Tech Know Learn (2013) 18:9–37
DOI 10.1007/s10758-013-9199-8

Biking with Particles: Junior Triathletes' Learning About Drafting Through Exploring Agent-Based Models and Inventing New Tactics

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Published online: 7 March 2013

Abstract The present research addresses a curious finding: how learning physical principles enhanced athletes' biking performance but not their conceptual understanding. The study involves a model-based triathlon training program, Biking with Particles, concerning aerodynamics of biking in groups (drafting). A conceptual framework highlights several forms of access to understanding the system (micro, macro, mathematical, experiential) and bidirectional transitions among these forms, anchored at the common and experienced level, the macro-level. Training was conducted separately with two groups, both 14–17 years old youth: an elite junior triathletes team (experts; 4 male, 3 female) and a local team (hobbyists; 6 male, 3 female). The goal was to explore whether agent-based models of bikers and air particles could be used to enhance athletes' understanding and performance, and whether this depends on expertise. The study lasted 3 days and included lectures, discussions, guided exploration of models, inventing new tactics, and biking in practice. Data included questionnaires, interviews, videotapes, and performance measures of heart-rate and biking duration. Athletes' designs were innovative and diverse, expressing well-known and new features in the sport. Local features were more dominant than global features. Their performance in bicycle drafting increased dramatically, with a gain of 20 %, at both individual and group levels. The experts mainly reduced their times. Hobbyists mainly reduced their effort. Some conceptual change was evidenced for the complex systems components but not for drafting. Results are discussed in light of learning about complex systems and the balance between cognitive-verbal and motor learning within competitive sports.

Keywords Agent-based models · Complex systems · Competitive sports · Physical education · Model-based learning

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1 Introduction

Can a constructionist complex systems approach support better understanding and performance in sports? In this paper, we describe research into young triathletes' invention and execution of new drafting tactics using computer models based on a complex systems approach. To support this study, we created a training program named Biking with Particles.

The study focuses upon the phenomenon of drafting in road bicycle triathlon competitions. As such, it touches on the domain of competitive sports training and physical education. "Drafting" involves a group of cyclists moving together (Fig. 1). In the fields of physiology and biomechanics the term is used to describe interactive tactical activity among individuals. Following a raging debate, in 1995 drafting was legalized for elite athletes and junior athletes by the ITU (International Triathlon Union). Opponents to this decision highlight the hazards of drafting and the unfairness that it produces as the leaders in drafting expend more energy than their followers. According to this view, inequality in contributions leads to an isolationist approach to cycling: using the advantages without contributing to the group. As we will show, athletes can invent interesting alternatives to an isolationist approach and even an "equal share" approach that adapts to the constraints of varying abilities.

Drafting is used to gain energy advantages in moving through the air (Hausswirth and Brisswalter 2008). The phenomenon of drafting offers unique insights into the delicate balance between competition and cooperation among collectives. On one hand, drafting offers up to 40 % savings on energy expenditure, rising with the biker's speed (McCole et al. 1990). On the other hand, the group speed may slow a biker down too much; in which case, a smaller group may "break-away", usually around a bend in the road. Thus the persistent question for a given cyclist is "stay or break away". Furthermore, the answer can change at any given moment. In a triathlon (sequenced as swimming, biking then, running), biking at a less than maximal rate and minimum energy expenditure is particularly advantageous in saving energy for the last leg of the competition.

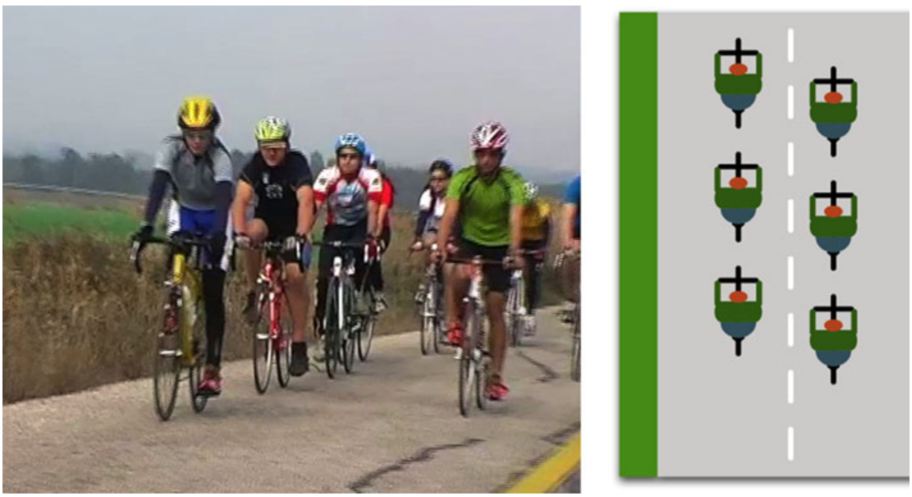

Fig. 1 Drafting cyclists in the Belgian Tourniquet ellipse-shaped rotating formation—successively each cyclist leads the group

The phenomenon of drafting was selected for this study for a number of reasons. One is long-standing difficulties in its conceptual understanding by athletes as they perform it blindly without understanding the basic underlying idea behind drafting and do not adapt to a changes in the environment.[1] Second is the large energy advantage it offers. Finally, drafting is in fact a general phenomenon viewed among racing cars, cross-country skiing, tailgating trucks, birds, fish and more. The most-commonly understood concept by bikers is that cycling through air causes the dynamics of the air to change around the biker in a way that forms a low-pressure area in the back and eddy streams (vortices) in the back/diagonals. Having another cyclist move in very close (professionals approach up to a number of inches!) means there is low pressure in front of him, decreasing the air's resistance to his motion. Additionally, having the second cyclist behind the first one reduces the turbulence by smoothing the eddy streams in the back-diagonals and reducing the drag on the first cyclist, though to a much lesser extent. Based on this idea, most drafting tactics involve a one-dimensional formation made up of straight or diagonal "cyclist-behind-cyclist" repeating units (USA Triathlon 2012). A simple tactic in drafting that is commonly used is a single line of closely packed bikers, forming a diagonal in case of wind. The most efficient tactic to date is the Belgian Tourniquet (hence, BT) (Fig. 1). In the BT, the cyclists form an ellipse (essentially a bent line) and rotate within it, so that successively each cyclist leads the group (Hausswirth et al. 2001). In this study, we wish to expand beyond these simple tactics and incorporate additional advantages one may obtain from a deeper understanding of the aerodynamics of clustered biking. This approach would be two dimensional, incorporating reasoning not only about the pressure between a front and back biker, but also along the sides. As hinted in the "smoothing the eddy streams" idea above, the bikers may be able to manage the air collectively, by transforming turbulent flow to laminar (smooth, less resistant) flow.

One way of understanding the aerodynamics of drafting involves considering the intricate framework of fluid dynamics through the use of differential equations. As an alternative, we chose a complex systems approach to present and help athletes learn the topic. According to a complex systems approach, a system's behavior arises from the local interactions between its members (Vicsek 2002). A central advantage to this approach is a greater generativity of understood phenomena from a small set of principles (Blikstein and Wilensky 2007), thus supporting a deeper understanding (Levy and Wilensky 2009a). This perspective is based on a much simpler causal substrate from which system-wide phenomena emerge. In this study, we use a particulate representation of air, interacting with a group of moving bikers, and the bikers interacting among themselves through the medium of air. One needs to understand only simple two-body collisions (among particles, and between bikers and air particles; modeled similarly to two billiard balls in motion colliding with each other). This makes phenomena like flow, waves, and changes in pressure an emergent result of these interactions, rather than principles one needs to incorporate into reasoning about the system ab initio. Making sense of the system involves a shifting focus between submicroscopic particulate interactions and experienced phenomena of a pack of bikers in motion.

In a previous paper (Levy and Wilensky 2009b) we have presented a conceptual framework underlying the design for learning about complex chemical systems and demonstrated it through the first chapter in the Connected Chemistry curriculum,

[1] The first author is an ITU (International Triathlon Union) competitive triathlon level 2 coach, with many years of experience in training, was the triathlon national team head coach and today, trainer of coachers. This claim is based on his personal experience and through his many conversations with other coaches worldwide.

(Levy et al. 2006). The main contributions of that paper are a theoretically motivated design for learning about complex systems, and a corresponding fine-tuned assessment of students' learning in light of this same conceptual framework. The current work is set within the same framework and expands its applicability.

Briefly, the framework (Fig. 2) depicts three spheres of knowledge: *conceptual understanding* of how interactions among particles and with and among bikers result in the system's global behavior, *symbolic-mathematical* expressions of the system's behavior and *physical experiences* of the explored phenomenon. Learning about the system is conceptualized through four canonical forms of access and bidirectional bridges between them: micro, macro, mathematical and experiential. The framework is *anchored at the experienced macroscopic level* that is common to the three spheres of knowledge. The Biking with Particles training program takes the experiences of biking and bikers interacting with each other and with the surrounding air as a hub. It encourages reasoning within each form of access (intra-level experiences), as well as bidirectional transitions among these forms (inter-level experiences).

