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Applying a system thinking learning approach to improve perception of homoeostasis - a fundamental principle of biology

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ABSTRACT

This research project sought to determine how the application of a system thinking learning approach (STLA) affects student perceptions of the fundamental biological principle of homoeostasis. This quasi-experimental study applied a two-group design and included 146 10th grade students attending heterogeneous public schools (ages 15–16). The quantitative results testify to the contribution of an STLA towards improving the perception of homoeostasis among the studied group. Qualitative analysis revealed that the characteristics of homoeostasis primarily promoted by an STLA were *efficiency, dynamics of a homoeostatic process*, and *environments*. The characteristics of *coordination and lack of randomness, control regulation and feedback mechanisms*, and *multisystems*, have been partially promoted, and the *energy* characteristic was found to be the hardest nut to crack. An STLA has the potential to help teachers meet their challenge to facilitate student understanding of the fundamental principle of homoeostasis.

KEYWORDS
Homeostasis; system thinking; fundamental principle

Introduction

Homoeostasis

Homoeostasis is a fundamental biological principle defined as the ability of every living organism to maintain a stable internal environment within defined boundaries; an internal environment different from its surrounding external environment. This is done through biochemical, physiological, and behavioural mechanisms. This fundamental principle is also a part of the Disciplinary Core Ideas (DCI) – Life Sciences (LS) (DCI – LS2): *Ecosystems: Interactions, Energy and Dynamics*, according to the reform efforts advocated in the National Science Education Standards (NSES) based on the National Research Council (NRC) framework for K-12 science education (NRC, 2012). In Israel, within the 10th grade biology curriculum promulgated by the Israeli Ministry of Education (2006), homoeostasis is a mandatory fundamental principle in general, and in relation to the human body in particular. Authors (2015, 2015) suggested identifying the fundamental biological principle of homoeostasis by the following characteristics: *coordination and lack of randomness* (including dependency between events within a system or process); *control regulation and feedback mechanism; dynamics of a homoeostatic process; multisystems*; and *environments*. We added the characteristics *efficiency* and *energy* (see component B in Table 1).

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Article description: Homoeostasis, which is a central organising principle in biology, is difficult to comprehend. This quantitative and qualitative research found that system-thinking instruction (STI) affects the perception of the fundamental biological principle of homoeostasis among students.

Table 1. The components of homoeostasis perception.

Components of homoeostasis perception		Component details	
A. Understanding the definition of homoeostasis		Biological knowledge	
B. Understanding the characteristics of homoeostasis	coordination & lack of randomness	This characteristic consists of two complementary concepts: the coordination of the various processes in the body, including dependency between events within a system or process, and the lack of randomness of the homoeostatic processes, which are guided by the entirety of the chemical and physical conditions existing in biological systems at different levels.	
	Control, regulation and feedback mechanism	Feedback mechanisms that activate regulation and control processes in the organism:	Understanding feedback processes Identifying and connecting between homoeostasis and feedback
	Dynamics of a homoeostatic process	Dynamism that is ceaselessly occurring, maintaining the stability of variables (physiological, chemical and physical):	Continuous changes Deviation and adjustment (bidirectionality) Different indexes
	Multi-systems	A characteristic expressed in the interdependence and cooperation between different systems in the body:	Processes occur simultaneously and cooperatively Homoeostasis processes occur ceaselessly in the living organism Identifying and understanding entire body
B. Understanding the characteristics of homoeostasis	environments	The internal environment in which homoeostasis occurs, and the external environment affecting it.	
	efficiency	The unique response of the various controls to constantly changing situations	
	energy	Energy is ceaselessly invested in the maintenance	
C. Application of homoeostasis		Explaining homoeostatic events in relevant homoeostatic terminology	

Challenges in teaching homoeostasis

Teachers find that the fundamental biological principle of homoeostasis is a complex effort to handle – for those who teach as well for those trying to learn (Simpson and Marek 1988; Westbrook and Marek 1992). There are two principal causes of this difficulty. First, the fundamental principle of homoeostasis requires overcoming significant challenges in order to comprehend the methods of operation of complex systems (Raved and Yarden 2014). Second, comprehending the way complex systems operate requires the internalisation of homoeostatic characteristics such as *control regulation and feedback mechanism* and *dynamics of a homoeostatic process*. In light of the difficulties in comprehending the fundamental principle of homoeostasis, Authors (2015) recommended teaching biological content by explicit instruction of the characteristics of the homoeostasis principle. In this research, we propose to improve the understanding of the fundamental principle of homoeostasis by an STLA.

Homoeostasis and system thinking

Biological systems are complex and open systems involving input and output of matter, *energy*, and information. They operate on several organisation levels, including organism, organ or system, cell, and molecule. They are dynamic, with structures and activities that may appear, disappear, and change, and their components operate in complex interactions (Boersma and Waarlo 2003; Hmelo-Silver and Azevedo 2006).

Researchers have described system thinking as the ability to understand and interpret complex systems (Evagorou et al. 2009). Ben-Zvi Assaraf, Dodick, and Tripto (2013) have analysed system thinking among 10th grade students in Israel. These were students who studied the part of the syllabus dealing with 'Human biology emphasizing homeostasis', without any intervention. Their research found that beyond identifying structural components, the students surveyed were experiencing system thinking difficulties. Most students examined showed a preference for structures rather than processes. They also preferred macro level elements rather than micro level elements. Students exhibited difficulty in comprehending interactions between system components and a compromised ability to identify dynamic interdependencies in the human body. They struggled to describe and understand the mechanisms and processes governing the interactions between the body's components. They also struggled to comprehend the system as a dynamic entity, probably because the processes are more difficult to understand. Although understanding the structures is necessary for understanding their activity, knowledge of the structures does not guarantee understanding the processes (Liu and Hmelo-Silver 2009). Further difficulties were found in comprehending hidden dimensions – such as the gas exchange in the lungs – and in temporal thinking that involves prediction and retrospection.

Ben-Zvi Assaraf, Dodick, and Tripto (2013) have suggested the system thinking hierarchical model that divides the development of system thinking into three hierarchal evolutionary levels. They argue that this hierarchy also reflects an understanding of the biology of the human body. The first level – structures in a system – includes 'the ability to identify components and processes within a system'. The second level – synthesis – includes 'the ability to identify interactions between and within system components', 'the ability to identify dynamic interactions in the system', 'the ability to organize system components, processes and their interactions', and 'the ability to identify cycles of matter and energy in a system – the cyclical nature of systems'. The third level – application – includes 'understanding the hidden dimensions of the system, understanding natural phenomena by models and hidden interconnections', 'the ability to make generalizations and solve problems by understanding the system's mechanisms', and 'the ability to think temporally: retrospection and prediction' – understanding that some of the processes in the system occurred in the past and that processes that may occur in the future are the result of present interactions.

This hierarchy represents the increase, for students, in the difficulty experienced in applying each skill, with each skill serving as the foundation for the development of the next skill. Ben-Zvi Assaraf, Dodick, and Tripto (2013) have argued that learning about the components of a biological system separately does not guarantee the development of system thinking. Ben-Zvi Assaraf, Dodick, and Tripto (2013) suggested that the fundamental principle of homoeostasis should be taught together with the principles of system thinking

System thinking, which is a high-order thinking skill, was found to be a necessary component of a student's ability to make the connection between human body mechanisms and the abstract fundamental biological principle of homoeostasis (Boersma and Waarlo 2003; Boersma, Waarlo, and Klaassen 2011; Jacobson and Wilensky 2006; Simpson and Marek 1988; Westbrook and Marek 1992). For example, the student may recognise that symptoms such as sweating, flushing, and an increase in heartrate or breathing rate are 'results' of homoeostasis. However, the processes and mechanisms that operate to maintain body temperature within a stable range are complex and not part of the student's concrete and immediate comprehension (Buddingh 1996). Students fail to see the phenomenon as a whole or to understand the mechanisms of its activity; they can see only the collection of details adding up to it. Understanding the whole, with the mechanisms of its operation, is a skill that requires system thinking (Feltovich, Coulson, and Spiro 2001; Hmelo-Silver, Marathe, and Liu 2004; Hmelo-Silver and Green Pfeffer 2004; Narayanan and Hegarty 1998).

Research rationale

The rationale of our research is based on the hypothesis that system thinking has the potential to help students understand concepts related to the function of systems in the human body – systems where interdependence and ceaseless change are characteristic (Ben-Zvi Assaraf and Orion 2005a, 2005b; Kali, Orion., and Eylon 2003; Senge 1995). While understanding that explicit teaching of the characteristics of homoeostasis is essential and that system thinking processes may help students accurately comprehend the principle of homoeostasis and its characteristics, these understandings have prompted the questions that underlie our research: 1. How does an STLA affect students' perceptions of the fundamental biological principle of homoeostasis and how are the various aspects of this perception interrelated? 2. What is particular to their perception of homoeostasis after they completed their study of this fundamental principle through an STLA?

