The characteristics of homeostasis: a new perspective on teaching a fundamental principle in biology

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ABSTRACT Homeostasis is a fundamental principle in biology that represents the biological essence of living organisms: the dynamic stability of the body. There are difficulties comprehending homeostasis, as there are concrete sensory aspects as well as scientific aspects that are abstract and complex. These difficulties have led us to define eight characteristics of homeostasis, in order to describe the 'homeostatic features' of physiological systems (processes and situations) in living organisms. We present perceptions regarding homeostasis of 12th grade biology students (age 17–18) who studied homeostasis through those eight characteristics. The students' perceptions reflect their understanding of the multifaceted appearance of homeostasis in living organisms.

Over many years, research has examined students' perceptions of physiological homeostatic systems and has demonstrated students' erroneous perceptions and difficulties in understanding the fundamental principle – homeostasis in the entire body. In order to develop a better understanding of homeostasis among students, we defined characteristics of homeostasis that may be used in the teaching and studying of homeostasis. We investigated how students understood homeostasis by its characteristics.

Defining and understanding homeostasis

Definitions and understandings of homeostasis have undergone many changes, beginning with Claude Bernard (1813–1878). Bernard first referred to the body's internal environment – *milieu interne* (Cannon 1929: 400). Walter Cannon (1871–1945) was the first to define the term *homeostasis*. He assumed that constancy and stability in the body require ceaseless change, and he explained that the dynamic stability is homeostasis (Cannon, 1929: 400). In his physiological research, Cannon (1929) also defined six 'homeostatic agents' navigating the operation of physiological factors that maintain homeostasis in the body. He emphasised the role that these factors play in maintaining constancy of the body, ceaselessly neutralising 'disturbing conditions'. He also referred to cooperation between homeostatic factors that affect processes synchronously.

For many years, homeostasis was studied primarily in specific physiological systems, such as the nervous and the cardiovascular systems. Then, homeostasis was studied on the cellular, molecular and ionic levels by applying mathematical, physical, chemical and cellular properties (Cheng, Jiang and Han, 2007). Recent studies have focused on examining homeostasis in long-term processes, which result in abnormal states, in cases such as change of body temperature, stress, weight loss, obesity and living at higher altitudes (Stewart, 2006). There is also reference to different levels of homeostasis throughout the natural lifespan in general, and in old age in particular (Calabrese *et al*., 2006).

Difficulties in understanding homeostasis

Physiological systems that demonstrate homeostasis in the body, such as the urinary, respiratory and cardiovascular systems, are particularly complex in structure and function. Memorising names of system components is not enough to understand the behaviour of the whole system (Hmelo-Silver and Azevedo, 2006). Students often exhibit difficulties in understanding homeostasis because formal thinking levels are required to understand this complex and abstract principle (Westbrook, 1987). These difficulties are expressed in the understanding of:

- **the complexity of the body** – the organism's body is composed of several physiological systems that function together; students often perceive the body as a '*black box*', and its internal processes (such as thermal regulation) as a complete mystery (Ben-Zvi Assaraf, Doddick and Tripto, 2013);

- **each physiological system is composed of several complex organs**, built of different tissues in an organised structure;
- **various physiological and biochemical processes occur simultaneously**;
- **each process is composed of sequential steps**, and occurs under control and regulation;
- **homeostasis is both a state and a process**;
- **homeostasis exists in different levels of organisation** – some phenomena are easier to understand on the organisation level of the entire body but more difficult to understand on a cellular or molecular level;
- **many terms are involved in description and definition of the homeostatic mechanism**, such as regulation, coordination, control, negative feedback, dynamic equilibrium, stability and internal environment;
- **internal contradictions are embedded in the classic definition of homeostasis** – examples of these contradictions are the terms 'dynamic stability', 'a constant internal environment' and 'dynamic equilibrium'.

Characteristics of homeostasis

We defined eight characteristics of homeostasis, based on the scientific literature and through consultation with two physicians, three biologists, five teachers and two science education specialists. Each characteristic is explained in Table 1. The characteristics are based on the following descriptions:

- **process dynamics** ('dynamics' and 'physiological balance');
- **biochemical-physiological mechanisms** ('control and regulation' and 'feedback');
- **location** ('environments');
- **interrelated systems** ('dependency between events' and 'multi-systems');
- the occurrence of homeostasis on **different levels** in living organisms, including prokaryotes ('levels of organisation').