Aerodynamics within such a perspective is viewed through Kinetic Molecular Theory, a sub*microscopic* theory that explains the forces between molecules and their kinetic energy in terms of the rules governing particles' behaviors, such as their random continual straight-line motion and the elastic nature of their collisions among themselves and with other bodies. *Macroscopic* patterns such as friction and resistance, eddy streams, and turbulence emerge from interactions between the air particles and the bikers moving in formation. The context of competitive sports introduces another form of representation,

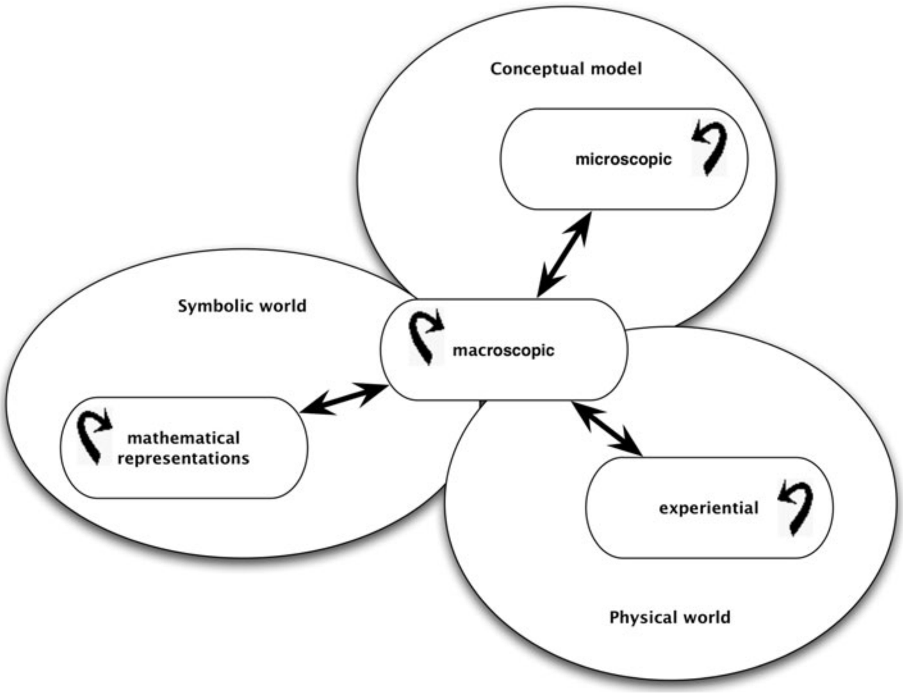

Fig. 2 Conceptual framework for supporting learning about systems through agent-based models. Larger circles signify spheres of knowledge; smaller ones are forms of access to understanding the system; arrows signify the activities' learning goals–understanding each form of access in itself and bridging among them

namely a quantitative *arithmetical symbolic* one. For example, heart-rate is measured constantly and used as one metric of effort. Training and competing requires bikers to observe this metric and adapt their actions. However, this metric is not used in its original form, as several transformations are necessary. One needs to subtract the resting heart rate to gauge the actual effort expended. Additional calculations narrow the range within which the heart-rate should be, related to the aerobic threshold and anaerobic threshold heart-rates.[2] Other quantitative metrics include time/speed and an ordinal scale of reported effort, RPE, Rate of Perceived Exertion.[3] While training, these metrics are recorded and analysed carefully to assess performance.

Our designed learning intervention was designed to test the assumption that activities that support forms of access to all the spheres of knowledge within our framework and bridging between them would lead to a deeper understanding of the system at hand. It was also designed with a commitment to constructionist principles of learning, propelling invention and construction as a central and important form of learning (Papert 1980). The result of our design was a 3-day program in which the athletes themselves invented new drafting tactics and tested them out. The intervention employed computerized NetLogo (Wilensky 1999) agent-based models: one with moveable cyclists and air particles (Bacalo et al. 2011), one based on an existing NetLogo model of flocking birds flocking (Wilensky 1998) with an addition of air particles and their interactions with the birds (Hirsh et al. 2011) (see Appendix). Effort in the model was viewed as the rate at which air particles hit a cyclist: when this rate grew air resistance to this motion increased. These models were used as an explorative medium to understand the phenomenon of drafting. Furthermore, they were used as a constructive medium to design new tactics in drafting, by creating a variety of spatial formations of moving cyclists within a swirling sea of particles. One of the minor goals of this study was to observe the athletes' invented ideas and create further tools for the design medium, so they could generate additional designs.

We expected that through harnessing the athletes' prior knowledge of competitive bicycle riding, learning would be deeper and the resulting tactics would be more variable (Williams et al. 2010; Mann et al. 2007). To test out this idea, the study was conducted with two teams of differing levels of expertise—elite[4] junior athletes training at the national sports center (experts) and a local team (hobbyists). Whether and how prior knowledge could be activated and used becomes comparable. The study addresses the possible learning advantages of such training, employing both biking performance and cognitive measures to gauge learning.

2 Literature Review

In the following sections, we describe several facets of the research including: a short introduction to the triathlon, the phenomenon of drafting, motor learning and its relation

[2] The aerobic threshold is the minimum speed at which a person is performing in the aerobic zone (below 65% of maximal heart-rate). The anaerobic threshold is the fastest speed at which a person can perform at a steady state where oxygen supply is adequate to meet muscle demands (80–90 % of maximal heart-rate). At higher intensities, lactic acid levels in the blood rise sharply, interfering with aerobic metabolism and causing muscles to fatigue.

[3] RPE is a subjective sensation that athletes report on that describes the level of effort. It is a common measure for identifying exercise intensity levels.

[4] An elite youth athlete is a child between the ages of 7–17 that demonstrates above average performance and reaches regional, national or international competitions.

with conceptual learning, expertise in sports, complex systems, and learning with computer models.

2.1 The Triathlon

The triathlon is a multisport event, which was established some 30 years ago. The three disciplines in the event are swimming, cycling and running. A triathlete performs the three sports in the specified sequence and strategizes effort and speed to obtain maximum effect in minimum time. The distance in each sport is determined by age. In the adult category the distance for swimming is 1,500 m, cycling 40 and 10 km for running. In the current study, our participants were youth and performed 50 % of the adult requirements in competitions.

Participating in a triathlon requires solving problems that come up in dynamic and stressful situations. These situations change according to the various specifications of each race. Swimming can take place in open water or in a swimming pool and can be affected by water currents and temperature. Cycling usually takes place on roads and depends on the conditions of the road, the grade of the path, and the resistance of the wind. Running can take place on a road or path and is impacted by the condition and grade of the terrain. This research focuses on one discipline alone: cycling.

2.2 Drafting

The term drafting (or slipstreaming) is mostly used in the field of physiology and biomechanics of sports to name the movement of closely packed individuals aimed at aerodynamic protection (Hausswirth and Brisswalter 2008). A peloton is a large group of cyclists that are riding together to create a network that spreads energy resources among the cyclists. A peloton is usually created spontaneously.

One of the main reasons for losing energy during cycling is due to friction with the air (more so than with the terrain due to the relatively small surface area in contact with the ground). The aim of drafting is to reduce this friction. Little research has been conducted into the impact of drafting in triathlon on physiological factors.

It is important to note the large extent to which drafting may assist a biker in competition. McCole et al. (1990) examined the relationship between different forms and speeds of drafting on oxygen consumption. They showed that riding in a pack saves cyclists 18 % in oxygen consumption at 32 km/h (speed measured as kilometres/hour), that pairs of cyclists at 37–40 km/h save 27 %, and that riding in a pack of eight saves the last rider 39 % (!) in oxygen consumption. It has been shown that among cyclists that are drafting behind a leader at a speed of 39.5 km/h there was reduction in four different physiological factors that represent energy output (Hausswirth et al. 1999). The heart-rate reduced by 7.5 %; oxygen consumption reduced by 14 %; the concentration of lactic acid[5] reduced by 0.2–0.5 mM[6]; pedalling rate reduced from 95 to 89 rpm (rotations per minute), showing evidence for a more efficient use of the aerobic system at the expense of limiting anaerobic components such as lactic acid. These sizable energetic savings are the basis for the current study. Cycling was selected because it's the largest "lever" for improvement in the triathlon.

[5] The measurement of lactic acid is used to assess levels of stress. Lactic acid is found in the muscles and blood stream and is released when the body exerts itself beyond the anaerobic threshold.

[6] M and mM are units of concentration, describing the relative proportion of a substance dissolved in a solvent.

One of the central features that distinguishes different tactics of drafting is whether or not there is turn-taking at leading the pack. In research conducted with ten international level triathletes, the impact of tactic on physiological measures was examined (Hausswirth et al. 2001). In one tactic, leadership alternated (ADT—Alternating Drafting Triathlon) and in the other, there was no alternation (CDT—Continuous Drafting Triathlon). It was found that the ADT tactic led to a greater energetic advantage and lower concentrations of lactic acid with respect to the CDT tactic. In addition, the athletes in the ADT condition were more ready physiologically at the running leg of the race, so that their times were greater than the CDT athletes. These findings accent the role of specific tactics on drafting and highlight the need for their further exploration.