In our research, an STLA was integrated into the teaching of the 'Human biology, emphasizing homeostasis' subject. This learning approach included developing high-order cognitive skills such as identifying components in biological systems and distinguishing between them, as well as explicit study of the characteristics, enabling significant learning of the fundamental principle of homoeostasis. Figure 1 shows the research model.

Methods

Research population

This quasi-experimental study included 146 students of middle-class socioeconomic background who attended nine heterogeneous 10th grade classes (ages 15–16) in seven public schools in Israel. Because the research is based on a single independent variable–STLA–we were able to randomly divide the participants into two research groups. One group was a system thinking learning approach group (STLAG) (n = 74) that received system thinking intervention; the other was a control group (CG) (n = 72) that did not receive such intervention. Nine experienced teachers agreed to participate and involve their biology classes in the research. The STLAG contained five classes with five teachers in four schools, while the CG contained four classes with four teachers in three schools.

Comparative examination of pre-intervention knowledge

In order to assess the initial differences between the two research groups, students passed an examination similar to the Programme for International Student Assessment (PISA) science test –

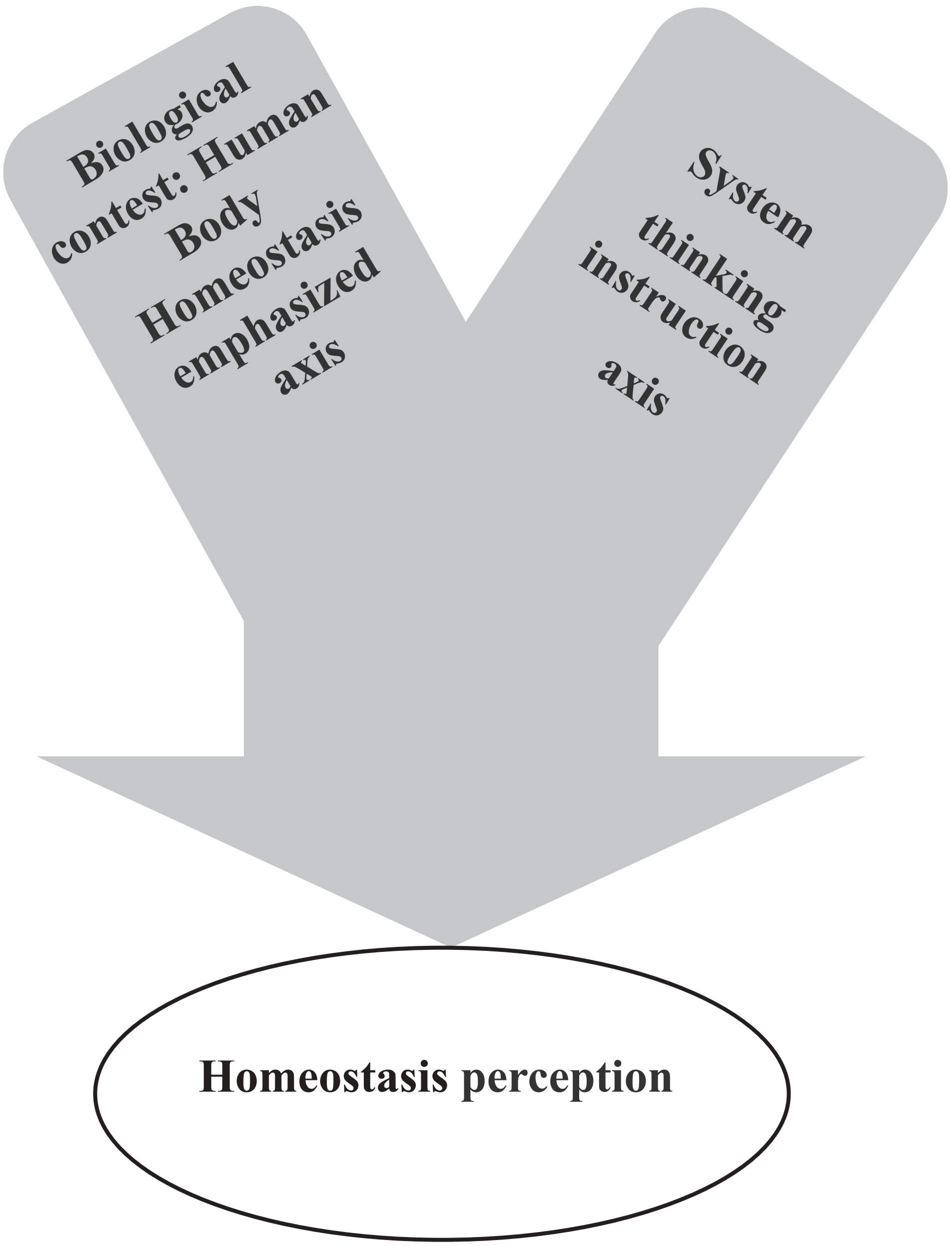

Figure 1. Research Model.

an examination found useful for assessing high school students majoring in biology (Sadeh and Zion, 2009). The test involved analysis of an adapted primary literature article that discussed the importance of breakfast for maintaining health. The test measured knowledge, comprehension and high-order thinking skills of students, took into consideration our expectations of the research population at the beginning of the intervention. The students were graded 0 to 100 on an evaluation scale that was constructed for the test. No statistically significant group difference was detected in these initial results: (STLAG: $M = 81.47$, $SD = 10.24$; CG: $M = 82.17$, $SD = 12.58$, $t(144) = 0.38$, $p = .706$, $d = 0.06$), which showed that students in both groups had similar capability levels at pre-test.

The intervention

The intervention lasted six months and was integrated into the teaching of 'Human biology, emphasizing homeostasis', a subject that all participants studied according to a uniform teaching sequence in all of the classes involved in the experiment. The human circulatory system was the first system taught, with all student participants carrying out independent homoeostasis-emphasised learning tasks (HELT). The learning tasks were put together based on two of the online lessons – 'The beating heart' and 'Cardiac output' (Keinan, Mintz., and Zand 2001). In these tasks the students were exposed to homoeostatic mechanisms that operate during physiological changes in the circulatory system, in a manner emphasising the various characteristics of homoeostatic activity, and its biological advantage. These tasks promote active student learning through animation, relevant knowledge highlights, invitation to inquiry, conclusion drawing, and reflective summary questions. The following question – number G5 from HELT – is an example of this type of question: *The first pacemakers, used during the 1960s and 1970s, produced pulses at a constant rate. What was the drawback? Explain using the term 'homeostasis' and the characteristics of homoeostasis.*

The STLAG carried out the same learning tasks as the CG, but their tasks also involved deliberate system thinking aspects. The first STLA learning activity, titled 'Another view of homeostasis', was carried out upon introducing the subject of homoeostasis. It emphasised the characteristics of homoeostasis expressed in the physiological processes that occur in the bodies of different animals, such as a shrew, an elephant, a snake, and a human, that is, at the entire-organism level of organisation. Further STLA activity was carried out as adjuncts of 'The beating heart' and 'Cardiac output', the two aforementioned online learning tasks. The STLA was based on system thinking skills defined by researchers Simpson and Marek (1988) and Westbrook and Marek (1992). It was conceived as a scaffold to stimulate a learner towards thinking about homoeostatic processes and mechanisms, not just about the concrete results of a specific activity. This learning approach included questions that promoted system thinking skills. For example, there was an item that related to the skill of '*identifying and distinguishing stages or components in the process*'. The item was encompassed by these two sentences: '*The mechanism regulating cardiac output comprises a chain of processes. List these processes by the order in which they occur*'. Another item related to the skill of '*understanding the mutual influence between processes occurring in the body and their influence on the body as a whole*'. It was presented in the following manner: *Give an example of a biological change occurring in the entire organism and resulting from a change in one of the processes you mentioned above*'. Table 2 deals with questions that direct students to system thinking and the system thinking skills to which the questions relate.

Research tools

In order to obtain reliable results, we constructed three research tools to collect data for examining the perception homoeostasis – a fundamental principle of biology, among students:

(i) A Homoeostasis Perception Questionnaire (HPQ)
(ii) A performance analysis of the – 'Cardiac output' homoeostasis-emphasised learning task (HELT)
(iii) Personal interviews

The tools are detailed below:

i. The HPQ (Appendix 1–3) Comprised of five questions – two multiple choice and three short answer questions that referred to a variety of examples of homoeostasis at the entire organism level – the HPQ was performed before and after learning. The questions were examined by five teachers holding MSc or PhD degrees in biology or science education; those teachers also

Table 2. System thinking skills and their instruction components in learning assignments.