Having defined the characteristics of homeostasis, we then set out to examine whether biology teaching that emphasises these characteristics can help students understand homeostasis as a fundamental principle.

Methodology

The research participants were 93 Israeli 12th grade biology students (age 17–18 years) attending municipal or regional high schools with heterogeneous classes of students from similar socio-economic backgrounds. The students studied homeostasis as demonstrated in the lactose operon by means of an instructional website *Homeostasis on the Molecular Level*. This website (for which the second author was the scientific adviser) contained several learning tools (dynamic simulations, analogies, virtual labs and a game) and applied these tools to illuminate the characteristics of homeostasis in the lactose operon. Moreover, the characteristics of homeostasis were demonstrated and highlighted in other physiological homeostatic situations and regulation processes. For, example, the characteristics were summarised by demonstrating the features of homeostasis in organisms such as a snake, an elephant and a shrew, in comparison with humans. By the end of this learning process the students were expected to have obtained a multidimensional image of homeostasis – from the molecule in a bacterium cell to the whole body.

We examined homeostasis understanding by administering a questionnaire (CHCQ: Comprehension of Homeostasis Characteristics Questionnaire). The questionnaire was initially developed by interviewing biologists, teachers and science education specialists. The content and components were examined and validated by experts: three teachers, two biologists and two science education specialists. Validation was carried out by examining the correlation between the questionnaire components and characteristics of homeostasis. A reasonable consistency of $\alpha = 0.734$ was found. The CHCQ contained two types of question:

1. questions about concrete phenomena and processes chosen to represent characteristics of homeostasis such as blood clotting (control and regulation of the clotting factors) and hormones (feedback);
2. questions that refer to images from which characteristics of homeostasis can be 'extracted' – we constructed an indicator (which was examined by two specialists in biology and science education) for analysing the students' responses and used it to rate student replies

Table 1 Content of the Comprehension of Homeostasis Characteristics Questionnaire (CHCQ)

Content group	Description of content
Dynamics of a homeostatic process	Homeostatic processes are characterised by the **active maintenance** of physiological, chemical and physical parameters. The processes occur **throughout time**, **all the time**, and there are **bidirectional, fluctuating and correcting deviations** in process rates or physiological parameters around average values. Homeostasis is the sum of all processes maintaining the stability of the internal environment.
Physiological balance	This characteristic emphasises the **dynamic equilibrium** in the body (or tissue, or cell) that is sustained physiologically throughout the lifespan of an organism. Homeostasis is a steady state, meaning that there is a dynamic equilibrium in which input and output of materials and energy are balanced.
Control and regulation of a homeostatic process	Homeostasis in complex organisms requires a mechanism that monitors changes, accompanied by regulatory mechanisms that return the altered state to a desirable one. The overall control of the body is integrated with the local regulation (enzymes, ions and co-factors (in any particular system and its micro-environment.
Feedback mechanism	The homeostasis mechanism relies primarily on the principle of **negative or positive feedback**. Feedbacks are expressed in the **effect of product concentration on a process rate**.
Environments	This characteristic is the most common regarding the definition of homeostasis. Homeostasis is the **maintenance of the internal environment in a relatively stable state in the face of changes in either the external or internal environment**. Both internal and external environmental factors act as stimuli for organisms in the maintenance of homeostasis.
Multi-systems (complex system)	**Physiological and biochemical systems** coordinate in harmony to ensure proper function and maintain homeostasis. Coordinated systems operate in the entire body, in each physiological system, and in each individual cell.
Dependency between events within a system or process	This characteristic describes **events comprising a process over time** (e.g. heart rate or the pace of walking in a healthy state). Dependency between events indicates a **correlation within a process**.
Levels of organisation	Homeostasis occurs in a variety of living organisms at **all levels of biological organisation: molecular, cellular, tissue, entire organism, and community**.

based on their accuracy: correct perceptions were rated highest and appear in this article.

Results

In Table 2 we present students' perceptions of homeostasis characteristics. The table shows excerpts from students' replies and gives the percentage of students that wrote similar replies.