2.3 Cognitive Aspects of Motor Learning in Sports

This study examines both conceptual learning and changes in performance. Performance is viewed through the motor program construct (Schmidt and Wrisberg 2008). The motor program is an abstract representation of movement, used to describe cognitive processes in movement planning that include both pre-programmed movements and responses to environmental stimuli. This construct is central in sports research. It is fundamental to the current study as we expected that the resulting motor program would include greater flexibility with respect to environmental conditions, and enhanced sensations with respect to air pressure, and flow. This flexibility is related to both sensing of input (sensorial input related to the tactile and haptic senses) and to related movement, such as shifting position to better locations within a configuration. In this section we focus on how conceptual learning may improve motor action.

We narrow the review to the choice of movement from an array of possible ones during long-term and complex action, namely an "open skill". This is different from much research that explores motor action and concentrates on movements that don't require choice, such as shooting an arrow at a target or typing, which are "closed skills" (Schmidt and Lee 2011). Motor learning is described as having three stages: (1) cognitive-verbal; (2) motor; (3) autonomous. Within this study, we have focused on the first stage, cognitive-verbal learning that may take place through exploring and discussing computer models.

In the cognitive-verbal phase, the learners do not yet know the topic and skill they will learn. During this time they talk to themselves, ask questions about confusing issues and ask self-monitoring questions. In Biking with Particles, we have provided a learning environment that encourages such talk and questioning, by providing several opportunities to self-explain, explain to others, listen to and assess explanations (Chi and VanLehn 1991).

Perceptual learning and conceptual learning are also conceptualized as part of motor learning. In the early stages of motor skill learning, the athlete needs to experience the skill at the conceptual and perceptual level (Schmidt and Wrisberg 2008). Supporting evidence is found in studies that show how understanding the physics of a ball's motion improves preparedness and anticipatory action of an athlete catching a ball and passing it on (Mayer-Kress and Newell 2002).

With our target participants, we expected conceptual learning to increase, as the athletes would be explicitly discussing various features of drafting and aerodynamics; we anticipated perceptual learning, hoping they would sense the air around them and subtle changes in it; we also predicted there would be motor learning, as their riding times and effort would improve in the process. However, we did not anticipate autonomous action as this results from longer-term training.

2.4 The Role of Expertise in Athletes' Knowledge

It has been claimed that in most fields of sports, athletes need to process information very quickly in an environment where time is a crucial factor (Williams et al. 2010). Therefore, athletes need to adapt themselves to unique constraints of the task by learning knowledge structures and cognitive processes that support their prediction of what will happen and deciding on the appropriate choice of action (Williams and Ford 2008). The above researchers claim that experts circumvent the limitations of short-term memory by learning skills that facilitate quick processing of information into long term memory and selective access to this information, as needed. After extended practice, experts tag information in such a way that enables anticipation of when it will be needed in the future. In a meta-analysis of the relationship between expertise and perceptual-cognitive skills, several distinctions were found among novices and experts in various domains in sport (Mann et al. 2007). Notably experts were better at identifying perceptual cues, as seen in their responses' precision and reaction time.

2.5 Complex Systems

The domain of complex systems has evolved rapidly in the past 20 years, developing novel ideas and tools, and new ways of comprehending old phenomena. Complex systems are made up of many elements (often referred to as "agents"), which interact among themselves and with their environment. The interactions of numerous elements result in a higher-order or collective behavior. Although such systems are not regulated through central control, they self-organize in coherent global patterns (Holland 1995; Kauffman 1995). The properties of a system's patterns cannot be reduced to just the properties of its individual elements (e.g., Bar-Yam 1997, p. 10; Holland 1998). These patterns can be counter-intuitive and unexpected (Casti 1994; Strogatz 2003; Wilensky and Resnick 1999).

2.6 Learning with Agent-based Models

A fruitful way of approaching the problem of bridging between levels and forms of representation is through exploring models, external and manipulable representations of the system under study (Gilbert and Boulter 2000). A model is a partial depiction or representation of a phenomenon one wants to understand (Bailer-Jones 2003). By simplifying the system so it includes only the most central parts and relations, it is possible to reach a deeper causal understanding. Agent-based modelling is a newer approach to creating models that represent complex dynamical systems. Within this approach, separate computation is made for each individual entity in the system and its local interactions with additional entities. Learning through exploring agent-based models has benefited learners in understanding systems, most specifically at the micro and micro-to-macro levels of description (Jacobson and Wilensky 2006; Levy and Wilensky 2009a). NetLogo (Wilensky 1999) in one such modelling environment. In this study, NetLogo was used to construct models of various phenomena related to drafting and support their exploration, prediction and explanation.

3 Research Questions

Given our design commitments and theoretical constructs, we asked the following research questions:

1. What features characterize the triathletes' invented tactics?
2. How does young triathletes' biking performance change as a result of training? How is this related to expertise?
3. What typifies conceptual change related to participating in the Biking with Particles program? How is this related to expertise?
4. How are changes in performance and conceptual learning related?
5. What are the athletes' perceived sensations of air pressure and motion following training?

4 Method

4.1 Participants

Participants included 16 junior triathletes from two teams that completed the training in separate times and places. Both teams included 14–17 years old youth: a team of elite triathletes training at the national sports center (experts; 4 male, 3 female, attrition of one female due to an intense test period at school) and a local team from the north of Israel (hobbyists; 6 male, 3 female; attrition of one male due to his transfer to another team). The elite team triathletes had been training for over 3 years, 7–12 training sessions a week, 15–20 h a week with much experience in national and international competitions. Some of them were the national champions of their age groups. The local team triathletes had been training for at least a year in an after/before school program, 5–8 training sessions a week, 8–12 h a week. They had participated in at least five competitions. Prior requirements were fluent use of computers and parental consent. The first author was the coach; the second author was the assistant coach.

4.2 Research Design

The study was conducted as a non-randomized comparison group pretest-intervention-posttest design. It commenced about 1 month (hobbyists) and 1.5 months (experts) into the training season, after a relatively slower pace of practice (three times a week instead of five to twelve). Two teams of athletes of differing initial abilities and practice participated separately in an identical sequence of training, made of up of two consecutive training days, and then, 2.5–3 months later, one more training day (Fig. 3).

4.3 Biking with Particles Training Sessions

The training program Biking with Particles is made up of short lectures (e.g. on the relationship between pulse and effort), several discussions (e.g. a comparison of birds' and cyclists' drafting), worksheet-guided exploration of computer models of particles, flocking birds and bikers in various configurations, and then using a particles and bikers model to

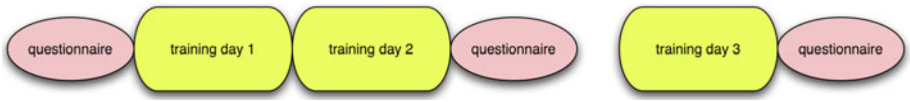

Fig. 3 Research design

create new possibly more efficient configurations, testing familiar and invented tactics out on the road (five tests, four heats each) and collaborative analysis and discussion of the pulse, time and effort data. The program and models are described in the Appendix. The design of the training sessions was based on the conceptual framework described in the introduction (Fig. 2) and was framed by the following design principles: (1) Trusting that the athletes can invent new and better drafting tactics, based on their experience and motivation; (2) Anchoring in a physical world phenomenon, biking in formation; (3) Successive shifting between theory and practice, and relating the two explicitly—designs were individually tried out with the models, collaboratively discussed and soon tested in practice, this process repeated five times; (4) Beginning with two distinct representations of the phenomenon (collision interactions; bird flocking) and gradually merging the two; (5) Using quantitative measurable performance goals.

4.4 Data Collection Tools

Several forms of data and its collection are described in Table 1.

A conceptual understanding questionnaire included 21 items; of these seven were multiple-choice, assessing the main concepts addressed by the training program. The items were grouped by dimension, as described in Table 2. Those related to a micro-level understanding have been used in previous research (Levy and Wilensky 2009a).

4.5 Data Analysis

The triathletes' designed and enacted tactics were categorized into spatial types. They were also analyzed as including one of several features: units of one-behind the other, diagonal placements, putting the strong cyclists in front, wrapping the weaker cyclists with other cyclists, rotation within the formation and the quality of the group contour in terms of aerodynamics.

