivity to time 72 may equally explain an abnormal movement slowness. In sum, this cognitive view of movement vigor 73 extends the more classical mechanistic views and offers a potential link with the psycho-economical 74 traits of an individual. In particular, one's relationship to the passage of time may be a higher-level 75 characteristic that shapes one's movement vigor.

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77 Several studies have investigated this premise and tested if there is a link between movement vigor 78 and cognitive factors during goal-directed actions. Often, a vigor score was assigned to each participant 79 in the task (e.g., based on their peak or average velocity). Whether those scores were proper to an 80 individual and correlated with various personality traits or decision-making variables was assessed. It 81 turned out that certain individuals were much more vigorous than others in the same motor task, and 82 a normally-distributed continuum was observed throughout the population (6-8,10). Vigorous 83 participants were also those having the fastest reaction times (17,29). Whether vigor was a trait-like 84 (i.e., stable) characteristic of an individual was also analyzed. Berret et al. (6) found that intra-individual 85 variations of vigor (within/across days) were much smaller than inter-individual variations in a reaching 86 task. Similar results were obtained by Choi et al. (7) for eye saccades. Other studies have shown large 87 but consistent inter-individual variations in vigor across different action modalities and effectors 88 (8,10). Interestingly, vigor did not appear to correlate neither with the biomechanical characteristics 89 of the individual (e.g., overall size or segment length (10)) nor with other physiological characteristics 90 (e.g., maximum force (30)). Reppert et al. (8) investigated the hypothesis that inter-individual 91 variations in vigor could be explained by an idiosyncratic sensitivity to accuracy. In their experimental 92 settings, however, individuals with high vigor were as accurate as less vigorous individuals. It was 93 concluded that the vigor of movements rather comes from an individual's choice to provide the 94 necessary effort. Using techniques from differential psychology, it was further shown that vigor scores 95 were correlated with some personality traits (assessed by questionnaires). High boredom proneness 96 scores were significantly and positively correlated with high vigor scores for reaching (6). Similar 97 trends, although not significant, were obtained between impulsivity and reach vigor (6), and between 98 impulsivity and eye saccade vigor (7). Although personality traits accounted only for a small portion of 99 the total variance of vigor scores, these results were coherent with the hypothetical link between a 100 subjective time-effort tradeoff and the idiosyncrasy found in movement vigor. 101

102 The above cognitive theory of movement vigor offers a potential window to study social interaction 103 through the lens of the kinematic invariants that underlie it. As vigor is a key characteristic of any 104 action, it could also be a key characteristic of social interaction. Indeed, the integration of the vigor law

105 at the cognitive level could allow us to judge, anticipate and adapt our speed to that of others, and to 106 interact appropriately with them in our environment. Many daily decisions we make are based on our 107 appreciation of others' movement pace (e.g., choosing to pass someone on the street). Numerous 108 works have been done on the relationship between action, action perception and motor imagery, 109 especially since the discovery of the mirror neuron system that links the action that an individual 110 observes with a motor representation of that same action (31). Since the same neural subsystem is 111 used to produce and perceive the same action, mentalizing the actions of others helps the observer 112 understand and judge the behavior or intentions of others (32). In this vein, Rizzolatti and colleagues 113 (33) formulated the direct-matching hypothesis, which states that an individual observing a movement 114 compares it to the motor representation they have of it. Thus, the individual's motor repertoire may 115 be used to gain insight into the observed action. Accordingly, several of the kinematic motor invariants 116 reviewed by Torricelli and colleagues, such as the two-thirds power law (34,35) and Fitts' law (36,37), 117 also seem at work when judging observed movements and imagining them, thus constituting cognitive 118 laws. Along the same lines, our recent work investigated whether the vigor law is at work in judging 119 the quickness or slowness of others' movements (displayed as a dot on a screen) (15). Another 120 objective of this same set of experiments was to determine whether the basis of this judgment was 121 the observer's own vigor law or a more generic motor representation formed from population 122 statistics (i.e., average vigor law of the population). The results showed that the speed and duration of 123 movements perceived as moving at natural speed (i.e., perceived as neither fast nor slow) both 124 increased with distance, demonstrating that the vigor law applies to perception. The results further 125 revealed that there was no correlation between the vigor produced and the vigor perceived by the 126 participants, and that the judgments seemed to be based on a populational rather than an individual 127 reference. This finding may be interesting to refine the nature of the motor representation possibly 128 encoded in the mirror system. The vigor law, which is a modernization of the historical isochrony 129 principle, thus has a close analogue in perception, which might reflect the statistics of the individual's 130 social environment more than their own vigor.

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132 In summary, we stressed that the vigor law is another type of kinematic invariant that might be 133 critically involved in higher-order phenomena such as social interaction and decision-making. This 134 kinematic invariant has a theoretical ground based on the *subjective* sensitivity to time and effort, 135 which readily suggests that it could constitute a cognitive law. Recent evidence confirms that the vigor 136 law also holds in perception and may serve as a basis for judging whether another person's movement 137 is abnormally fast or slow, and behaving accordingly.

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139 **Declaration of competing interest**

140 The authors declare that they have no known competing financial interests or personal relationships 141 that could have appeared to influence the work reported in this paper.

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