STH levels according to Ben-Zvi Assaraf and Orion, 2005		System thinking skills required to understand homoeostasis according to Simpson and Marek 1988; Westbrook and Marek 1992	Instruction components for system thinking in learning assignment
Structures	Process components	1. Identifying and distinguishing stages or components in the process.	1. Cardiac output is regulated by a chain of processes. List these processes by order.
	Cause and effect	2. Identifying and understanding cause and effect relations between stages or components in the process.	2. The cause of this chain of processes is ___ and the effect is ___.
	Organisation levels	3., 4. Distinguishing between different organisation levels on which biological processes occur, such as: regulating enzyme activity, organ activity, heart rate, and kidney exretion of water and solubles	Below is a list of homoeostatic processes. Some represent homoeostasis on the entire body level, some represent homoeostasis on the cellular level. The processes are: increased production of red blood cells after giving blood, storing glycogen in the liver, changes in myocardial contractility, blushing, skin regeneration after injury, sensation of thirst on a hot day. 3. The bodily processes are: ___ 4. The cellular processes are: ___
Synthesis	Dynamic interaction between processes on different organisation levels	5. Understating interdependence of processes on different organisation levels, for instance: an increase in cellular respiration processes influences the release of heat and the organism's body temperature.	5. A change in cellular processes influences body processes and vice versa – body processes influence cellular processes. Give an example of changes in cardiac output to support this argument. A homoeostatic process in a living organism includes biological changes as well as adjustments made by different mechanisms maintaining stability of biological indexes.
	Understanding interdependence	6. Understanding interdependence of processes occurring in the body and their influence on the organism as a whole.	6. Write down an example of a biological change occurring in the organism as a whole, following a change in one of the processes that you listed above
Synthesis	Understanding interdependence	6. Understanding interdependence of processes occurring in the body and their influence on the organism as a whole.	6. Write down an example of a biological change occurring in the organism as a whole, following a change in one of the processes that you listed above
	Variable deviation adjusted Nature of adjustment	7., 8. Understanding that some of the changes occurring in the organism result in a deviation of physiological variables, a deviation that is adjusted by biochemical, physiological and behavioural mechanisms which keep the physiological variables stable.	7. Is it possible to say that the control of cardiac output is an example of such an adjustment mechanism? Elaborate. 8. What is the adjustment achieved by the mechanism controlling cardiac output? Elaborate.
ApplicationApplication	Making generalisations	9. Viewing different stages of a process as parts of a structured whole.	9. Elaborate what would be your considerations in choosing another example of a homoeostatic process in a living organism.

serve as matriculation evaluators for the Ministry of Education. Inter rater agreement was examined with Kendall's W and was found good: W = 0.83 ($p < .001$) for the pre-test, and W = 0.85 ($p < .001$) for the post test.

ii. 'Cardiac output' HELT performances. Five experienced biology teachers examined the validity of the HELT performances. They reached unanimous agreement on the factors involved. Seven other biology teachers, whose experience is focused on the subject of homoeostasis, then examined the issue of reliability of the judges. Inter-rater agreement was examined with Kendall's W and was found good: W = 0.89 ($p < .001$). With the assistance of these seven teachers, a detailed indicator was set up to quantify, for the students, their levels of comprehension and application, based on their answers to the questions.

iii. Personal interviews. A total of 28 interviews were conducted with 13 STLAG students and 15 CG students. All were oral semi-structured interviews. Student answers were content-analysed with reference to characteristics of the fundamental biological principle of homoeostasis.

Research analysis

The descriptions of the research analysis tools are arranged to match the research questions. We begin by describing the quantitative analysis, referring to the first question, which dealt with the influence of an STLA on student perceptions of homoeostasis. We then describe the qualitative analysis, referring to the second question, which dealt with particular characteristics in the perception of homoeostasis among those students who had studied this fundamental principle using an STLA.

All five questions of the HPQ questionnaire were quantitatively analysed in light of the first research question, while the three open questions were also qualitatively analysed in light of the second research question. All three of the HELT questions concerning the perception of homoeostasis were quantitatively analysed in light of the first research question, as well as being qualitatively analysed in light of the second research question.

Quantitative data analysis

i. HPQ analysis: The quantitative analysis of homoeostasis perception by the HPQ referred to three components (see Table 1): **a**. Understanding the definition of homoeostasis. The grade for this component was defined as the mean of two dichotomic coded (1 = true, 0 = false) items. The two items were positively related but not significantly so. **b**. Overall understanding the characteristics of homoeostasis. The grade for this component was defined as the mean of three items (0–1). Internal consistencies were: pre-test $\alpha = .54$, post-test $\alpha = .66$. **c**. Application of homoeostasis (explaining homoeostatic events in relevant homoeostatic terminology). The grade for this component was defined as the mean of three 1- to 5-graded items, where 5 was a complete and correct answer that explained the physiological process, using the relevant homoeostatic terms; 4 was a correct but incomplete answer with some reference to homoeostasis; 3 was a general understanding of the homoeostasis principle, but the biological concepts mentioned were wrong; 2 was a biologically superficial answer with no reference to homoeostasis; and 1 was an incorrect or irrelevant answer, or no answer at all. Internal consistencies were: pre-test $\alpha = .55$, post-test $\alpha = .59$. Additionally, a total score combining the understanding of the definition of homoeostasis, overall understanding of the characteristics of Homoeostasis, and application of homoeostasis, was calculated as a mean of the three aspects. A conversion of the grade for 'application' was executed and the overall score was in the range of 0–1. Low internal consistencies were noted, but these are to be expected with items of knowledge, where participants know the answers to only some, but not all, questions.

Pre-study group differences in the perception of homoeostasis were analysed with a series of t-tests. Group and time differences in the perception of homoeostasis (questionnaire) and HPQ scores were analysed with repeated measures analyses of variance and pairwise comparisons for significant interactions.

ii. HELT analysis: The quantitative analysis of performance levels was based on the three short-answer thinking questions regarding biological knowledge, which the students were asked to answer while carrying out HELT. A biology-related question, for example, was: *During illness, heartrate also increases. What is the importance of increasing heartrate during stress, physical exertion, and illness? What is the importance of returning to a relatively moderate rate during relaxation?* Quantitative analysis of homoeostasis perception by the '*Cardiac output*' HELT referred to three **components** (see Table 1): **a**. Understanding the definition of homoeostasis reflects proficiency in the subject. Graded 1–5. The two items correlated significantly r = .40 (p < .001). **b**. Overall understanding of the characteristics of homoeostasis expressed in students' answers. Internal consistency α = .35. The low internal consistency should be noted. However, as before, it may be expected, as participants knew the answers to only some, but not all, questions. **c**. Application of homoeostasis (explaining homoeostatic events in relevant homoeostatic terminology) in the '*Cardiac output*' HELT on a 1–5 scale, scored as follows: 5: A complete and correct answer that explains the physiological process using the relevant homoeostatic terms, 4: A correct but incomplete answer with some reference to homoeostasis, 3: A general understanding of the homoeostasis principle but mentioning incorrect biological concepts, 2: A biologically superficial answer without reference to homoeostasis, 1: An incorrect or irrelevant answer, or no answer. The two items correlated significantly r = .54 (p < .001).

Additionally, a total score was calculated by combining the understanding of the definition of homoeostasis, an overall understanding of the characteristics of homoeostasis, and the application of homoeostasis. Internal consistency α = .79. The grade for each aspect examined in the HELT is the average grade of the three items for each of these aspects, on a 1–5 scale. The higher the score – the better the comprehension. Differences in HELT data were analysed with a series of t-tests and Cohen's *d*. Data were analysed with SPSS ver. 25. Internal consistencies were examined with Cronbach α. Pre-study group differences were analysed with a series of t-tests, for both HPQ and HELT. Due to different cell sizes, this was used rather than a multivariate analysis of variance. Group by time differences in HPQ were analysed with repeated measures univariate analyses of variance. Changes in HELT were analysed with a series of t-tests (again due to different cell sizes). Cohen's d scores were calculated (Cohen 1988). Pearson correlations were calculated between the various dimensions of knowledge.

Qualitative analysis

The three research tools, *HPQ, HELT and the interviews*, were content-analysed in relation to homoeostasis perception and to comprehension of homoeostasis characteristics: *coordination and lack of randomness, control regulation and feedback mechanism, dynamics of a homoeostatic process, multisystems, environments, efficiency* and *energy*. This analysis was based on sensitising concepts and homoeostasis characteristics and included mapping student answers and categorisation of the responses collected by the three research tools. It involved conceptualising and combining pieces of information according to the relevant characteristics found in the content, taking special notice of concepts and keywords that were found or missing in the answers (Shkedi 2003, 2011).

The analysis referred to the prevalence of the perception characteristic represented in the category. For example, for the 'homeostasis mechanisms always operate in the living organism' category (an aspect of *dynamics of a homoeostatic process*), the analysis sought to determine whether students refer to this always, often, seldom, or not at all? Another type of analysis was the degree of prominence of the perception characteristic represented in the category. When students mention that homoeostasis mechanisms are always at work, the analysis sought to determine: whether they mention this in a significant, marginal, or meaningless manner? (Shkedi 2003, 2011).

Results

The descriptions of the results are arranged to match the research questions.