Performance was analyzed from the heart-rate and time data. Heart-rate was adjusted with respect to resting heart-rate by subtraction, so that only effort was included. A new measure of efficiency was created to assess output/input and support comparison between

Table 1 Research variables and data collection tools

Research variable	Data collection tools
Creative products	Athletes' invented tactics for drafting in two main forms: (1) designed within the computational environment; (2) drawn and discussed on the board; (3) acted out in practice after further discussion before setting out
Performance in drafting	Time to complete 2 km of flat road riding Heart-rate measurement right after cycling with a heart-rate transmitter around the chest and a watch-type monitor; Heart-rate measurement upon waking up to obtain its resting value for the baseline RPE (Rate of Perceived Exertion) effort self-report
Conceptual understanding of drafting	Identical questionnaire administered three times Impromptu interviews with athletes during training
Reported sensations of air motion while biking	Questionnaire administered at the end
Qualitative process data	Videotapes of all the training sections, their filled worksheets, intermediate products such as sketches, impromptu interviews

Table 2 Sample questions from the conceptual understanding questionnaire

Dimension	Sample Item
Drafting: basic	Define drafting What kinds of drafting tactics are you familiar with?
Drafting: problem solving	The following item is part of a realistic scenario described from a perspective of a triathlete participating in a particular competition at a location familiar to all the participants I am drafting in a pack. I feel the northern wind blowing against my face. I catch a glimpse of the airport on my left side. My thoughts drift to a nice calm vacation by the sea. I ask myself "Why do I need all of this? Why are these five cyclists drafting closely behind me without helping me lead the pack?" *This situation has to change very soon. Otherwise our friend will burn out. Give him a quick and effective solution to change the situation. Explain your solution
Drafting: aerodynamics	 Pair break-away  Single break-away Compare the effort expended by the pair and single cyclists in the figures above A single cyclist expends more effort The pair of cyclists expends more effort The single and the pair of cyclists expend a similar effort I don't know Explain your answer
Physical effort	Define pulse What is the relationship between heart-rate and the level of effort?
Particulate nature of air	When two gas particles collide Both their speed and direction will change Their direction can change but not their speed Their speed can change but not their direction Neither their speed not direction will change
Micro/macro relations	What is the relationship between the heart-rate of a cyclist and the density of the surrounding air? Explain

tactics. It is framed as speed (output)/effort (input). As distance was a constant, speed is related to the reciprocal of time. It is computed as 10^6/(time x normalized heart-rate). Performance of the new tactics was compared to performance of the BT that was done in both parts of the study (Days 1, 2 and 3) to compensate for possible increased performance between Day 2 and Day 3. It was also calculated as the relative gain: (efficiency of the best new tactic—efficiency of the recent BT)/(efficiency of the recent BT).

Conceptual understanding was analysed from the questionnaire data, focusing on the pretest and second posttest (Day 3). The athletes' answers were coded, grouped by dimension, averaged and a learning gain measure was computed. In order to typify the athletes' concepts of aerodynamics in drafting, the entire questionnaire was searched for the highest level explanation of drafting among four: No description of air movement; air as mass (*when there is a face wind, the first one* [cyclist] *blocks the wind*), one-dimensional pressure topography (*the first rider expends more effort because he rubs against the air particles and side wind most. In comparison, the second rider, even though he has a wind from the front, he is next to the first rider, where the first rider reduces for him the friction with the air particles, when he blocks the wind from air particles*) or two-dimensional pressure topography that includes flow (*at a distance of 7–10 meters, the air particles move turbulently so there isn't any drafting*).

5 Findings

In this section we describe the Biking with Particles program through the eyes of one athlete, report on the athletes' designed tactics and their performance in drafting, their conceptual learning and inter-relations among them and between groups and their perceived sensations regarding air movement following the training program.

5.1 Leah's Move from Periphery to Center

The following portrays the training program from the perspective of one participant.

Leah was a 16-year old triathlete. She had been training and competing in the past 5 years and placed 10–15 out of 30 young women competitors of her age-group in Israel. She practiced about 6 times a week.

Leah was selected for this vignette as she is quite representative of the hobbyist group of athletes. Her performance in competitions is middling. From pretest to posttest, she portrays the group's average conceptual learning as the majority of the athletes on most items (mainly micro-level particle behaviors and micro/macro level connections, as will be shown in a further section of the findings) and conceptual non-learning in drafting (definition, problem-solving, aerodynamics). In the first day she was more reticent and less participatory. The reason she provided was that she hadn't road-biked and met her teammates for a long time. This was true for all the participating athletes, as the experimental training took place about a month after the winter vacation in triathletes' training. Similar to Leah, two other athletes showed initial reticence in participation that abated over time.

Overall, in transitioning from the first to last day of the study, we saw changes along several dimensions. In response to the questionnaires, we see her handwriting shift from illegible minimalistic writing with a narrow vocabulary of the sport to clearly written, articulated and detailed writing. In the pretest, she mentioned only a small number of drafting tactics: *drafting in a line… drafting in an ellipse…* In the posttest, she detailed several tactics, in fact exhibiting the widest range of tactics among participants in the study: *Drafting in an ellipse, drafting in a line without changing the leader, drafting in a line where the leader changes, riding arranged in two lines where the pair of leaders gets replaced at the same time, riding in a circle, riding with a row of riders in the front, a row of riders in the back, and a vertical row in the middle… drafting where the leaders keep changing, riding where the leaders ride in a diagonal line, and those behind them follow in a line*. From pretest to posttest, she increased in her micro-level understanding of how air particles behave and interact, learning that when they collide they change both speed and direction, and that upon hitting a large body, they do not change their speed. She discussed drafting in the pretest using concepts of energy and friction, e.g.: "Drafting is a way of riding one after the other. *The first rider fights the wind and the air more than anyone else. The riders behind the first rider save energy because they have less friction with the air*". In the posttest she sustained these two macro-level concepts, adding a micro-level description of air particles: *Drafting is a way of riding; that is a group of people riding together, where the leader rubs against [or "frictions"; in Hebrew, the verb and noun for friction are from the same root] the air particles and the rest of the group saves energy for the rest of the way*. When asked about the relationship between air density and a rider's pulse, in the pretest she wrote that she does not know. In the posttest she wrote: [The relationship] *between the pulse of a bike rider and the air density around him, is that when there is air density around him, then the pulse of rider goes up and it's harder to ride in comparison to a situation where the air density around the rider is very low, so it's less hard for the rider and he expends less effort.*

We now observe how learning unfolds.

Food is very important to teenage athletes in training. They are ravenous after physical practice and consume large amounts. Their parents are devoted to their nourishment and prepare a variety of dishes (mainly pasta and salads). In this domain, Leah was a leader. She organized the athletes in collaboratively determining who would bring which food, and in dividing the preparation of the meal and subsequent clean-up. Her voice was clearly heard as she directed people to perform the different tasks.

Conversely, in the Day 1 training sessions she was very reticent. Initially she sat at the back of the class by herself. She later moved up to sit by her teammate, Shira. While filling out the questionnaire she periodically peeked at Shira's writing. Her participation in the lively group discussions, such as comparing flocking birds and drafting while biking, was minimal. She talked only when directly addressed by the trainer. Even then, her answers were very short. The trainer first asked the whole group regarding the efficiency of a particular tactic. She did not volunteer an answer. The trainer then turned to her: *Leah, what do you think about this?* to which she answered: *The wind that came from the right side, the riders tried to get away from it*, an unclear idea that was not continued. When writing up her answers in the worksheets that accompanied exploration of the computer models, she was hesitant and halting.

On the road before riding, heated conversation took place geared at organizing implementation of each tactic. Leah did not participate in these group discussions. While riding the BT, her teammates were upset with her technique and voiced their exasperation. She rode at a distance that was too large from the biker in front of her. One of her teammates, Tom, repeatedly called out: *Leah, close the gap!*

In a later interview reflecting on the training program, Leah explained that on the first day she was insecure about her riding, as she hadn't ridden a road bicycle for a while. Since the beginning of the season, they had trained on mountain bikes. Additionally, she had not seen her teammates for a period of time *I didn't control biking so well as I hadn't biked for awhile, and I hadn't seen the children* [teammates*] with whom I was riding*.

On Day 2, she chose to sit at the head of the class. She began expressing her opinions regarding the new tactics that were designed and discussed by the team. Her comments were well directed and concise. Immediately following execution of a group of tactics, they were discussed in class. In discussing Joel's tactic, she contributed her interpretation of the individual and group results. She mentioned central advantages: *Joel's tactic was better because of a low RPE, a low heart-rate and a shorter time*. Her ability to combine the various quantitative measures supported reasoning about the quality of the tactic. Her teammates soon noticed the change she had undergone, both in discussions and in biking. The number of derisory remarks about her cycling technique was notably reduced from Day 1.

Following these 2 days, there was a 3-month-long lull before Day 3.

A complete change was observed on Day 3. In the first ride, the team repeated and improved on some tactics they had tried out on Day 2. They were surprised that Leah had seriously improved her biking technique in the BT, keeping only a few centimeters from the wheel of the rider in front. She assisted in coordinating the bikers' configuration. While riding in one of the heats, she repeatedly called out to her two female teammates: "Don't press so hard on the brakes!" Moreover, in the following heat, she helped her friend and teammate deal with physical hardship in keeping up with the group on one of its best tactics: *Shira, don't give up! Stay close to me.*

Following this ride, the athletes went back to improve their invented tactics by using the computer models. The tactics were named after their designer, such as "Shira's tactic", "Leone's improved tactic". After working on their designs individually, each participant presented their tactic. Four out of eight designs would be voted for execution by the team. Leah presented "Leah's tactic" as well. Her idea elaborated on a previous one, "Leone's tactic" using an overall shape of a hammer: a diagonal of riders in the front (head) followed by a line of riders (handle) (Fig. 4a). Different from the previous design, she added rotation among the riders in triplets. She divided the group in three: hammerhead, front handle and back handle. The three triplets would rotate their roles to share the load of leading. Her claims were logical and mainly clear. However figuring out and explaining the detailed local behaviors of each rider is not simple. First one teammate stood up to discuss and help her work it out at the board, then another (Fig. 4b). The team voted her tactic as one out of four for implementation (Fig. 4c).

