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The vigor law as a kinematic invariant at work in perceptual-cognitive processes

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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.

76
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.

131
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.

138 139 **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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