Influence of the STLA on student perceptions of homoeostasis

The first research question sought to determine how an STLA affects the perception of the fundamental biological principle of homoeostasis among students. In order to answer this research question, the perception of the fundamental principle of homoeostasis was examined in quantitative measures. The quantitative measure consisted of three aspects – understanding the definition of homoeostasis, overall understanding of the characteristics of homoeostasis, and application of homoeostasis – explaining homoeostatic events in relevant homoeostatic terminology.

First, pre-study group differences in HPQ were analysed to assess whether initial differences were significant and thus needed to be controlled when examining change. Due to different cell sizes, these were analysed with a series of t-tests, rather than with a multivariate analysis of variance. To assess differences in change, group by time differences were analysed with repeated measures univariate analyses of variance.

Pre-study group differences in HPQ were non-significant for the total score ($t(146) = 1.01$, $p = .313$, $d = 0.17$), as well as for the three subscales ('Understanding the definition of homeostasis' $t(144) = 0.96$, $p = .340$, $d = 0.16$; 'Understanding the characteristics of homeostasis' $t(129) = -0.32$, $p = .752$, $d = 0.06$); and 'Application of homeostasis' $t(143) = 1.09$, $p = .276$, $d = 0.18$). Thus, repeated measuers analyses of variance were used to assess group by time differences in the perception of homoeostasis, as reflected in the HPQ scores (Table 3). Significant group by time differences were found for all dimensions. Post hoc analyses of the significant interactions, with pairwise comparisons, revealed significant increases in all dimensions, in both the STLAG and CG, yet the magnitude of the change is significantly greater in the STLAG group.

Next, due to different cell sizes (Table 4), differences in HELT were analysed with a series of t-tests, rather than with a multivariate analysis of variance. Significant group differences were found for 'Understanding the definition of homeostasis' and for 'Application of homeostasis'. In both cases, scores in the STLAG are higher than in the CG.

Finally, Pearson correlations were examined in order to assess the mutual, bidirectional relationships among the study variables. They were calculated between the three categories: 'Understanding the definition of homeostasis', 'Understanding the characteristics of homeostasis', and 'Application of homeostasis', regarding the HPQ data at post-test, and regarding the HELT data. In the HPQ data, a significant, positive, and high correlation was found in both groups between 'Understanding the characteristics of homeostasis' and the 'Application of homeostasis' (STLAG: $r = .66$, $p < .001$; CG: $r = .77$, $p < .001$). Other correlations, involving 'Understanding the definition of homeostasis', were non-significant. The pattern of correlations in the HELT data is somewhat different. In STLAG, a significant, positive, and high correlation was found between 'Understanding the definition of homeostasis' and 'Application of homeostasis' ($r = .77$, $p < .001$), a significant and positive correlation between 'Understanding the definition of homeostasis' and 'Understanding the characteristics of homeostasis' ($r = .31$, $p = .015$), and a non-significant correlation between 'Understanding the characteristics of homeostasis' and 'Application of homeostasis' ($r = .21$, $p = .081$). In the CG group, all three correlations were positive and significant ('Understanding the definition of homeostasis' and 'Understanding the characteristics of homeostasis' $r = .70$, $p < .001$; 'Understanding the definition of homeostasis' and 'Application of homeostasis' $r = .82$, $p < .001$; and 'Understanding the characteristics of homeostasis' and 'Application of homeostasis': $r = .36$, $p = .003$).

Are particular characteristics in the perception of homoeostasis different among students who studied this fundamental principle through an STLA compared to students of a control group?

Tables 5–11 present qualitative findings according to the students' own thinking during the learning process. A profile of homoeostasis perceptions was drawn by qualitative content analysis of the

Table 3. Perception of homoeostasis by group and time, questionnaire data (HPQ) (N = 146).

	STIG (n = 74)		CG (n = 72)				Analysis of the interaction	
	Pre M (SD)	Post M (SD)	Pre M (SD)	Post M (SD)	F_{time} (η^2)	$F_{time\ x\ group}$ (η^2)	STIG	CG
Total score of homoeostasis	0.24 (0.15)	0.49 (0.18)	0.27 (0.14)	0.40 (0.19)	$F(1, 144) = 121.53$*** (.458)	$F(1, 144) = 12.04$*** (.077)	$F(1, 144) = 106.51$*** (.425)	$F(1, 144) = 28.14$*** (.163)
Understanding the definition of homoeostasis	0.30 (0.31)	0.60 (0.36)	0.35 (0.32)	0.49 (0.37)	$F(1, 144) = 33.81$*** (.192)	$F(1, 144) = 4.51$* (.031)	$F(1, 144) = 31.50$*** (.182)	$F(1, 144) = 6.81$** (.046)
Understanding the characteristics of homoeostasis	0.18 (0.11)	0.43 (0.17)	0.17 (0.11)	0.33 (0.21)	$F(1, 144) = 119.49$*** (.495)	$F(1, 144) = 5.60$* (.044)	$F(1, 144) = 84.35$*** (.409)	$F(1, 144) = 38.54$*** (.240)
Application of homoeostasis	1.98 (0.80)	2.89 (0.83)	2.13 (0.84)	2.56 (0.99)	$F(1, 144) = 48.16$*** (.256)	$F(1, 144) = 5.91$* (.040)	$F(1, 144) = 44.53$*** (.241)	$F(1, 144) = 10.03$** (.067)

*$p < .05$, **$p < .01$, ***$p < .001$

Table 4. Perception of homoeostasis by group, task data (HELT) (N = 146).

	STIG	CG	
	M	*M*	
	(*SD*)	(*SD*)	*t*
	(*n* = 74)	(*n* = 72)	*d*
Total score of homoeostasis	3.02	2.87	t(144) = 0.86
	(1.03)	(1.10)	*d* = 0.14
Understanding the definition of homoeostasis	3.84	3.43	t(109.06)[1] = 2.09*
	(0.90)	(1.21)	*d* = 0.38
Understanding the characteristics of homoeostasis	3.29	3.46	t(144) = −1.28
	(0.74)	(0.81)	*d* = 0.22
Application of homoeostasis	2.96	2.49	t(144) = 2.22*
	(1.26)	(1.30)	*d* = 0.37

1 ¯ p for An equal variances

responses of students from both research groups. It focused on responses regarding the characteristics of the fundamental principle of homoeostasis – *coordination and lack of randomness, control regulation and feedback mechanism, dynamics of a homoeostatic process, multisystems, environments, efficiency* and *energy*.

Qualitative analysis of the HPQ, HELT and the interviews, revealed that the homoeostasis characteristics that were better understood by 10th grade students were *dynamics of a homoeostatic process, environments*, and *efficiency*. The characteristics of *coordination and lack of randomness*, as well as *multisystems*, were moderately understood, while the characteristics of *control regulation and feedback mechanism* as well as *energy* were unclear or unfamiliar to students. There was an improvement in understanding feedback mechanisms described in a schematic diagram, but there were difficulties in identifying control, regulation and feedback mechanisms in familiar everyday phenomena. Misunderstanding of the *energy* characteristic and its relation to homoeostasis mechanisms was prominent.

We found erroneous perceptions of homoeostasis characteristics. In the *dynamics of a homoeostatic process* characteristic, for example, we noted a misunderstanding that oscillation, deviation, and adjustment were a steady state. We also found that the concepts of equilibrium, balance, and variable, which are part of the terminology used in the classroom when discussing the human body, were unclear to students. In the multisystem characteristic of homoeostasis, we also found a misunderstanding that homoeostasis mechanisms were permanently operating in the living organism, and that homoeostasis was operating in the body in extraordinary and extreme situations only. In the *environments* characteristic of homoeostasis, we discovered the erroneous notion that the internal environment was kept steady. There were some misunderstandings about the *environment*s characteristic and about the *control regulation and feedback mechanism* characteristic. We also discovered a misunderstanding of the importance of homoeostasis mechanisms and a perception that maintaining the stability of the internal environment 'just happens', as if it was accomplished 'automatically'. There was also a misunderstanding of the connection between adaptation of the body to the environment and the operation of homoeostasis mechanisms. Another interesting finding of the interviews was that students struggled to demonstrate how a homoeostasis characteristic – any characteristic of their choice – was expressed during a particular physiological activity.

Discussion

The first research hypothesis was that an STLA improves student perceptions of the fundamental principle of homoeostasis. The findings confirmed our hypothesis almost completely. The improvement in the perception of homoeostasis, as revealed using our three research tools, testifies to the contribution of an STLA towards improving the perception of homoeostasis among 10th grade students in all three aspects after learning.

Table 5. Mapping the qualitative findings regarding the efficiency characteristic of homoeostasis, during and after learning[1].