Each of the invented tactics were led and organized by their designer. When the group executed Leah's design, one could observe her confidence and leadership as she organized the athletes into configuration, with almost no contrary comments or disturbance from her teammates.

In the final questionnaire, Leah wrote that learning about Biking with Particles through theoretical training with the models provided her with new ideas on how to improve her efficiency She also commented on its importance for training and competition, described how she learned to *sit against the wind*, her *learning new tactics* and highlights an *important improvement in confidence in bicycle riding*. Her claims and expressions included perspectives learned through exploring and experimenting with the models (*contact with air particles*), physiology (*loss of power and energy as a result of leading the pack did not change*) and movement biomechanics (*form of sitting on the bike*). However, they do not include drafting and its aerodynamics. She expressed a sense of ownership and responsibility as well. In the final interview she described her feelings about the part where the team implemented her tactic: *This is my tactic. I need to be responsible for it and I need everybody to do it well.*

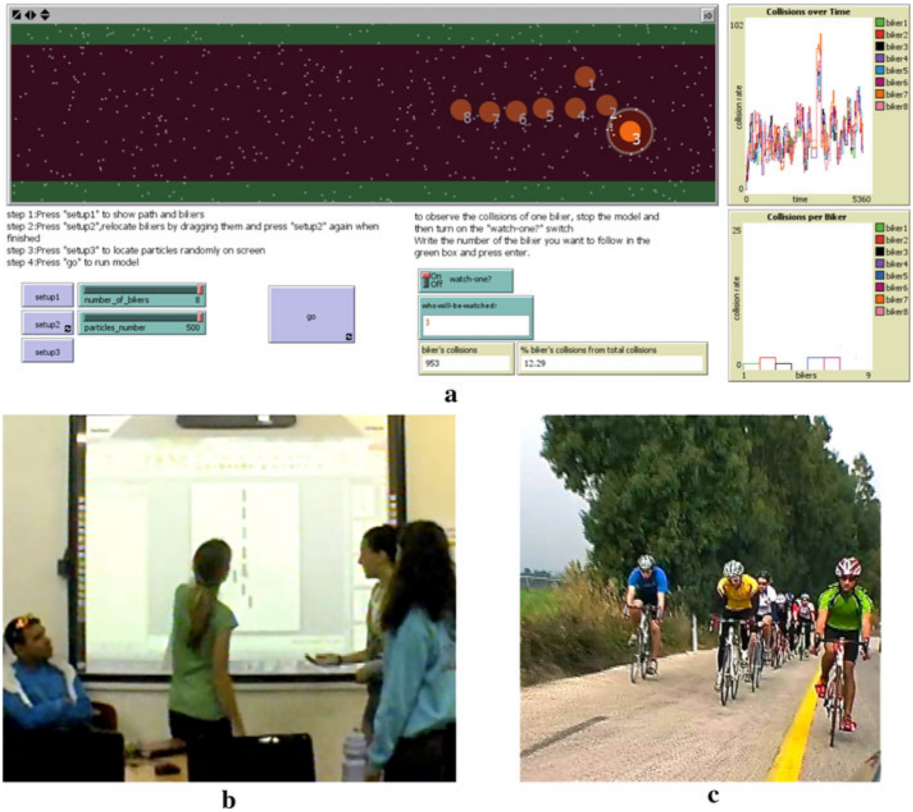

Fig. 4 Leah's hammerhead tactic designed with the computer model (**a**), presenting and discussing at the board with two assisting teammates (**b**) and during execution (**c**)

To summarize, we saw Leah's move from the periphery of the triathlon team to its center as her confidence increased, both in biking and in interacting with her teammates. From a minimal and forced participation she gradually began expressing her ideas clearly, performing better at biking and collaborating with her teammates. This culminated in the public display of her invented tactic that was taken up by the group. Her understanding of the topic of drafting increased substantially and included references to and processing of the new physical ideas that were learned, specifically the micro-level air particles, their density and the interactions between bikers and air particles. Her social standing improved, and she grew to understand the inter-relations between individual contributions and group achievements. In her own words, Leah described the implementation of her tactic as such: *We worked hard each one separately, but succeeded as a group.*

5.2 Invented Drafting Tactics

Figure 5 displays the work of Ofer, another youth athlete as he outlined a few ideas on paper before testing them with the computer model. The top-left configuration was the final one. However, reaching this design, one can see elements in the other drawings: bottom-right was an attempt to incorporate internal motion (seen as arrows) into the design that

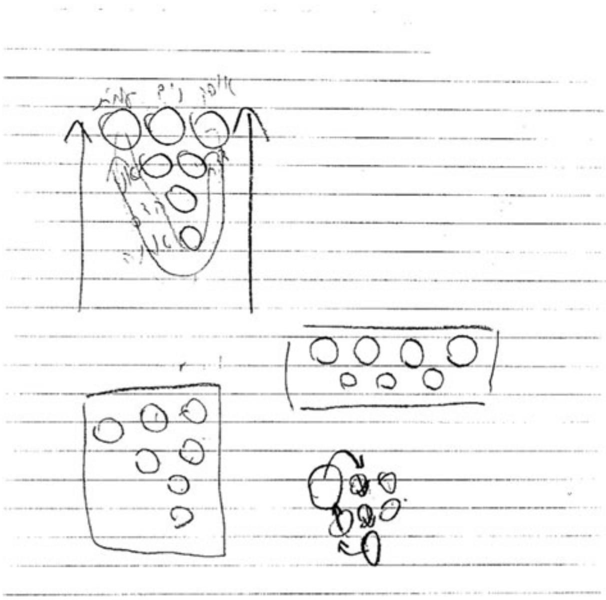

Fig. 5 Progress in designing a drafting tactic

didn't make it to the final design; in the middle-right were two staggered columns, made up of one-behind-the-other units and the diagonal relative positions; bottom-left showed a spatial configuration that he later used in the final design. The final design elaborated on this by adding the direction of motion (large arrows) and the names of the triathletes in each position: the strong ones are in the front; the national champion is in the middle.

The process of designing the new tactics was an individual activity. Each athlete worked on her or his own computer. The computer model (Fig. 4a) was used in the following way. The bikers (large circles) were first added onto the track. The athlete then dragged each of the bikers to a desired location. Then, particles were added and the model simulation initiated. While the model was running, a graph on the side describes the rate at which air particles hit each of the bikers. Since the resistance increased as the rate of air particle/biker collisions increased, the value was also related to the increase in effort by each rider. While running the model, the bikers could be moved around to obtain optimal effort, as seen in the rate at which particles collide with each rider. Upon completing the design process, group discussion ensued as described in the case study above.

The two groups' designed tactics were first analysed separately. As the distributions are similar, they are presented together. 17 of the triathletes' designed tactics as they were enacted in practice were analysed. All tactics were new in terms of being unfamiliar in the sport. In terms of the spatial layout they fell into five spatial categories (Fig. 6).

Figure 7 shows the frequency of various features in the tactic designs. Diagonal placements were the most frequent, followed by one-behind-the-other units. Placing the strong riders in the front and the weaker ones in the middle showed up to a certain extent. Least frequent were a good aerodynamic contour for the whole group, which involves more of a macro-view of the system, and rotation within the moving spatial configuration. It is interesting to note the design of tactics that had a division of labor distinct from the classical BT. Rather than divide the leading time equally, the weaker riders do not lead at

	Wrapped riders: Some bikers (usually the weaker ones) are surrounded on all sides by other bikers in a variety of spatial configurations (6/17)
	Hammer-head: A diagonal of stronger riders leads the pack; a column follows them, with the weaker riders up ahead (4/17 designs).
	Arrow-head: One rider the front, the rest following at diagonals of the previous ones (3/17 designs).
	Shape boundary, variety of shapes (3/17)
	Two lines (1/17)

Fig. 6 Spatial categories of invented tactics. The riders are moving from *left* to *right*. Numbers of designs in each category are in parentheses

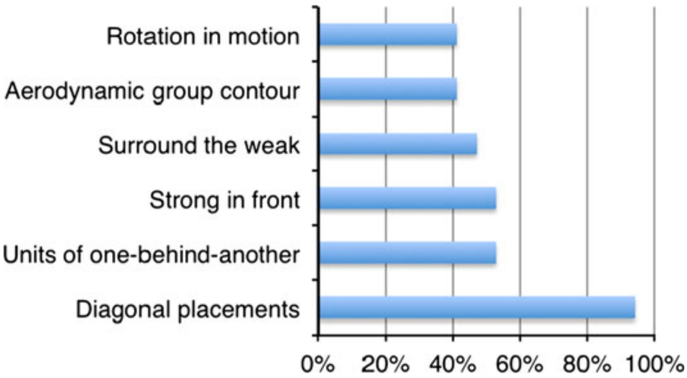

Fig. 7 Presence of features of triathletes' designed drafting tactics

all, as they will slow down the group. The weaker riders are instead "wrapped" in a variety of forms by the rest, so they need to expend very little energy in the process. This idea was novel in the domain. While most designs tried to benefit the individual riders, less than half considered the global shape of the group by making it aerodynamic.

