Chapter 7

Experts' Views on Translation Across Multiple External Representations in Acquiring Biological Knowledge About Ecology, Genetics, and Evolution

Konrad J. Schönborn and Susanne Bögeholz

Introduction

Students' successful communication as biologists is closely related to their competence in interpreting multiple external representations (MERs). Acquiring knowledge in the domains of ecology, genetics, and evolution involves *translating* across and between MERs that depict concepts and principles at different levels of biological organization and in varying modes of representation. Promoting translation processes in learners is pivotal to the development of biological understanding. This study is a follow-up from the research reported in Schönborn and Bögeholz (2009). A Delphi approach was adopted to collect a second round of data from the same expert panel that was interviewed 3 years ago. Specifically, the purpose of the study was (1) to investigate the validity of four types of biological knowledge identified in the first expert data collection, (2) to elucidate experts' views on the challenges facing learners upon engaging translation processes in constructing biological knowledge, and (3) to reveal experts' opinions of what overarching requirements are necessary for effective translation in the development of biological knowledge. The content focus of the present study was directed to the domains of ecology, genetics, and evolution.

K.J. Schönborn (✉)
Division of Media and Information Technology, Department of Science and Technology (ITN), Linköping University, Campus Norrköping, SE-60174 Norrköping Sweden
e-mail: konrad.schonborn@itn.liu.se; konsc@itn.liu.se

S. Bögeholz
Biologische Fakultät, Georg-August-Universität Göttingen,
Waldweg 26, 37073 Göttingen, Germany
e-mail: sboegeh@gwdg.de

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Theoretical Background

Types of Biological Knowledge

Analysis of the German national standards for biology education (Kultusminister-konferenz, 2005) and the core biology curriculum for the federal state of Lower Saxony (Niedersächsisches Kultusministerium, 2007) identified four hierarchical types of biological knowledge that learners are expected to acquire at the secondary level (see Fig. 7.1) (Schönborn & Bögeholz, 2009). Use of *types* of knowledge refers to "static knowledge about facts, concepts, and principles that apply within a certain domain" (de Jong & Ferguson-Hessler, 1996, p. 107).

The four types of knowledge (see Fig. 7.1) are defined as follows. *Type 1* knowledge (*biological terms*) constitutes the building-block *elements* of biological knowledge and could include *predator*, *prey*, *DNA*, and *genotype*. When the semantic relationship between two or more biological terms conveys biological meaning (e.g., a biological process), then this relationship exists as a biological

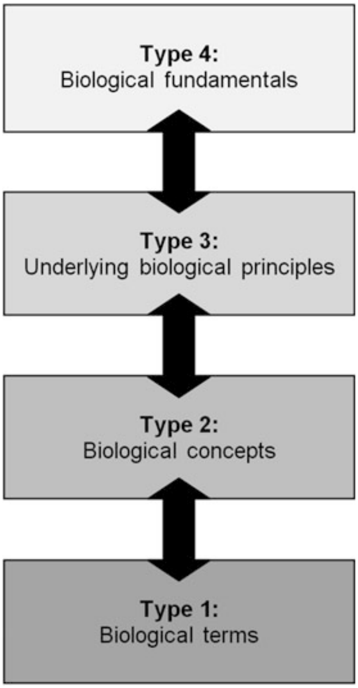

Fig. 7.1 Four types of biological knowledge that learners are required to develop at the secondary school level in Germany

concept (*type 2* knowledge: *biological concepts in* Fig. 7.1). At the school level, each biological concept exists on a continuum ranging from *broad* to *narrow* depending on the degree of the biological meaning that is communicated (e.g., *protein synthesis* vs. *DNA-methylation*). When a collection of biological concepts mutually communicates an underlying biological meaning, then this relationship exists as an underlying biological principle (*type 3* knowledge: *underlying biological principles*) (cf. Niedersächsisches Kultusministerium, 2007). Examples of biological principles could include the *principle of recapitulation* and the *competitive exclusion principle*. Lastly, when an underlying biological principle shares meaning with others, then together, they constitute components of *type 4* knowledge: *biological fundamentals*. For example, three fundamentals operationalized in the Kultusministerkonferenz (2005) document consist of *system*, *structure and function*, and *development*.