	System Thinking Instruction Group		Control Group	
Stage of learning	Insights	*Quotes*	Insights	*Quotes*
During	General perception is correct; describing physiological phenomena without reference to changes in needs or indexes No reference to the significance of the efficiency of homoeostasis, describing occurrences **without referring to change in components**	***There is a problem** with disrupting homoeostasis … **if there is no adaptation to the condition–to the activity and the need.*** *When the body is in different conditions, first the heartrate rises and then the body returns to a normal state. **It is significant that the heart does not run too fast and works properly.***	Describing physiological phenomena **without understanding that they are expressions of homoeostasis mechanisms, perceiving them as 'automatic,' confusing between terminology of cardiac arrest and homoeostasis mechanisms, and between popular health concepts such as 'heart attack' and scientific concepts and their interconnections. For instance, confusing cardiac relaxation as part of the heartbeat and the body being at a relaxed state**. There is an understanding of the changes resulting from change in conditions.	*The significance of increasing heartrate during stress is that **the body is under stress and the heart automatically begins to beat faster** because there are variables that change heartbeat and heartrate … during physical exertion the heart beats faster than during rest and this is actually good. It [the heart] pumps blood to the body during illness. **There could be stress caused by cardiac arrest and this is not good**. The significance of returning to a moderate pace during rest is important, **as it enables the body to take rest and relax.***
After	General and in-depth perception are correct, the changes occur following a change in indexes, and adjust to these indexes Understanding that homoeostatic changes improve efficiency of physiological processes	*Opening stomata at night is part of homoeostasis, in order to regulate water level …* *At first, **the body was not accustomed** to the new condition (rising altitude), **it accustomed itself by homoeostasis that adapted the body to the new conditions**, by **producing more red blood cells** containing haemoglobin and **making it easier to breathe in an environment low in oxygen**.* *… by the time it is has warmed up,**the body realises it is warm** and begins to eject water, which is perspiration. There are other ways to cool itself, through the blood (interviews).* *… perspiring to cool the body. When breathing rate and heartrate increase **and this supplies more energy for the cells (interviews).***	**No reference**	

Table 6. Mapping the qualitative findings regarding the **coordination and lack of randomness** characteristic of homoeostasis, during and after learning.

	System Thinking Instruction Group		Control Group	
Stage of learning	Insights	*Quotes*	Insights	*Quotes*
During	**Little reference**. Most students apparently experience difficulty. Among some, there is an understanding of the coordination of the activity of various systems in the body and the importance of this coordination. Understanding that processes do not occur by coincidence.	White blood cells arrive faster to help with the illness; during stress the blood carries hormones faster to the body and during [physical] activity the blood supplies oxygen faster . Changes in heartrate and breathing rate are caused by homoeostasis, in order to stabilise oxygen level in the body. During illness, stress, and physical exertion there is an increase in blood flow to the required location, which also means more white blood cells reach the diseased location.	**No reference.**	
After	**Explicit statement of coordination is still rare** More frequent indications of understanding the coordination of the activities of different systems in the body. Limited ability to supply concrete examples.	Coordination ... that every process in the body adapts itself to every other process in the body ... what happens is that respiration is increased and more oxygen reaches the blood cells. The blood cells absorb more oxygen and the rate of blood flow is increased. The oxygen actually reaches the cells in the body and there is greater and more efficient production of energy in the cells.	**No explicit or implicit reference to coordination and to lack of randomness.**	

The correlations pointed out that there is a connection between all three aspects of homoeostasis: 'understanding homeostasis', 'understanding the characteristics of homeostasis' and 'application of homeostasis'. That is, improvement in one of the aspects of homoeostasis perception using an STLA was accompanied by improvement in the other two aspects as well.

In two of the aspects, 'understanding homeostasis' and 'application of homeostasis', improvement was already observable during learning. Contrary to our expectations, no during-learning advantages resulting from an STLA were found in the 'understanding the characteristics of homeostasis' aspect. The difference between 'understanding the characteristics of homeostasis' after learning, and its condition during learning, may provide insight into the special difficulty of 10th grade students who struggle to understand the characteristics of homoeostasis. These difficulties indicate that formulating an overview of the subject requires a long process of learning and internalisation on the student's part.

The second research hypothesis was that an STLA improves students' perceptions of homoeostasis by particular characteristics. The characteristics of homoeostasis primarily promoted by an STLA were *efficiency, dynamics of a homoeostatic process*, and *environments*. The characteristics of *coordination and lack of randomness, control regulation and feedback mechanism*, and *multisystems*, have been partially promoted, and the *energy* characteristic was found to be the 'hardest nut to crack'. A detailed account follows:

Efficiency

An STLA has promoted a thorough and complex understanding of the *efficiency* characteristic. This is in contrast to CG students, who perceived the body as an 'automaton' that just 'runs itself', a 'black box', without reference to the mechanisms of homoeostasis.

Table 7. Mapping the qualitative findings regarding the **feedback** characteristic of homoeostasis, during and after learning.

	Understanding feedback processes			
	System Thinking Instruction Group		Control Group	
Stage of learning	Insights	Quotes	Insights	Quotes
During	No reference		No reference	
After	Among some of the students there are clear indications of understanding the significance of feedback processes in the body; No reference to visual descriptions or simple statements, or any other method that would help illustrate how the mechanisms operate. Apparent difficulty in independently coming up with an explanation about the operation of feedback mechanisms, deviation and adjustment of indexes. Identifying and connecting between homoeostasis and feedback	The iron level in the body may decrease **and by homoeostatic process** the available **level of iron** in the cell will return, The iron level is maintained; **fluctuations occur once in a while but the body overcomes them**. When there is a deficiency or an overload of iron in the cells **the body takes care to return the level to normal and by this maintain a stable internal condition**.	No understanding of feedback mechanisms and their significance. Erroneous mixture of terminology.	*There is quivalence between iron level and time, the iron level is constant.* *The iron must always remain at the same level, which is why the homoeostasis mechanism keeps working.*
During	Understanding that homoeostasis has a relationship with feedback, which is perceived as a sequence of events. No reference to specific details of a feedback mechanism. Hormones are understood to be 'somehow' related to the feedback mechanisms but the mechanics of that relationship are unknown	White blood cells arrive faster to help with the illness. During stress, **the blood brings different hormones faster in the body** and during activity the blood supplies oxygen faster.	Understanding that homoeostasis involves feedback mechanisms. No reference to specific details of the feedback mechanisms. Misunderstanding: perceiving the mechanisms as **'automatic.'** Understanding that mechanisms operate as needed.	The heartrate is influenced by external stimuli that are transferred the brain by the nervous system, and from the brain signals are transferred through the nervous system to accelerate or decelerate the heart's activity, as needed. *The significance of raising heartrate in stress conditions is that the body is under stress and the heart automatically begins to beat faster because there are variables changing heartbeats and heartrate.*
After	Some of the students exhibit the understanding that homoeostasis involves feedback mechanisms and an understanding of how these mechanisms work, including their bidirectional quality. Understanding that homoeostasis has to do with balancing indexes, without reference to feedback mechanisms, confusing stability and constancy	*The cell needs a certain level of iron. When there is a deficiency, negative feedback kicks in and returns the iron to the desired level. After a while the body realises that heartrate is too high and will stop secreting adrenaline. (interviews)* *When a person is afraid, they secrete adrenaline. Now adrenaline is running through the blood and reaches the heart, increasing its rate This, increases the speed of blood flow, increasing the quantity of oxygen reaching the cells, which increases the energy we receive. (interviews)* Homoeostasis is a mechanism that corrects the deviation. Homoeostasis maintains a stable level of iron.	Understanding that homoeostasis involves feedback mechanisms. No reference to specific details of the feedback mechanisms. Some of the students understand that homoeostasis involves balancing indexes, without reference to dynamism	When it is cold outside body temperature drops but rises again to a normal state because of increased respiration processes. Homoeostasis manages a normal iron level in the cell

Table 8. Mapping the qualitative findings regarding the **dynamism** characteristic of homoeostasis, during and after learning.

Stage of learning	System Thinking Instruction Group: Insights	System Thinking Instruction Group: Quotes	Control Group: Insights	Control Group: Quotes
		Continuous changes		
During	General understanding Understating that changes are ceaseless and result from changing needs	Using pacemakers interferes with homoeostasis because **when the body needs to increase heartrate it will not be able to do so**. During illness, cells require more oxygen and the heart's role is to supply it. This is the importance of homoeostasis. The early pacemakers **did not enable a change in heartrate** and **created pulse at a constant rate**.	General comprehension that changes occur and that they result from changing needs **No distinction between 'constancy' and 'stability'**	**The disadvantage** of (early) pacemakers was that they regulate heartbeats **at a constant rate that is not influenced** by external factors such as physical exertion.
After	In-depth understanding that homoeostasis involves continuous dynamism Understanding that when deviations occur above or below a certain value the system reacts by correcting the deviation. Among some the students: difficulty perceiving homoeostasis as a state of constant fluctuations; there is no distinction between stability and constancy. Others understand fluctuation, deviation and its correction as a **steady state**.	Homoeostasis maintains the **availability** of iron in the body, which is why there are **up and down fluctuations** When the cell uses iron to produce haemoglobin, **the body takes action to replenish the quantity of iron** used, taking *care to return the level to normal, thereby maintaining a stable internal state*. **It takes several days for the homoeostasis mechanism to start working ......** So, they do need homoeostasis ... **because nothing is constant in a given condition**.	Understanding that homoeostasis has to do with dynamism Less common, but an understanding was found that deviations occur above or below a certain value, and the system reacts by correcting the deviation **Difficulty understanding fluctuation, deviation, and correction as continuous changes, and misconception as if they are disruptions of the system** **Using daily life terms in a 'canonic' way, without any in-depth understanding** ('keeping proper physical condition').	**The iron must always remain on the same level** and this is why the homoeostasis mechanism keeps working If the iron level rises or drops, homoeostatic mechanisms return it to a normal level ***In a normal state, deviations do not occur*** *but if there is a deviation the system overcomes it, homoeostasis takes care to correct the deviation, homoeostasis prevents deviations, homoeostasis is supposed to maintain a constant normal internal physical well-being [and in Danny's story that was not the case].*

(*Continued*)

Table 8. (Continued).