5.3 Changes in Biking Performance

Table 3 presents the triathletes' biking performance results for the variety of tactics. The specifics associated with each tactic are under review and being prepared for submission elsewhere and are thus not described here. The comparison is between the invented tactics and the BT, a commonly used and efficient tactic. To account for changes due to other factors, the BT was measured on Days 1 and 3, and used as a base for comparison. Tactics conducted in Days 1 and 2 were compared with the Day 1 BT. Tactics conducted in Day 3 were compared with the Day 3 BT.

Table 3 Group performance results of elite and local teams

	Group	Hobbyists[a]			Experts[b]		
	Heat	Time[c]	Normalized heart-rate[d]	Efficiency[e]	Time	Normalized heart-rate[d]	Efficiency[e]
Day 2	BT	4:09	100 (25)	.72 (.22)	3:28	79.5 (12)	1.03 (.17)
	Invented tactic 1[f]	**3:57**[f]	100 (24)	4.45 E-5 (1.4 E-5)	**3:15**	96.5 (17)	.910 (.17)
	Invented tactic 2	5:22	**85 (24)**	4.0 E-5 (1.2 E-5)	**2:50**	94.3 (11)	**1.05 (.15)**
	Invented tactic 3	4:08	**80 (15)**	***.86 (.13)***	**3:14**	87.0 (9.6)	1.00 (.11)
	Invented tactic 4	–	–	–	**3:10**	94.2 (9.6)	.939 (.10)
Day 3	BT	3:50	89 (19)	.85 (.18)	2:52	104 (13)	.94 (.12)
	Invented tactic 5	**3:45**	**79 (26)**	**1.02 (.34)**	**2:58**	105 (14)	.91 (.12)
	Invented tactic 6	4:18	**80 (15)**	.83 (.12)	**2:44**	110 (12)	.93 (.11)
	Invented tactic 7	5:07	**84 (16)**	.67 (.13)	**2:50**	**100 (8.1)**	**.99 (.079)**
	Invented tactic 8	5:18	**86 (16)**	.63 (.15)	**2:44**	110 (12)	.93 (.11)
	Invented tactic 9	4:42	**83 (17)**	.74 (.14)	**2:46**	110 (10)	.92 (.085)
	Invented tactic 10	–	–	–	**2:47**	118 (8.5)	.85 (.061)

Bold results are better than those for the Belgian Tourniquet of the same day

[a] Local team

[b] Elite team

[c] Time to ride the distance of 2 kilometres

[d] Normalization is subtraction of resting heart-rate

[e] Efficiency is a variable created for this study, which takes the general form of output/input, or 10^6/(time × normalized heart-rate)

[f] The specifics associated with each tactic are nuanced and beyond the scope of this paper, although they exhibited features shown in Fig. 6. A lengthier discussion of these specific tactics will appear in a future document

RPE results are not included, as they do not add meaningful information. Additionally, the proportion of athletes who were operating outside of their aerobic range is not reported.

The efficiency and time results showed superior performance of the experts with respect to the hobbyists. A similar pattern is observed for both days: the hobbyists lowered their effort in all tactics (as measured by normalized heart rate); the experts lowered their times in most tactics; each group obtained one new invented tactic that was more efficient than the BT on both days.

For each group, the tactic with the best efficiency was compared with the BT. The experts improved in efficiency by 19 %. The hobbyists improved in efficiency by 20 %. For each athlete, the best efficiency among all invented tactics was recorded. The mean efficiency was .99 (.18), with higher mean efficiency for the experts [1.13 (.11)] than for the hobbyists [.86 (.13)], with an unpaired $t(11) = 4.01$, $p = .002$. The greatest efficiency was converted into a performance learning gain by comparing it with the efficiency in biking the BT. The proportion of improvement in efficiency averaged 20 % (25 %) with a high distribution. No significant differences were found between groups or genders.

5.4 Conceptual Change

A questionnaire was administered three times throughout the study (Table 2). The athletes' answers to the questionnaires were coded and analyzed by dimensions and described in

Table 4 Conceptual learning, N = 14

Dimension	Pretest score[a]	Posttest score[b]	Paired *t* test (*t*)
Overall	65 (17)	78 (11)	2.72*
Drafting: basic	53 (21)	70 (21)	1.90
Drafting: problem solving	73 (11)	71 (17)	.525
Drafting: aerodynamics	38 (23)	51 (32)	1.1
Physical effort	100 (0)	100 (0)	.512
Particulate nature of air	54 (23)	71 (32)	2.43*
Micro/macro relations	43 (51)	100 (0)	3.74**

* $p < .05$

** $p < .01$

[a] Reported in %

[b] Second posttest at the end of the third day

Table 4 Of greatest interest to us were the changes from the first to last questionnaires, as those represented pre- and post-intervention changes. No differences were found between genders. Between the two groups, differences were found regarding only one dimension: basic understanding of drafting in the pretest. For this dimension, the experts obtained a higher mean score (*SD*) of 66 (5) % compared to the hobbyists 43 (23) %, as determined with an unpaired $t(8.03) = 2.73$, $p = .026$. As no other differences were observed, the results are reported for the whole group of athletes, who all underwent the same Biking with Particles treatment. There appear to be significant changes in conceptual understanding, particularly due to understanding the micro particulate level of air particles and in understanding of micro/macro relations, of how the particles and athletes interact.

5.5 Change in Performance and Conceptual Change

The learning gain results for performance and conceptual understanding were compared and related. Significant correlations between the two were found for one conceptual dimension: basic understanding of drafting. Improved understanding of drafting was related to improved performance, with a medium Pearson correlation of $r = .563$ ($p < .05$).

5.6 Sensation of Air Movement

A questionnaire asking the athletes' about their perceived sensations of air movements and their possible relations to drafting was administered at the end of the study. Out of 14 athletes, 11 reported that they could feel the bodily sensation of air movement. With respect to previous drafting, three felt a very large difference in their ability to sense these motions, four felt a small improvement, and six felt no difference.

The following examples were the athletes' descriptions of their sensations. The descriptions were all related to their motions and actions during riding. They spoke of the aerodynamic phenomena in terms of pressure/resistance, treating the wind as an entity or, a spatial topography of pressure. None of these descriptions related to the micro-level air particles.

Pressure and resistance: *When I was behind someone while drafting, he blocked most of the air and I was in sub-pressure* [vacuum]. *Once I moved to the right or passed him,* *I could feel the air pushing against me again; When I was first or second, and then went down from leading, I felt how the air reduces its resistance.*

Wind as entity: *When someone rides in front of you, he splits the wind for you; There is much less wind working against me. So it helps physically but also psychologically.*

Contained space: *Today in drafting, I felt that I "sat" and did not lead, that I was in this bubble. That I don't need to work hard, just to hold on to the group.*

5.7 Perception of Training Program's Utility

Out of 14 athletes, 12 athletes felt they could use what they had learned in the Biking with Particles program for improved future drafting. In describing how they could use this understanding several factors are mentioned. Most of these factors involve the personal benefit of the individual cyclist within drafting. They do not relate to the collective or group perspective.

New forms of drafting: *Now, with models I can organize drafting while competing.*

Personal aerodynamics: *I can use what we learned with the models in the way I sit and ride against the wind.*

Greater adaptation to environmental changes: *Awareness of the importance of different tactics results in my being more focused and aware of what is happening around me while drafting and then I can respond accordingly.*

6 Discussion

In the introduction, we asked whether a complex systems constructionist perspective could advance understanding and performance in sports. The answer is no and yes. This study approached learning as evidenced in junior triathletes' design of collaborative action while drafting in bicycle competitions, their execution of these designs, related conceptual change, and reported perceptions of air movement. We had applied a complex systems approach to the aerodynamics of drafting using several agent-based computer models that offer a simple way of making sense of the system. These models offered both an explorative and a creative medium for the athletes as they designed new drafting tactics. We turn now to a discussion of the findings.

6.1 What Features Characterize the Triathletes' Invented Tactics?

We had found the triathletes' designs to be innovative, proliferate, and diverse. Their inventiveness goes beyond the single and double line, or the Belgian Tourniquet described for triathlon competitions. Older central triathlon coaching texts do not mention drafting at all (e.g. Town 1985; Anchwer 1998). The newest coaching text to date (US Triathlon 2012) describes only the rudimentary tactic of a single line. As drafting is a relatively new and still-contested feature in triathlon competitions, it seems that there could be much room for growth in this respect. The junior triathletes introduced several new tactics into the field of competitive bicycle riding in triathlons, a significant achievement.