Dynamics

This characteristic was examined regarding two homeostatic parameters – heart rate and temperature – during normal activity, over time, and under alternating conditions of stress and relaxation. The students were asked to draw and explain a graph representing their body temperature and a graph representing their heart rate over several hours, explaining what they had drawn. They understood the dynamic stability of the internal environment, expressed in the parameters of body temperature and heart rate. The students emphasised that the body's internal environment is not fixed or permanent; this environment is stabilised by slight correctional variations, constantly occurring as a result of internal and external factors. Dynamics of homeostasis was also examined using various images, such as ocean waves, a moving train, a man ascending stairs, a man riding a unicycle and a clock mechanism. Students were required to identify and explain the images that represent characteristics of the dynamics of homeostasis. These replies also indicated that students perceived homeostasis as being constantly in motion, bidirectional and fluctuating due to ongoing deviations from an average and subsequent correction.

Physiological balance

The questions focused on a concrete system characterised as existing in 'equilibrium'. The purpose of these questions was to examine the degree of students' ability to distinguish between spatial balance on the one hand and homeostasis

Table 2 Students' perceptions about homeostasis (the percentages are the proportions of students who gave a similar reply)

Biological process or parameter	Students' perceptions
Characteristic: Dynamics	
A homeostatic process constantly operates to achieve an active stability of the internal environment. 69% ($N=93$)	*'Our internal environment is more or less constant. Body temperature is never constant. There are small variations due to different bodily and environmental factors.'* *'When activity is normal, heart rate remains quite constant, though with slight deviations up or down, because activity level might change. Small changes that would be expressed in small changes in heart rate.'*
Total for the following three perceptions: 56% ($N=93$)	
Homeostasis exists in an internal, defined and stable environment.	Regarding ocean waves as an analogy to homeostasis: *'Because waves appear at random and not in a steady, defined pattern. Homeostasis expresses a stable and defined internal environment.'*
Homeostasis is a bidirectional process.	Regarding a moving train as an analogy to homeostasis: *'Because the train travels always in one direction and there are no fluctuations. Homeostasis, however, is fluctuant: sometimes there is a deviation from the constant value, then a correction and return to the constant value…'*
Comprehension of homeostasis as a complex system.	Regarding a clock mechanism composed of cog wheels as an analogy to homeostasis: *'Because one fault in the gear will halt the instrument, that is, all of the parts depend on each other and affect each other. In homeostasis, a change in the activity of one factor, usually external, will not necessarily shut down the entire system.'*
Characteristic: Physiological balance (comprehending the distinction between spatial balance and homeostasis)	
Physical balance of weight. (Is it homeostasis?) 67% ($N=89$)	*'This is not homeostasis. There is no distinction between internal and external environments, but rather the use of a balancing organ for walking on a beam.'*
Dynamic stability existing in a circumscribed internal environment comes into contact with an external environment. Dynamic equilibrium in an open environment (habitat) is not homeostasis. 45% ($N=89$)	*'Homeostasis is maintaining values in an internal environment (achieved by a chain of processes intended to balance the situation). In an ecosystem, it is not an individual's internal environment, but rather an external environment. It is* [e.g.an ecosystem] *an example of a normal value range, but not in an internal environment, and therefore is not homeostasis.'*
Characteristic: Control and regulation	
A. Homeostatic systems operating by dynamic stabilisation of a homeostatic parameter	
Blood clotting. Understanding the system by identifying the homeostatic parameter that remains dynamically stable. 82% ($N=89$)	*'If blood clotting would not occur, blood volume would decrease. This is one way to maintain stable blood volume.'* *'Blood volume in the body is constant, and should remain constant. Blood clotting prevents blood loss, and is therefore linked to homeostasis.'* *'A cut on one's finger will result in blood loss – and therefore – the blood volume will change. Blood clotting… prevents the change in blood volume, thus maintaining a stable internal environment.'*
Stomata activity in plants. 75% ($N=89$)	*'Plant's internal environment behaves in some way resulting from the external environment. Homeostasis makes the plant open and close the stomata in different quantities in order to keep the quantity of water as stable as possible.'*