Stage of learning	System Thinking Instruction Group		Control Group	
	Insights	Quotes	Insights	Quotes
		Deviation and adjustment (bidirectionality)		
During	Understanding that there are fluctuations and deviations, but without understanding of the process or in-depth perception of the mechanism. Difficulty understanding fluctuations as corrections of deviations. No reference to specific indexes.	The disadvantage is that during physical activity the pacemaker should increase its operation rate **in order for more blood to be pumped into the cells and for more energy to be produced** In the old pacemakers there was no **use of the homoeostasis mechanism** because **heartrate was constant – this became a drawback** because even during physical activity, with the pacemaker the blood flows **at the same rate and does not deliver enough oxygen for the cells [that require more]**	**No reference to deviation and correction**	
After	Understanding homoeostasis as a mechanism for correcting deviations without delving into a specific mechanism; no understanding that fluctuations are an integral part of homoeostatic processes. Reference to indexes and detailed description of the balancing process. Some students **perceive corrections as unidirectional** In-depth understanding of the correction element	Change of rate as a result of something is **a deviation of the body**, and homoeostasis is **a mechanism that corrects the deviation. When iron is deficient** homoeostasis will operate **to produce more iron** or take it from someplace else in the body **During the body's attempt to return to the normal state** it will simply try to lower the temperature, until it is lower than normal, just so that there is recognition that there is a balance between high and low, and then return to the normal state . . . **it does not maintain a constant value but tries to keep it as close as possible to a constant. Homoeostasis does not prevent deviations, it balances deviations.**	**Perceiving correction as unidirectional** **Erroneous perception of homoeostasis as a state of no deviation, and lack of distinction between 'stability' and 'constancy'**	*When it is cold outside, body temperature drops, but it rises again to a normal state due to increased respiration processes* *If a cell requires more iron, the homoeostasis mechanism enables a balance and produces its required level* **Homoeostasis correct deviations and creates a constant temperature** **I think that the changes (in heartrate and breathing rate) contradict the concept of homoeostasis because at the beginning haemoglobin level was low and the body is supposed to preserve the internal environment** **It does not repair what is damaged, it just prevents damage from occurring**

(*Continued*)

Table 8. (Continued).

Stage of learning	System Thinking Instruction Group: Insights	System Thinking Instruction Group: Quotes	Control Group: Insights	Control Group: Quotes
		Different indexes		
During	Few replies refer to specific indexes such as CO_2 or O_2; most responders refer to the biological level of the organism. Difficulty in understating that homoeostasis operates in specific indexes separately from others	During illness, stress, and physical exertion there is an increase in blood flow to the required location, which also means more white blood cells reach the appropriate location	**Difficulty in understating that homoeostasis operates in specific indexes, each one separately from the others**	During stress the arteries contract, distributing less blood to the different organs. The heart therefore beats with increased force to supply enough blood
After	General reference to familiar everyday indexes such as heat	While running, because of the metabolic process in the cells, considerable **heat** energy is produced in addition to the energy required for activity. This significantly heats the body, **so the body just tries to cool itself by perspiration … To balance the heating, to cool down as much as possible towards the normal temperature**	**No reference**	
		Balance, equilibrium		
During	**No reference**. Few responses refer to 'equilibrium,' 'balance' or specific indexes such as CO_2 or O_2		**No reference**. Few responses refer to 'equilibrium,' 'balance,' or specific indexes such as CO2 or O2	
After	The concept of 'equilibrium' is vague and intangible for students, making it difficult for them to develop an in-depth understanding	*We do not really see (what is equilibrium), we don't talk that much about how it is expressed in the body, we don't really see.* ***What is equilibrium? Maintaining breathing rate, heartrate?*** *… (interviews)*	Difficulty understating the concept of 'equilibrium.' Erroneous perception of equilibrium, as if a balance between two different indexes (iron and time).	***There is an equivalence between iron level and time*** ***Homoeostasis is supposed to maintain a normal internal physical condition*** *and in Danny's story (breathing rate and heartrate increased immediately with elevation and red blood cell count increased over time) this is not what happened.*

Table 9. Mapping the qualitative findings regarding the **energy** characteristic of homoeostasis, during and after learning.

Stage of learning	System Thinking Instruction Group		Control Group	
	Insights	*Quotes*	Insights	*Quotes*
During	Only some of the students understood that generating energy is necessary for the operation of homoeostasis mechanisms. Most students did not mention this fact and are apparently unaware of it.	*In order to maintain a stable internal environment in changing environmental conditions, which is homoeostasis, a special investment of energy is required.*	**No reference**	
After	Correct perception of the importance of energy for homoeostasis processes Erroneous perception as if there is no connection between the operation of homoeostasis mechanisms and the processes of energy production, and as if a physiological process such as the body's defence from invasion 'disrupts' energy production.	As a result of damage to energy, white blood cells will not be produced and therefore homoeostasis mechanisms will not operate. When invaders enter the body, white blood cells, thanks to homoeostasis, know where to locate the infection; they rush to provide assistance and neglect important processes such as generating energy.	**No reference**	

Dynamics of a homoeostatic process

After learning, an STLA contributed to understanding of the *dynamics of a homoeostatic process* characteristic, to the ability to distinguish between constancy and oscillation, and to understanding that oscillations in living systems are bidirectional, ceaseless, and periodic. Many 10th grade students focus on the visible, physical level of organisation and do not 'see' the level of intracellular and molecular organisation, even after learning.

The definition of homoeostasis as an inclination towards a balanced state on the one hand and a perpetual process on the other hand, is a duality known to be a source of student misconceptions (Buddingh 1996). This study noted the terminology confusion between 'stability' and the 'constancy of variables'. This was also found in Authors (2015) study of 12th grade students majoring in biology. Authors (2015) explained this as the source for perceiving homoeostasis as a situation, rather than a process. The STLA in our research emphasised the relationship between mechanisms and processes and the relationship between various processes. An STLA was advantageous to fostering an understanding of the *dynamics of a homoeostatic process* characteristic of homoeostasis and its various aspects, and to internalising the notion that a state of ceaseless changes is the 'normal' state.

Environments

We may say that an STLA contributes more to the understanding that homoeostasis mechanisms adapt the body to the environment, and less to understanding the autonomy of the internal environment. Nevertheless, STLAG students have advanced in knowledge and understanding of the *environments* characteristic. At the same time, however these same students indicate difficulty in perceiving how interactions between *environments* operate and maintain the stability of the internal environment; this is a key insight that requires high-order thinking skills.

Coordination and lack of randomness

An STLA has been found to be effective in the long-term development of understanding interdependencies: the connection as well as coordination between systems. This is in contrast to CG students, who did not refer to this characteristic at all.

Table 10. Mapping the qualitative findings regarding the **multi-systems** characteristic of homoeostasis, during and after learning.