At least five spatial categories were proposed, that involved distinct contours of the drafting group. The athletes continued using well known principles of keeping behind somebody else in a low-pressure range and smoothing the drag by moving on the diagonals. While these elements are known it is important to state that their actual implementation is inventive. There is an infinite number of ways one can combine these local features to obtain global patterns. Moreover, new features were introduced and developed in several tactics that involve an uneven share of the load. The stronger athletes take upon themselves more than an equal share of effort, and the weaker ones less. Weaker riders were nested among additional riders in low-pressure bubbles that supported very easy riding, so that they would not keep the group back. As the dilemma of "stay or break away" (cooperate or compete) is constantly there, the athletes have developed the "stay" part of this delicate balance, so that the gains for individuals and the group would be greater. Without our intervention, triathlons include drafting and collaboration. Our athletes have developed similar ideas in two separate teams that introduced a more nuanced way of drafting they can benefit from in competition.

It is important to note that the features least common in the designed tactics are rotation within a spatial configuration and having an aerodynamic contour. Rotation within the spatial configuration introduces an additional dimension into the aerodynamic considerations–time-and is thus more challenging. Moreover, the computer model that was used to design these tactics did not include an option for rotation while moving. We are currently working on a more advanced model that includes rotation among the cyclists and several other environmental features such as wind and non-horizontal terrain (Bacalo et al. 2012). Having an aerodynamic contour involves zooming out from local to global features. During the training period, the athletes learned about interactions between individual air particles and the cyclists and interactions between the cyclists. They even connected some local and global features, such as the simpler relationship between air density and effort. Considering both levels is more difficult as evidenced in research into understanding a variety of complex systems, and this consideration usually comes later in the learning process (Levy and Wilensky 2009a; Levy and Lahav 2011). One may expect that further learning could result in the athletes incorporating such a micro-to-macro view, so that considering aerodynamics of the group's contour would be part of their designs.

Both participating teams were devoted to their sport, as it took a central place in their lives, even though their performance results are distinct. One of the goals of the Biking with Particles intervention was to help the athletes have a greater competitive edge, a goal that sits at the heart of their hopes and efforts. We have seen them engage at length both individually at the tactic design stage and collaboratively in discussing the benefits and shortcomings of each tactic and testing them out. This finding strengthens the constructionist claim that learning is deeper and more passionate in the context of constructing towards personal goals and then sharing them within a community (Papert 1980).

6.2 How Does Young Triathletes' Biking Performance Change as a Result of Training? How is this Related to Expertise?

We have seen a radical change in performance, not usually evidenced in the domain of competitive sports. The triathletes improved their efficiency (speed with respect to effort) by 20 %, both as a group and as individuals. Improved performance is related to greater speed, expending less effort, and staying within the aerobic range. A methodological contribution of the current study is developing a metric for the main factors as a single efficiency measure. This measure supports comparison between tactics.

One of the findings regarding the differences between the experts and the hobbyists is their distinct performance. As expected, the experts' initial and later performance is better than that of the hobbyists. Greater expertise involves more efficient and adaptive action. However, the training program benefited both groups similarly in terms of efficiency, both with around 20 %. The Biking with Particles advances both experts and hobbyists in their performance and understanding.

A less expected difference involves the performance components they improved on. The experts mainly raised their speed and the hobbyists mainly lowered their effort. One explanation for this may come from the more fierce competition among first-place elite athletes. In competition, one may strategize to conserve energy and use it wisely, but the direct measure of success is time to complete the race. Another explanation involves the relative abilities between swimming, biking and running. Experts in triathlon are particularly strong runners. Running is the last leg of the race. To save energy for this crucial section, it is important that they benefit from reduced effort through drafting. However, also within drafting, they need to keep their competitive edge. Thus while enjoying the benefits of drafting, they use this benefit to compete better.

6.3 What Typifies Conceptual Change Related to Participating in the Program? How is this Related to Expertise?

We have seen a small but significant rise in conceptual understanding, particularly due to understanding the particulate nature of air and micro/macro relations of how particles and athletes interact. However, conceptual understanding of drafting—basic definitions, aerodynamics and problem solving—did not change through training with Biking with Particles. We may conclude that a complex systems perspective was learned, but this did not create a greater understanding of the phenomenon of drafting. We elaborate in Sect. 6.6.

As their greater experience would predict, experts knew more of the basic definitions and ideas regarding drafting with respect to the hobbyists before training began. However, no other differences in learning or later understanding were found.

6.4 How are Changes in Performance and Conceptual Learning Related?

It was found that one component of conceptual learning was related to performance improvements: basic knowledge of drafting. This highlights the importance of a conceptual understanding of drafting to its use. This suggests that possibly improving the learning environment to enhance such understanding may be related to greater performance gains. No changes in other components of conceptual knowledge were meaningfully correlated with better performance.

6.5 What are the Athletes' Perceived Sensations of air Movement Following Training?

At the end of the research period, most the athletes stated that they could feel the air as they biked. Half reported that this sensation increased as a result of the training program, to a smaller or greater extent. They described sensations of pressure difference, changes in the air as a mass and spatial topographies of low and high pressure. Some described a greater ability to adapt to environmental changes.

In designing Biking with Particles, one of the problems we addressed was a non-adaptive "mechanical" performance while drafting. Through understanding the changes in pressure and flow, we hoped to sensitize the athletes to their changing ambience (perception) and provide for new performance elements that could be applied (action). These results offer a possibility that the training program has aided the athletes in creating more refined perception–action schemes.

6.6 Conceptual Learning and Changes in Performance

One may wonder as to the small rise in conceptual understanding when such a large increase in performance was under way. While the athletes learned the basic physics of air particles' motion and could use the ideas of air density to understand effort, they did not improve their understanding of drafting. Moreover, this increased conceptual understanding is not related to improvement in performance, aside from one component: individually doing better at drafting is related to learning more about basic notions of drafting, such as defining it and acquaintance with a larger number of drafting tactics. One would not need the Particles and Bikers training program to learn these topics.

This curious phenomenon can be understood when one considers the athletes' personal goals in learning and processing limitations (Miller 1956). They are devoted to their sport, practice several times a week, and participate in competitions. While understanding the physics related to the sport may be more or less interesting to them, they all share a passion for competing well. The central role of personal goals has been discussed above as explaining differences between experts and hobbyists. Thus, improving their performance is of prime importance. After learning some of the basic principles described above, learning seems to have been diverted from further conceptual learning to motor learning of the new drafting tactics.

Motor learning has been described as going through three stages: (1) cognitive-verbal; (2) motor; (3) autonomous (Schmidt and Lee 2011). It seems that in this study, the cognitive-verbal stage was cut short, and partly "skipped over" so that most of the learning happens at the motor stage. This finding begs the question of whether the first stage is a necessary pre-requisite for the second stage. It suggests that with motor skills, one does not have to verbalize what one understands in order to perform it. Processing in the motor learning stage involves making performance more adaptive and efficient. It would seem that the visual and spatial information provided by the models and completed by the athletes' imagination and mental simulation could be enough to create a solid basis for improved action. The highly visual and dynamic quality of the computer models leads to incorporating the ideas they offer into perceptual-motor schemes without going through the channel of verbal explanation. Complex systems models present a challenge to cognitive verbal learning. With agent-based models, users can detect global patterns and imagine themselves locally as one of the biker representations. Working with spatial patterns supports circumventing the verbal channel, verbal articulations that may be too complicated to express without the related physics language. It may be that motor learning theory could be elaborated in light of the observations made in the current study.

Another important finding is the diversity of designs, the wide array of tactics the athletes' created. The training program was designed so that inventing tactics started out as an individual activity and only later was brought to discussion by the team. This process ensured that at the first stage, the athletes would not be influenced by each other ideas,. This broad range of tactics made up a dataset that supported collaborative research into several avenues that could improve performance. By working individually and later together, there was much room for creating new ideas and improving them incrementally.

6.7 Limitations of the Study

This study is limited is several respects. As it is the first research into the topic, it carries with it an air of exploration. The sample is small, so that concluding from the results is limited. The questionnaires could have been designed better so that one topic that displayed a ceiling effect (understanding physical effort) could be measured and in order to introduce opportunities for the athletes to express additional aspects of their understanding. Including semi-structured interviews would enhance capturing their conceptual understanding. The athletes' sensations of air was measured only at the end and using a self-report questionnaire. More behavioral measures would be helpful in determining their perception of pressure changes and flow. Future research will address these limitations.

6.8 Implications for Physical Education and Competitive Sports

In the modern triathlon, drafting takes a central role in coaching methodology, however coaching theory is lacking. Training methods have changed as a result of permitting drafting in youth and elite competitions but not enough. In the current study, the participants were exposed to the issue of drafting and understanding its physical causes. The Biking with Particles training program was engaging for the athletes, enhanced their performance and to a lesser extent, their understanding. Coaches may use this program and its computer models to illustrate and analyse tactical moves to their trainees. In the field of physical education, the results of this study may serve to help students understand processes in which individuals interact within groups while using physiological aspects to monitor and advance their abilities. Moreover, using computer models in physical education to understand and represent various skills is advanced.