Biological process or parameter	Students' perceptions
B. Changing the rate of processes over time, in the lifespan of a living organism – a new level of homeostasis is created	
Respiration rate throughout life. 49% (*N* = 89)	*'The respiration rate is adjusted by different oxygen requirements at different ages. The change in the respiration rate is due to a different requirement in oxygen quantity – thus maintaining the required quantity.'*
Ageing (blood constitution in a young and old body). 47% (*N* = 89)	*'At 70 – the needs of the body are different, and the blood constitution is accordingly different, in order to maintain balance and normal operation of the system.'*
Characteristic: Feedback mechanism	
Several hours after a meal, the glucose level decreases to a certain point but not below it. Understanding the mechanism of the process as negative feedback. 20% (*N* = 93)	*'Because there was a deviation in the body and the constant value of blood sugar rose, the body goes through some mechanism or correction by the insulin hormone… that is, more glucose molecules penetrate the cells and so blood sugar decreases. There was a correction = a negative feedback.'*
ADH hormone activity. Identifying the mechanism of the process as negative feedback. 42% (*N* = 93)	*'When water decreases, secretion of ADH rises, then urination decreases, and therefore a decrease in ADH occurs. The hormone caused some activity that caused a decrease in its quantity.'*
Characteristic: Environments	
Homeostasis in various conditions of the internal and the external environments. 39% (*N* = 93)	*'Homeostasis mechanisms operate in both frogs, affecting a difference between solution concentrations in the internal and external environments.. in the second species of frog (sea), the mechanisms make the internal concentration lower than the external.'*
Characteristic: Dependency between events within a system or process	
Regulating cell iron levels. Understanding dependency between events in the homeostatic system regulating cell iron level. 43% (*N* = 72)	*'When iron ions are deficient, ferritin in the cells releases free iron ions from these cells. Because there is homeostasis, the internal environment, the iron ions, adapt to the external environment.'* *'The higher the concentration of available iron, the lower the number of transferrin receptors on the cell membrane, as no more iron is "needed". Number of ferritin molecules – the higher the concentration of available iron, the higher the number of ferritin molecules, as the function of ferritin is to bind "excess" iron.'*
Secretion of hormones from the hypothalamus 49% (*N* = 72)	*'Here the concentration of hormones secreted is maintained. If the hormones are not necessary, their secretion will cease. Therefore, the secretion of hormones keeps the stability of the internal environment.'*
Characteristic: Multi-systems	
A connection between two complex, multi-systems factors – body temperature and metabolic rate – in a homeothermic and poikilothermic animal. 47% (*N* = 78)	*'Homeotherm – has a fixed body temperature, regardless of the environment's temperature. If the temperature drops, it has control and regulation mechanisms to prevent its cooling. The metabolic rate will rise because the animal has lost heat, and in order to produce heat, its respiration rate will increase, burning glucose by oxygen and raising the metabolic rate. A poikilothermic organism maintains its body temperature by external mechanisms.'*
Characteristic: Levels of organisation	
The operon system in bacteria. Identifying the bacterial operon system as a homeostatic system that maintains the physiological parameter of energy level. 65% (*N* = 74)	*The homeostatic system in bacteria involves maintaining a more or less constant energy level. As long as the bacteria are supplied with glucose or lactose, the energy produced in cellular respiration remains at the same level.'* *'Cellular available energy level must remain within a certain range, so when glucose runs out, concentration of the enzymes breaking down lactose is raised, ensuring enough energy is produced to maintain the bacterial cell. There is maintenance of a fixed value range for available cellular energy.'*

and 'dynamic equilibrium' (an expression that is often used to describe homeostasis) on the other. The students' replies indicated that they differentiated absolutely between maintaining spatial balance, and the existence of homeostasis in the body's internal environment. That is, the students generalised the terms 'balance' or 'equilibrium' in an appropriate manner to homeostasis. They realised that these expressions pictorially illustrate deviation corrections making up homeostasis, like the dynamic equilibrium of blood sugar levels or body temperature.

Control and regulation

This characteristic was examined in relation to various biological systems and processes. The students were asked about several systems and processes, and whether or not they relate to homeostasis and, if so, how. Students were expected to identify and define the dominant homeostatic parameter (biochemical or physiological) that is subjected to control and regulation in each system or process. The systems and processes presented to the students were the blood clotting system, mitochondria in different cells, the respiration rate throughout the lifespan, stomata activity in plants, and ageing. In reference to blood clotting, students' responses indicated that they accurately identified the homeostatic parameter of blood volume. They understood that the blood clotting process is a homeostatic process regulating blood volume, and the result is the maintenance of blood volume stability. Students' reference to blood clotting as a homeostatic process, as part of the body's homeostasis, departed from classical teaching approaches depicting blood clotting as a stand-alone, multi-step process of the blood system. Referring to other examples, such as stomata activity, students identified a homeostatic parameter under control and regulation – water quantity in the plant. Students understood that water quantity in the plant is not arbitrary but controlled by opening and closing of stomata.