Stage of learning	System Thinking Instruction Group: Insights	System Thinking Instruction Group: Quotes	Control Group: Insights	Control Group: Quotes
Processes occur simultaneously and cooperatively				
During	Few show an understanding of the mutual effect and cooperation between systems.	Heartrate is affected by external stimuli and these are transmitted from the brain by the nervous system; they can increase or decrease heartrate by necessity.	**No reference.**	
After	Only a few students referred to the multisystemic connection characteristic of homoeostasis, illustrating that most students have difficulties understanding this characteristic.	When it is cold outside, body temperature decreases, but then rises again to a normal level as a result of increased respiration processes. When a person is afraid … he secretes adrenaline. Adrenaline flows through the blood, reaches the heart, and increases its rate. At this point, heartrate increases the speed of blood flow, which increases the amount of oxygen reaching the cells, which increases the energy that we get.	**No reference.**	
Homoeostasis processes occur ceaselessly in the living organism				
During	*No reference.*		No reference.	
After	Difficulty understating that homoeostasis processes continue without any interruption, leading to the erroneous perception that they operate only in instances of emergency. Among some of the students, an understanding that changes are incessant.	**Homoeostasis is supposed to know when to kick in**. So they do need **homoeostasis working all of the time … because nothing is constant in a given situation**. It (homoeostasis) **must adapt itself to conditions at every moment** (such as temperature variations) **and it changes at every moment.**	Difficulty understating that homoeostasis processes continue incessant, leading to the erroneous perception that they operate only in instances of emergency or on specific occasions in a living creature's life.	*In the sprouting process) it takes several days for the homoeostasis process to kick in …* *There was a serious deviation in the body's systems and the homoeostasis system took some time to overcome it.*
Identifying and understanding entire body homoeostasis in extraordinary conditions				
During	Understanding that in extreme conditions changes occur that have to do with homoeostasis mechanisms	During illness, stress, and physical exertion there is an increase in blood flow to the location in need .	Understanding that in extreme conditions changes occur that have to do with homoeostasis mechanisms.	During stress the arteries contract, distributing less blood to the different organs. The heart therefore beats with increased force to supply enough blood during stress.
After	Understanding that in extreme conditions changes occur that have to do with homoeostasis mechanisms.	When starting to run, as time passes, his heartrate begins to rise, his body heats up, he begins to perspire, to pant; these things happen because our body attempts to cool itself and add to its energy.	Understanding that in extreme conditions changes occur that have to do with homoeostasis mechanisms.	*During physical activity there is more breakdown of sugar in the cells … in order to increase cellular respiration in the muscles … there is a (sugar) storage in the body. If there is a deficit, it breaks down to substances essential for the body and the body raises its sugar level or you feel hungry.*

Table 11. Mapping the qualitative findings regarding the **environments** characteristic of homoeostasis, during and after learning.

	System Thinking Instruction Group		Control Group	
Stage of learning	Insights	Quotes	Insights	Quotes
During	Among some of the students, a misunderstanding that homoeostasis mechanisms operate to preserve the body's internal environment, according to changing needs. Among some of the students, an understanding that there is a connection between the environments – the internal and the external.	***During physical exertion cardiac output rises to maintain a stable energy level in the body …*** ***During physical exertion cardiac output rises and this maintains an oxygen level sufficient for the body …*** *The drawback in this is that in changing environmental conditions, which is homoeostasis, a special investment of energy in order to maintain a stable internal environment is required.*	**Poor understanding**.	
After	Some of the students in this group, throughout the course of their studies, progressed in understanding the connection and mutual influence between the internal and the external environments. No differences in the types of erroneous notions were found between the two treatment groups. **Erroneous perception** as if the adjustment occurs by itself, regardless of homoeostasis, and misunderstanding that the body adapts to the environment by homoeostasis mechanisms.	*There is a connection between the environments; the homoeostatic mechanisms balance deviations …* *The colder the external environment, the more heat the body produces …* *Homoeostasis mechanisms maintain **a constant body temperature …*** ***Homoeostasis works – keeping a stable internal environment, even when changes occur in the external environment …*** ***Homoeostasis is required because they (desert plants) open their stomata at night so as not to dehydrate during the day.*** ***Plants need homoeostasis mechanisms – without them they would dehydrate because the stomata would not know when to open.*** ***Both (species of fox) have become adapted to the environment, as the body adapts itself to the environment …***	Decrease in Control Group understanding of the connection and the mutual influence between environments. **Erroneous perception** as if the adjustment occurs by itself, regardless of homoeostasis, and misunderstanding that the body adapts to the environment by homoeostasis mechanisms.	… .Yes, because the body remains at 37°C and the body shivers just because the internal environment is not affected by the external environment *There is a connection between the internal and the external environment, which means they have no homoeostatic mechanisms …* *I think that desert plants have grown accustomed to heat and dryness in the desert, and therefore do not require homoeostatic mechanisms,* *The plants have already adapted to living there but they still need homoeostasis, in case they were someplace else they would require homoeostasis mechanisms,* *[transpiration in desert plants] is a homoeostatic mechanism, but it helps only with certain things.*
After				*… Yes, it means there is no connection between the internal and the external environment because even when it is cold in the external environment, body temperature can be high as a result of increasing cellular respiration processes* *The connection between environments – internal and external – makes homoeostasis no longer necessary.* *The connection between environments is selective* *The creature got used to it.*

Control regulation and feedback mechanism

An STLA seems to contribute to student understanding when *control regulation and feedback mechanisms* and their significance are presented through the use of illustrations or graphs, or even by simple statements. However, if students encounter a homoeostatic event in a less expected, more coincidental context, they still struggle to provide an explanation on their own initiative. The contributions that an STLA has made to understanding that this activity is bidirectional can be seen in the study results. The partial contributions of an STLA to the understanding of *control regulation and feedback mechanisms* as a means of adjusting deviations and maintaining the balance of variables, is also evident. Understanding the variables is important for appreciating the significance of balancing processes, that is, for comprehending the significance of homoeostasis processes. Most 10th grade students with limited knowledge of chemistry find it difficult to perceive the levels of intracellular and molecular organisation; they still lack sufficient training in formal thinking skills. It seems that certain system thinking skills promote understanding of the relationship between homoeostasis and feedback processes. Such skills include 'distinguishing stages or components of a process', 'interdependency of processes at different organization levels', or 'interdependency of processes, and their effect on the entire organism'. We emphasised these thinking skills in the STLA that was carried out in our research.

Multisystems

Understanding the multisystem characteristic is a complex challenge for 10th grade students (Barak and Gorodetzky 1998; Hmelo-Silver and Azevedo 2006; Snapir et al. 2017). It seems that an STLA is of little contribution to understanding that processes take place simultaneously at all levels of organisation in the body, through cooperation between systems. However, discussing these processes can make a significant contribution, especially after learning, to comprehension that homoeostasis mechanisms are permanently active in the living organism. The most common examples of homoeostasis discussed in the classroom are usually related to extreme conditions, such as water deficiency or heat stress. Classroom discussion lacks explicit reference to the fact that homoeostasis ceaselessly occurs in the body at every moment of our lives.

The ability to link the concrete, tangible aspects of homoeostasis, such as sweating, blushing, and heart and respiration rates, with the scientific, abstract, and complex aspects, such as the processes and mechanisms that keep body temperature within a stable range, is not readily available to the student (Buddingh 1996). This ability requires formal thinking – which is necessary for system thinking (Simpson and Marek 1988; Westbrook and Marek 1992). According to Babai and Levit-Dori (2009) and Babai and Mor-Yosef (2014), only 40% of 11th and 12th grade science-majoring students have developed formal thinking.

Authors (2015, 2015) argued that the understanding of homoeostasis also relies on pre-existing notions, specifically those based upon bodily sensations and macro level perceptions of the body, with no reference to micro-level factors such as small-scale structures and local processes. One example they supply is the multisystem characteristic of homoeostasis that pertains to the connection between the systems that govern metabolism rate and the systems that regulate body temperature. Many students wrote about an internal (general, obscure) mechanism operating in the body and maintaining temperature without any reference to the body's metabolism rate.

During our intervention, in the first half of the 10th grade school year, students were exposed to a limited variety of systems in the human body. It is possible that upon completing their study of the entire subject, once they have become familiar with a much wider variety of examples for homoeostasis, this characteristic would be better understood. We recommend introducing a greater number and variety of examples for everyday homoeostatic activity in various body systems – not just extreme cases, in order to clarify this aspect. This, combined with STLA-aimed learning tasks like HELT, while emphasising cooperation between different body systems, may contribute to understanding this aspect and to developing a holistic view.

Energy

The concept of 'energy' is too abstract for 10th grade students, which explains their difficulty trying to understand the *energy* characteristic of homoeostasis. According to Authors (2015), even 12th grade students who major in biology exhibited difficulties comprehending the importance of energy for life processes. The findings of our study suggest that it is unusual to expect 10th grade students to understand the *energy* characteristic thoroughly, certainly at the earlier stages of studying 'Human biology, emphasizing homeostasis'.

Recommendations

We believe that an STLA can improve the understanding of homoeostasis and its characteristics among students. There are many system thinking skills that can contribute to the students' perception of the homoeostasis characteristic of *coordination and lack of randomness*. These skills include 'distinguishing between different organization levels on which biological processes occur', 'understanding interdependence of processes on different organization levels', and 'understanding interdependence of processes occurring in the body and their influence on the organism as a whole'.

There are also system thinking skills that can prepare the students' perception of the homoeostasis characteristic *multisystems*. These skills include 'identifying dynamics' and 'viewing different stages of a process as parts of a structured whole'. Awareness of how variables are balanced by homoeostasis can help the student see not only the organism level and the physiological parameters such as heart rate and respiratory functions, but also the intracellular and molecular levels, each with their own specific variables. The system thinking skill of 'understanding that some of the changes occurring in the organism result in a deviation of physiological variables', can contribute to the students' perception of the homoeostasis characteristic *dynamics*.