7 Conclusion

In this study, we have had a meeting of minds between competitive sports, constructionist learning of physics, and a complex systems perspective. A much-contested topic in the triathlon sport was approached: drafting, We have seen "learning in levels" for at least two dimensions: understanding drafting aerodynamics in terms of air particles and bikers; understanding how bikers interact through the medium of air to create energetic advantages. The first involved explicit and verbal learning with computer models that was expressed through writing into structured questionnaires. The latter kind of learning took place by changing perception–action schemes as the riders re-arranged themselves into more optimal patterns, part of it explicit—in designing and conducting the tactics, and some of it implicit—in gentle rearrangements of location to reduced friction with the air. These latter gentle re-arrangements involve increased sensitivity to air pressure and air flow and were reported on by half of the athletes. Explicit articulation of the actual aerodynamic patterns of airflow was beyond our athletes. Yet it seemed that they could use this implicit knowledge to enhance their performance in a dramatic way.

Acknowledgments We are particularly indebted to Ronnie Lidor, currently president of Wingate College, the main Israeli sports academic and Olympic center, who has provided much support in spirit, in designing the study and thinking through the theory. We thank Uri Zilberman, the elite team's coach, who supported, accompanied and encouraged us in this study. We are grateful to the athletes in the two teams that participated in the study and engaged with all their hearts in the training, providing thoughtful reflection and advice. We thank Wingate College and an anonymous northern local school for providing us with their facilities and support during the study. We gratefully acknowledge Osnat Gal, Asher Kakoon, Yoni Bacalo, Ariel Asaf and Lital Zar who worked with us on creating the computer models.

Appendix

Biking with Particles Training Program and Models

A triathlon training program named Biking with Particles was created. It is made up of some short lectures (e.g. on the relationship between pulse and effort), several discussions, exploring computer models of flocking birds and bikers in various configurations and then using the models to create new possibly more efficient configurations, testing familiar and invented tactics out on the road (five tests, four heats each) and collaborative analysis and discussion of the pulse, time and effort data (Appendix).

See Table 5 and Figs. 8, 9, 10, 11.

Table 5 Biking with particles training program

Days	Activity
Day 1	Pretest questionnaire
	Opening: presentation of program, elicitation of athletes' knowledge about drafting
	Birds and triathletes: group viewing of videos and discussion of pros and cons of drafting. The videos combined movies of flocking birds and various situations while drafting in triathlon competitions
	"Flocking birds" model exploration: guided exploration (Figure **) followed by discussion
	Physiology of heart-rate and effort measurement: Lecture
	Biking set 1: riding in four heats of coach-determined tactics (alone, line, two lines, BT)
	Analysis of results Discussion focused on the individual and group results in Biking set 1
	Flocking birds: lecture on cranes, individual characteristics and collective behavior
	"Big Particles" and "Birds and Particles" model exploration: guided exploration (Figures ** and **)
	Discussion and conclusion of first day
Day 2	Biking set 2: riding in four heats of coach-determined tactics (alone, two forms of breakaway, BT)
	Analysis of results Discussion focused on the individual and group results in Biking set 2 and of drafting.
	Design of tactics with "Of Particles and Bikers" model (Figure **)
	Discussion and voting on tactics: each participant presents their tactic, followed by discussion of pros and cons. Vote on tactics to be executed.
	Biking set 3: riding in four heats of inventor-led tactics
	Analysis of results Discussion focused on the individual and group results in Biking set 3, comparison among tactics
	Conclusion
	Posttest 1 questionnaire
Day 3	Opening session; Reminders of activities on the first and second days; introduction to Day 3
	Discussion of invented tactics from Day 2: presentation of invented tactics and their quantitative results; Pros and cons; selection of tactics to be executed
	Biking set 4: riding in four heats of both coach and inventor-led tactics (BT, invented)
	Analysis of results Discussion focused on results, comparing Biking sets 2 and 3, comparison among Biking set 4 tactics
	Design of tactics with "Of Particles and Bikers" model
	Discussion and voting on tactics: each participant presents their tactic, followed by discussion of pros and cons. Vote on tactics to be executed
	Biking set 5: riding in four heats of inventor-led tactics
	Analysis of results
	Posttest 2 questionnaires
	Summary discussion

Models used in the study

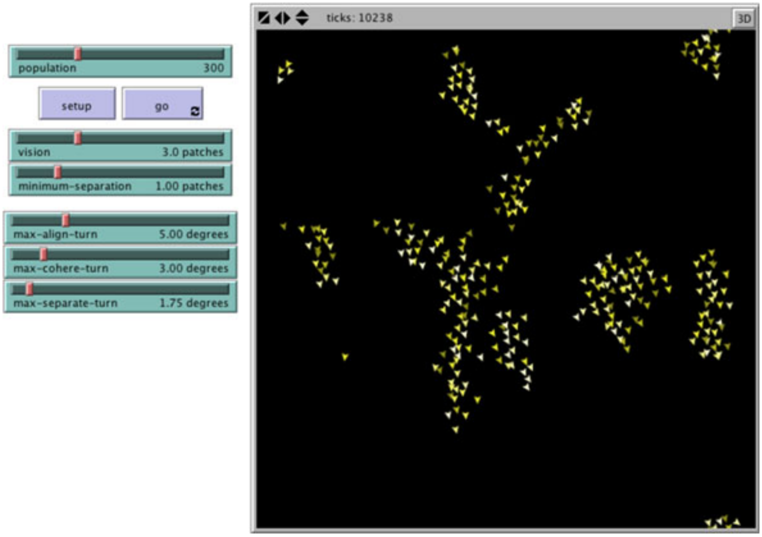

Fig. 8 Flocking (Wilensky 1998)

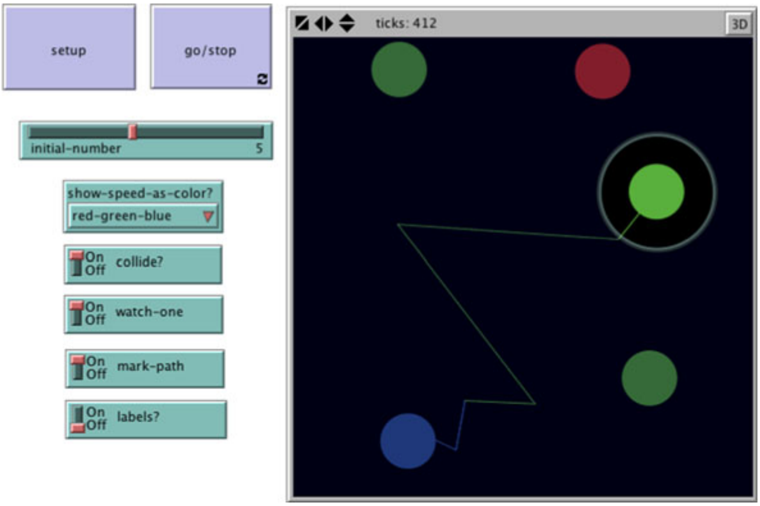

Fig. 9 Big Particles—adaptation of the "Connected Chemistry 3 Circular Particles" model (Wilensky 2005)

Fig. 10 "Birds and particles"—adaptation of the flocking model above, to include air particles and their interactions (Hirsh et al. 2011)

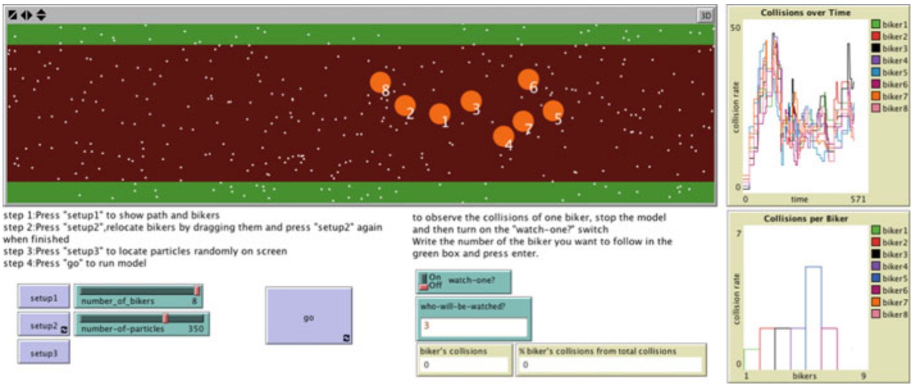

Fig. 11 "Of particles and bikers": bikers (*orange circles*) move from *left* to *right*. One can adjust several features in the model, and most importantly change the spatial configuration of the bikers. On the *right*, one can observe the rate at which each biker is getting hit by particles, and how this changes over time. This rate is related to the effort expended by the moving through the air (Bacalo et al. 2011)

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