Feedback mechanism

Students' comprehension of this characteristic was examined by highlighting the distinction between feedback and homeostasis, defining negative feedback, identifying a situation of negative feedback, positive feedback or no feedback, and understanding mechanisms of specific feedback loops operating in the body. In various examples, such as maintaining blood sugar or ADH hormone activity, the students described a feedback mechanism correcting deviations from a stable, constant state. The students also related negative feedback to hormone activity (for instance, understanding insulin's role in regulating blood sugar by transferring it into the cells).

Environments

The homeostatic characteristic of the relationship between environments was represented in questions requiring the students to argue whether and how the state described is homeostasis. The question referred to two kinds of frog (the marsh frog and the sea frog). In each frog, the internal environment is similar to the external. The question was: '*Is there a "need" for homeostasis in that state (e.g. when the internal environment is similar to the external)?*' Students' replies indicated that they understood the constant requirement for homeostasis – equilibrium between external and internal environments is one of these conditions. The students also expressed an understanding of the characteristic 'dynamics': the influence of the external environment on the internal environment is especially noticeable in aquatic fauna, which display fluctuations of salt concentration in the internal environment. The students clearly understood homeostasis as a collection of correcting mechanisms in response to changes, according to various factors influencing the internal and external environments.

Dependency between events

This characteristic was examined by analysing how students understood the dependency between events within a single system comprising several events and components, such as the system regulating cellular iron levels. Students' replies indicated that they understood the event maintaining cellular iron concentrations and availability, and the dependency among the factors influencing them. The results showed that students understood the complexity of the homeostatic system regulating the body's iron levels.

Multi-systems

This characteristic links with the dependency between events in defining homeostasis as a complex system. The multi-systems characteristic was examined by analysing students' understanding of the connection between two complex, multi-systems factors – body temperature and metabolic rate – in a homoeothermic and a poikilothermic animal. Students' replies indicated that they knew that body temperature is maintained autonomously by control and regulation mechanisms. These replies expressed an understanding of the complexity of maintaining body heat. Students mentioned all of the participating factors: body temperature, environment temperature, metabolic rate, heat energy and respiratory rate (glucose burning). Understanding of the characteristic 'multi-systems' was expressed in an adequate explanation of the relationship between metabolism as a result of several systems in the body (digestive, respiratory, endocrine) and temperature and body heat.

Levels of organisation

This characteristic was examined by analysing students' ability to identify common attributes ascribed to homeostasis. This was expressed in a homeostatic system on a molecular level in humans (iron concentration) and in bacteria, as well as on the macro level in animals and humans. For example, regarding the lactose operon in bacteria, students were asked about ATP concentration in the bacterial cell over time. They were required to explain how the operon constitutes a homeostatic state in the bacterial cell. These answers indicated that students saw ATP as a parameter maintained within a certain range by a control and regulation mechanism. They understood the complexity of the system – the connection between the ATP level and the levels of enzymes required for its production (by breaking down lactose and glucose). Students also emphasised that the characteristics of homeostasis mentioned above – 'dynamics' (fluctuation), 'control and regulation', 'environments' and 'dependency between events' – were all expressed both on the micro and molecular levels in the bacterial cell.

Discussion

Homeostasis is a fundamental principle

Our research stemmed from the question of how a fundamental principle in biology that is abstract and difficult to comprehend should be taught (Leyser, 2014). Understanding homeostasis must be viewed on two levels: the theoretical abstract level, and the applicative level of physiological processes and the mechanisms of action that operate them. Processes do not occur separately. Therefore, a process must be studied in light of an overruling principle, explaining its occurrence in the body. That is, studying a process such as respiration or heart function should be approached both by its physiological mechanistic details and by its homeostatic aspects. With similar research to ours, Wilson *et al*. (2006) suggested teaching multi-step and composite processes as dynamic systems that are governed by common organising principles. An example of such a principle is the conservation of matter. An essential step in learning this principle is tracing matter in and between systems, such as photosynthesis and cellular respiration. In their research, Wilson and his colleagues (2006) found that students have difficulties tracing matter between systems. They concluded that effective instructional changes, which are needed to promote the application of the tracing matter principle, would help students to understand the function of dynamic systems in the body. Thus, they suggested that students study other typical dynamic biological processes in which tracing matter is an organising principle, such as cell division (mitosis and meiosis), transcription, and translation.

