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Reply to comments

Physics' insights into pedestrian motion and crowd dynamics Reply to comments on "The emergence of design in pedestrian dynamic: Locomotion, self-organization, walking paths and constructal law"

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Abstract

Pedestrians' world is not a static one, but rather one which is constantly in flux. The pedestrian dynamics is subject to a wide range of influences and displays an interesting phenomenology. Along with collective self-organization phenomena (e.g., streams of people, rivers of people, collective synchronization), there are also a multitude of applications in the context of crowd management, design of pedestrian facilities and urban planning. Here, I address comments from the discussants of my review paper from the viewpoint of elementary physics laws paying particular attention to the self-organization phenomena in crowds.

Keywords: Crowd dynamics; Self-organization; Collective synchronization; Multiscalar dynamics; Constructal law

1. Towards more effective understanding of pedestrian dynamics

An exceptionally large brain relatively to body size and bipedal morphology are distinctive features of the humans [1]. Human bipedal locomotion includes two gait classes, namely walking and running [2]. Walking is the most basic form of transportation, undertaken by almost every able person. Nearly all journeys begin and end with a walk, and sometimes a run (to catch a bus or train), regardless of the transportation modes used in between. A good understanding of pedestrian dynamics is an important challenge for modern societies that has a direct impact on our

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quality of life. This understanding is essential not only to the planning and design of street networks, public transport stations, shopping malls, airports, etc. [2–4], but also to the organization of events and the control of crowds [5–7]. By resorting to elementary physics' laws, we are able to better describe, predict and optimize both the movement of people and their flow paths. The constructal law, for instance, is precisely about the generation of flow design (shape, configuration, structure, patterns) and its field of application is that of dissipative systems, i.e., systems that cannot exist independently of their environment [7–10].

The commentaries of Y. Ventikos [11], J. Delgado [12], A. Bejan [13], F. Venuti [14], R.M. Tavares [15], G. Stanescu [16] and T. Bello-Ochende [17] have highlighted many important issues and raised several thought-provoking questions about my paper, which I now attempt to address.

Yiannis Ventikos [11] reminded us of importance that "movement" played in the evolution of species, and the interest it raises amongst academics in different fields. He draws attention to the multiscale perspective of human mobility covered by the constructal law. Human mobility manifests itself directly or indirectly over a multitude of scales, from "vasculature that perfuses the musculature of the body (10^{-5}–10^{-2} m)" to "transportation corridors and the evolution of cities (10^4–10^6 m)". One of the main features of the constructal is precisely an attempt to bridge the "small" and the "big". This enables us to anticipate design in a multitude of scales and develop new applications in emerging fields. The universality and simplicity of constructal law suggest that there is a fundamental principle underlying natural flow systems that covers several orders of magnitude in length and mass [10].

João Delgado [12] noted that although my paper is focused on the literature review, a few new unpublished results are also included. He stressed the broad view of the constructal law that accounts for the generation of flow configuration in man-made systems but also in animate and inanimate systems. Also important is his observation that the freedom to morph is a key issue in the evolution of design, and hence that a natural flow system that is free to morph "wants to flow more efficiently, and over time will shape itself to do so" [12].

Adrian Bejan [13] pointed out some other important studies that look at pedestrian flows from the constructal law's viewpoint and "makes several additional connections" between them and the topics described in my review paper. He also put forward a timely reflection about the meaning of "resistance" in pedestrian dynamics, a concept first associated to electricity and fluid dynamics.

Turning to the roots of concept, resistance occurs when the electrons and particles of fluid give up the energy they carry. Think in charge carriers (electrons) that are flowing in a metal (wire). If e, c and M_e are the charge, concentration and mass of carriers, respectively, and τ is the mean free time, the electrical resistance may be considered as $\sim M_e/(ce^2\tau)$, which is the Drude equation [18]. For a gas streaming through a pipe of length l and radius r, the resistance is $\sim M_g nv\lambda L/r^4$, where M_g is the mass of gas, n is the number of molecules per volume, λ is the mean free path, and v is the speed of molecules [19,20]. In both cases, the "frictional" process that underlies resistance is associated to things that have mass and experience motion. Things are charges or particles but may also be objects, fish, birds, people, ... This is why resistance is omnipresent in our daily lives: in our world, for everything that has mass, resistance to motion is an everyday experience.

Fiammetta Venuti [14] examined the breadth of scales covered by the constructal law in pedestrian dynamics, from the "microscopic scale" (i.e., single pedestrian dynamics), to the "macroscopic scale" (i.e., collective pedestrians flows), and the "global scale" (i.e., paths design for pedestrians flows). She also drew attention to the interesting phenomenon of "collective synchronization" that occurs in crowd dynamics, and called upon researchers working under the constructal law principle to attempt an explanation for it.

Collective synchronization is a ubiquitous phenomenon found at many different scales, from the metabolic processes in our cells to the highest cognitive tasks, and from children interacting to people working or walking. Such processes are hence the focus of research in many areas, like biology, ecology, sociology and engineering [21,22]. Kuramoto's model was proposed as an analytically tractable system to study collective synchronization [23], and it has become the paradigm for predicting temporal organization in a large variety of natural systems far from thermodynamic equilibrium. Drawing a parallel, we can say that constructal law is the thermodynamics law of nonequilibrium (flow) systems with configuration. The tendency of these systems to morph into evolving configurations of higher performance is the action of this law [7–10]. Therefore, collective synchronized oscillations that arises when a population of oscillators auto-organizes should be well within the field of application for the constructal law.

Collective synchronization is a cooperative phenomenon [22], similar to the generation of patterns in aggregates of organisms, like bacterial colonies and stony corals [24–26]. It is a remarkable powerful factor of self-organization. Think of a system composed by a number of entities that has sufficient freedom to change its configuration, in the