In addition, after teaching with the application of an STLA, we found certain correlations between all three aspects of homoeostasis perception. Based on those correlations, we recommend that an STLA be applied. This can be effective if it is done while explicitly highlighting for students the connection between the aspects of 'understanding homeostasis', 'understanding the characteristics of homeostasis', and 'application of homeostasis'.

We suggest taking a step-by-step approach, so that each lesson exposes the student to a few new aspects of system thinking that will gradually be added to those that are more familiar, preventing the overwhelming, intimidating burden of the unfamiliar. This way, the student may gradually assimilate more and more system thinking skills, implementing them through various examples. We recommend introducing numerous examples and exercises by creating a wide variety of learning tasks that are focused on a wide variety of homoeostatic events. The STLA learning tasks should include a set sequence of questions to serve as a skeletal guideline, with adjustments by the relevant subject matter and class – similar to the instruction activities carried out in this study.

Pedagogical change in the classroom will take place only if teachers take the initiative – and they must be equipped with the right tools and the right knowledge to lead the way. In order to plan and implement an STLA, teachers must be versed in the different aspects of system thinking and their biological significance, properly trained in system thinking, and a positive attitude regarding its important role. It is essential that teachers be taught how to instruct their students to develop system thinking, teaching them how to exercise and implement an STLA on the subjects in the biology curriculum. Teachers must also learn how to develop **pedagogical scientific discourse** in the classroom, properly applying system-thinking concepts. The preparation of biology teachers must therefore cover the subject of system thinking with an emphasis on homoeostasis, while also training teachers to develop the system thinking skills of their students through the explicit instruction of homoeostasis characteristics.

According to the Next Generation Science Standards reform, developing thinking skills must be an integral part in the teaching of every subject matter, being just one aspect in the changing role of the teacher. This reform also includes the adjustment of the curricula to give time and space for the development of scientific and engineering practices and thinking skills, as well as the implementation of suitable instructions that are specifically focused towards these practices and skills (Fick 2018).

Research limitations

The teachers were inexperienced in the instruction of system thinking. They were introduced to the necessary skills only in the framework of the training they received from the researcher while preparing for the intervention. All the post-learning tests in this study were conducted mid-year, when the students completed the study of the human circulatory system. No similar tests were conducted upon completion of the entire part of the syllabus that dealt with 'Human biology emphasizing homeostasis'. An interesting follow-up study would involve investigating the perception of homoeostasis among 10th grade students after they have completed the entire subject. This follow-up would take place at the end of the school year, as well as at the end of 12th grade. We conclude with a quote from one of the students: 'Homeostasis again?! Why do they have to make it complicated in biology?!'

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Appendix 1 Similarities and differences between questions in the HPQ

Items 1 and 2 are identical in the pre and post learning questionnaires. Items 3, 4, and 5 are similar in the pre and post questionnaires and are actually two versions of the same item. In each case, different homoeostasis events are described, but in both cases the descriptions lead to the same question.

Example of an item from the pre learning questionnaire (question 3):

Many mountaineering expeditions arriving at the Himalayas since the beginning of the 20th century hire the indigenous Sherpas as guides and porters. The relatively short statured Sherpas are used to high altitude and carry 50 kg loads on routes that prove very challenging for non-locals, even for professional mountain climbers carrying no extra weight. Is it possible to conclude from the above that Sherpa people do not require homoeostasis mechanisms?

Example of an item from the after learning questionnaire (question 3):

Plants lose water by a process called transpiration: small pores on the leaf surface, known as stomata, open – and through these pores water evaporates. Desert dwelling organisms are subject to extreme conditions such as water *scarcity and possible dehydration. Opening their stomata during the dark, desert plants avoid more significant water loss. Is it possible to conclude from the above that desert plants do not require homoeostasis mechanisms?*

Appendix 2A Homoeostasis questionnaire

Pre-learning

Part A

For questions 1 and 2 – choose the single most appropriate answer:

(1) **Which of the following conditions indicates the existence of homoeostasis in the living organism?**
  (a) All bodily functions are equally operating.
  (b) The internal environment is independent of the external environment.
  (c) The amount of food ingested by the organism is equal to the amount of substances excreted from the body within a given period of time.
  (d) The internal environment is different from the external environment.

(2) **A homoeostatic system operates to maintain a steady state in the human body. This means that for a particular factor (such as heart rate, body temperature, etc.)**
  (a) Deviations occur above or below a certain value and the system responds by correcting deviations.
  (b) The homoeostasis system maintains a constant value by preventing deviations.
  (c) Normally no deviations occur, but if there is any deviation, the system will overcome it.
  (d) It is the homoeostatic system itself that generates deviations in order to adapt the body to changing conditions.

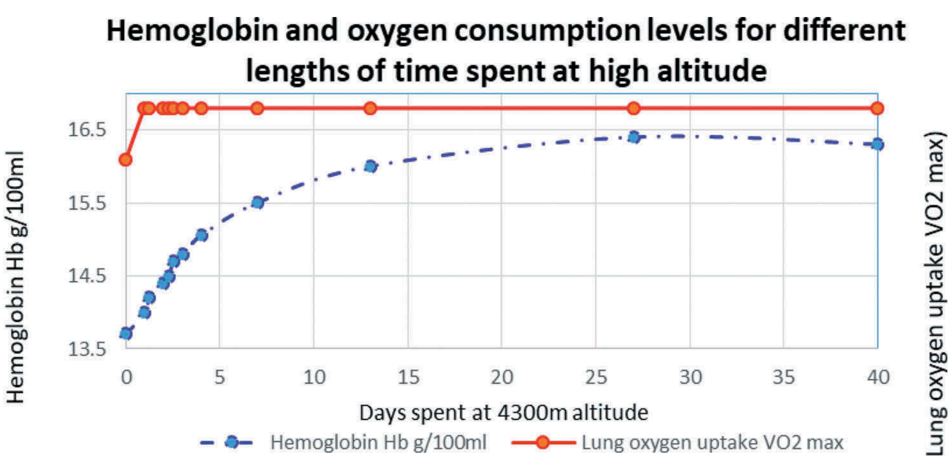
For questions 3, 4, and 5 – write your answer.

(3) Many mountain climbing expeditions have arrived at the Himalayas since the beginning of the 20^{th} century. They hire the indigenous Sherpas as guides and porters. The relatively short-statured Sherpas are used to high altitude and can carry 50 kg loads on routes that prove very challenging for non-locals, even for professional mountain climbers carrying no extra weight. **Is it possible to conclude from the above that Sherpa people do not require homoeostasis mechanisms?**

(4) On cold days, when the surrounding temperature drops to 10°C, the body temperature of a healthy human body temperature remains stable due to an increase in cellular respiration. **Does this mean that there is no connection between the internal and the external environments?**

(5) An Israeli backpacker arrived at the Peruvian city of Huaraz – which is 3091m above sea level. For the first few days following his arrival, he suffered headaches, and felt weak and dysfunctional. After a few days of medical follow-up and rest, the backpacker regained his vitality. The chart below shows test results for the backpacker's haemoglobin levels and oxygen consumption over a two-week period.

In your opinion, do the changes in haemoglobin levels and oxygen consumption contradict the concept of homoeostasis? Explain.



Appendix 2B Homoeostasis questionnaire

Post learning

Part A

On questions 1, 2 – choose the single most appropriate answer:

(1) **Which of the following conditions indicates the existence of homoeostasis in the living organism?**
 (a) All bodily functions are equally operating.
 (b) The internal environment is independent of the external environment.
 (c) The amount of food ingested by the organism is equal to the amount of substances excreted from the body within a given period of time.
 (d) The internal environment is different from the external environment.

(2) **A homoeostatic system operates to maintain a steady state in the human body. This means that for a particular factor (such as heart rate, body temperature, etc.)**
 (a) Deviations occur above or below a certain value and the system responds by correcting deviations.
 (b) The homoeostasis system maintains a constant value by preventing deviations.
 (c) Normally no deviations occur, but if there is any deviation, the system will overcome it.
 (d) It is the homoeostatic system itself that generates deviations in order to adapt the body to changing conditions.

On questions 3, 4, 5 – write down an answer.

(3) Plants lose water by a process called transpiration: stomata, which are small pores on the leaf surface, open – and through these pores water evaporates. Desert dwelling organisms are subject to extreme conditions such as water scarcity and possible dehydration. Desert plants avoid more significant water loss by opening their stomata during the dark. **Is it possible to conclude from the above that desert plants do not require homoeostasis mechanisms?**

(4) A fox inhabiting the warm south and a fox of the cold north share a similar body temperature. **Does this mean that there is no connection between the internal and the external environments?**

(5) Danny arrived from Israel to Mexico City, the Mexican capital elevated 3500m above sea level. Immediately upon arrival, the enthusiastic traveller set out to explore the city markets. Within a few hours he began to feel weak and out of breath – and was hospitalised.

The chart below shows Danny's cardiorespiratory test results over two weeks. Danny was feeling better after five days. **In your opinion, do the changes in heart rate and respiratory rate contradict the concept of homoeostasis? Explain.**