In our research, we suggest teaching homeostasis by its characteristics, demonstrated in many biological processes. We can define three types of characteristics of homeostasis:

- **time** – homeostatic processes through time: throughout the day and the different stages of life;
- **location and environment** – relationship between external and internal environments;
- **space** – where homeostasis occurs: from the entire body to the molecular level.

Furthermore, the characteristics of homeostasis represent three aspects of a homeostatic system:

- **dynamics of process and mechanism** – 'feedback', 'regulation and control', 'physiological balance', 'dependency between events';
- **location among other body systems** – 'multi-systems', 'levels of organisation';
- **relation to the external environment** – 'environments'.

Students' replies, both in questionnaires and interviews, revealed that they could perceive homeostasis in action and understand the dynamics of a homeostatic process.

Example 1
The characteristic 'dynamics' was represented by an image of ocean waves. The student was asked to explain whether these waves represent homeostasis. The student's reply indicated that his 'image' of homeostasis is stability, not randomness. This student actually emphasised the strongly fluctuating quality of the ocean waves, as depicted in the illustration, as opposed to the limited fluctuation of homeostatic parameters such as heart rate and body temperature, a fluctuation leading to stability.

Example 2
In relation to 'multi-systems' and 'dependency between events' characteristics, the student was shown an image of a set of pipes, connected to each other, and identified an analogy between this system and homeostasis. That is to say, the state of a system or several systems, operated by a coordinated connection, consists of intertwined components under regulation.

Example 3
The characteristic 'environments' is a dominant characteristic in students' mental image of homeostasis. Referring to homeostasis, many students 'see' environments, both internal and external. This might lead to an erroneous conception of homeostasis, resulting in the students 'searching' for environments in every process or situation that they are required to examine.

Learning by adopting these characteristics of homeostasis requires systems thinking, as homeostasis is expressed both in a single system, in the coordinated activity of several systems working together, and in integration of levels of organisation. In addition, homeostasis applies to all levels of organisation in the organism. These two components, required for conceptualisation of homeostasis, are detailed below.

Systems thinking

Systems thinking focuses on recognising the interrelationships among components of a system, synthesizing them into a unified view of the whole (Ben-Zvi Assaraf and Orion, 2010). Systems thinking requires stepping outside the system's boundaries of time and space in order to discover its hidden aspects. Systems thinking can be defined by several aspects:

- understanding a dynamic process – feedback cycles, delays and deviations, and their effect on the system's flow;
- understanding the 'behaviour' of a system over time by analysing the interactions of its components;
- identifying a non-linear web of connections in a system.

These aspects of systems thinking are reflected in the students' responses, especially those responses referring to the characteristics 'Dynamics' and 'Levels of organisation' (see Table 2).

Integration of levels of organisation (macro–micro)

Verhoeff (2003) regards integration between levels of organisation as an aspect of systematic thinking. Other researchers, such as Duncan and Reiser (2007), regard it as a separate thinking skill in its own category. Many science education research projects reveal a difficulty in bridging the gap between macro and micro levels in many biological subjects, such as the respiratory system (Hmelo-Silver, Holton and Kolodner, 2000). Models for overcoming this difficulty have been suggested. Knippels (2002), for example, suggests a model of alternating teaching and learning. Known as a 'yo-yo' strategy, in this model, cycles of teaching and learning focus on the micro and macro level, and go back and forth between the molecule, cell, organism and population levels. Other researchers (Barrett, Peles and Odum, 1997) have indicated that the study of each level separately is the cause of confusion, and is responsible for the difficulty of bridging the gap between them. They termed this 'the tragedy of fragmentation' (Barrett *et al.*, 1997: 531). Their research suggested a general model for teaching seven fundamental principles in biology, cutting across all levels of organisation (cell, tissue, organ, physiological system, and the entire body) and integrating them. The purpose of this integration is to emphasise the dominance of a fundamental principle throughout all levels of organisation, and at the same time study the principle separately at each level. The students' responses indicated that they identify homeostasis in any level of organisation – in the entire body, as well as at the molecular level. Teaching the fundamental principle of homeostasis through its characteristics, surfacing in different examples from different fields of biology, can contribute to upgrading a student's understanding of biology from novice to expert. Jacobson (2001) and Wilensky and Resnick (1999) perceive systems thinking as an identifying characteristic differentiating between 'experts' and 'novices' in a given field of knowledge. An additional distinction between 'novice' and 'expert' was suggested by Liu and Hmelo-Silver (2009) and termed 'functional understanding'. This term refers to the understanding of mechanisms and the function of a system, and the relationship between them. This expression is also appropriate for homeostasis, which includes mechanism and function, especially regarding the characteristics of dynamics, control and regulation, feedback, physiological balance, and environments.

Implications for instruction and learning

Teaching and learning homeostasis through a study of its characteristics enables teachers to present a view of the principle, but some reservations should be pointed out. Using this method of studying, students might prefer rote-learning the characteristics. Furthermore, students may apply the characteristics in the explanation of phenomena in which these characteristics are irrelevant (remember that not all characteristics occur in each homeostatic system). Therefore, teachers must be aware of their students' understanding, so that students will retain correct perceptions of homeostasis.

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References

Barrett, G.W., Peles, J.D. and Odum, E.P. (1997) Transcending processes and the levels-of organization concept. *BioScience*, **47**(8), 531–535.

Ben-Zvi Assaraf, O., Doddick, J. and Tripto, J. (2013) High school students' understanding of the human body system. *Research Science Education*, **43**, 33–56.

Ben-Zvi Assaraf, O. and Orion, N. (2010) System thinking skills at the elementary school level. *Journal of Research in Science Teaching*, **47**(5), 540–563.

Calabrese, V., Stella, A.M.G., Calvani, M. and Butterfield, D. (2006) Acetylcarnitine and cellular stress response: roles in nutritional redox homeostasis and regulation of longevity genes. *Journal of Nutritional of Biochemistry*, **17**, 73–88.

Cannon, W.B. (1929) Organization for physiological homeostasis. *Physiological Reviews*, **9**(3), 399–431.

Cheng, H., Jiang, X. and Han, X. (2007) Alterations in lipid homeostasis of mouse dorsal root ganglia induced by apolipoprotein E deficiency: a shotgun lipidomics study. *Journal of Neurochemistry*, **101**(1), 57–76.

Duncan, R.G. and Reiser, B.J. (2007) Reasoning across ontologically distinct levels: students' understanding of molecular genetics. *Journal of Research in Science Teaching*, **44**(7), 938–959.

Hmelo-Silver, C.E., Holton, D.L. and Kolodner, J.L. (2000) Designing learning about complex systems. *Journal of the Learning Sciences*, **9**(3), 247–298.

Hmelo-Silver, C.E. and Azevedo, R. (2006) Understanding complex systems: some core challenges. *Journal of the Learning Sciences*, **15**(1), 53–61.

Jacobson, M.J. (2001) Problem solving, cognition, and complex systems: differences between experts and novices. *Complexity*, **6**(3), 41–49.

Knippels, M-C.P.J. (2002) *Coping with the Abstract and Complex Nature of Genetics in Biology Education: The Yo-Yo Learning and Teaching Strategy*. PhD thesis. Utrecht University, Netherlands. Available at: dspace.library.uu.nl/bitstream/handle/1874/219/full.pdf?sequence=2.

Leyser, O. (2014) What should be in the biology curriculum? *School Science Research*, **95**(352), 43–45.

Liu, L. and Hmelo-Silver, C.E. (2009) Promoting complex systems learning through the use of conceptual representations in hypermedia. *Journal of Research in Science Teaching*, **46**(9), 1023–1040.

Stewart, J.A. (2006) The detrimental effects of allostasis: allostatic load as a measure of cumulative stress. *Journal of Physiological Anthropology*, **25**(1), 133–145.

Verhoeff, P. (2003) *Towards Systems Thinking in Cell Biology Education.* PhD thesis. Utrecht University, Netherlands. Available at: www.ecent.nl/servlet/supportBinaryFiles?referenceId=1&supportId=1471.

Westbrook, S.L. (1987) *A Cross-age Study of Student Understanding of Four Biology Concepts*. Doctoral dissertation, UMI No. 8804364. Norman, OK: University of Oklahama.

Wilensky, U. and Resnick, M. (1999) Thinking in levels: a dynamic systems approach to making sense of the world. *Journal of Science Education and Technology*, **8**(1), 3–19.

Wilson, C.D., Anderson, C.W., Heidemann, M., Merrill, J.E., Merritt, B.W., Richmond, G., Sibley, D.F. and Parker, J.M. (2006) Assessing students' ability to trace matter in dynamic systems in cell biology. *Life Sciences Education*, **5**(4) 323–331.

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