In this chapter, the knowledge types (see Fig. 7.1) are applied to the domains of *ecology*, *genetics,* and *evolution*. These three domains provide a concrete platform from which to consider learners' construction of biological knowledge. For example, Kinchin (2010) described evolution as a *disciplinary threshold* and guiding principle in biological understanding, Tsui and Treagust (2007) highlighted the centrality of genetics in modern biology education, and Kuechle (1995) described ecological knowledge as a principal field for an integrated biology education.

Translation Processes and Communication Competencies

Contemporary curricula stress the development of core *competencies* for promoting biological understanding (e.g., Labov, Reid, & Yamamoto, 2010). For example, in Germany, such an orientation (Kultusministerkonferenz, 2005; Niedersächsisches Kultusministerium, 2007) includes the competence area of *communication*, which also contains the ability to use MERs, such as photographs, micrographs, diagrams, drawings, graphs, and physical models in biology learning.

In biology, MERs communicate knowledge at different *levels* of biological organization that include the *subcellular*, *cellular*, *organ*, *organism*, and *population* levels and in different *modes of external representation (ER)* (e.g., *realistic* vs. *abstract* ERs) (Schönborn & Anderson, 2009). Kozma and Russell (1997) referred to the skills associated with interpreting different ERs as *representational competence*. A central cognitive component of engaging MERs in learning biology is the process of *translation*, which concerns the processing, mapping between, and moving across ERs (Ainsworth, 1999). Translation requires comprehending relationships between MERs and linking different ERs to the idea that is represented (Ainsworth, 2006). Engaging translation processes is necessary for successful biology learning (e.g., Tsui & Treagust, 2003).

Translation Across MERs in the Acquisition of Biological Knowledge

Schönborn and Bögeholz (2009) postulated the role of translation across ERs in the acquisition of different types of biological knowledge (see Fig. 7.1). To construct knowledge about a biological concept (type 2), learners may need to interpret and link the MERs that all depict the concept in the same or in varying modes of representation. Doing so may require applying knowledge about biological terms (type 1) to the necessary biological concept that is being represented and vice versa (bidirectional arrow in Fig. 7.1). For instance, examples A_1 and A_2 (biological concept) provided in an online Appendix I[1] require *translating horizontally* from one ER to another at the same level of biological organization. Examples B_1 and B_2 (biological concept) in Appendix I require *translating vertically* between ERs at different levels of biological organization.

To construct knowledge about an underlying biological principle (type 3), learners may need to interpret and link the MERs that each represent different biological concepts but collectively, depict one underlying principle. The MERs could depict the biological principle in the same or in varying modes of representation. Acquiring type 3 knowledge may require applying knowledge about biological concepts (type 2) to the underlying biological principle that is being represented and vice versa (see bidirectional arrows in Fig. 7.1). For instance, examples A_1 and A_2 (biological principle) in Appendix I require *translating horizontally* across ERs at the same level of biological organization. Examples B_1 and B_2 (biological principle) in Appendix I require *translating vertically* between ERs at different levels of biological organization. We hypothesize here that performing *horizontal* and *vertical* translation across MERs constitutes essential processes in students' acquisition of biological concepts and principles.

Delphi Approach for Obtaining Experts' Views

Delphi studies have the overall goal of attaining agreement or stability in an expert panel's opinions and judgments about a particular *problem* (e.g., Linstone & Turoff, 2002). Two main features of the Delphi technique are anonymity among participants and multiple *rounds* of data collection (e.g., Murry & Hammons, 1995).

The *first round* of a typical Delphi study is an open-ended collection of experts' opinions, often through open-ended questions or interviews. Following this, the researchers qualitatively summarize the responses, which inform the design of more focused questions. Together with communicating a summary of results

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[1] Appendices I and II are permanently available at http://www.ep.liu.se/PublicationData/diva-85510/Appendix_I.pdf and http://www.ep.liu.se/PublicationData/diva-85510/Appendix_II.pdf, respectively.

from the first round to the panel, more focused questions constitute data collection in the second and subsequent rounds. The Delphi approach is considered complete once consensus or stability is reached.

Examples of Delphi studies in science education research include those by Osborne, Collins, Ratcliffe, Millar, and Duschl (2003) on experts' views of what key ideas should comprise school science curricula and by Häussler and Hoffmann (2000) on experts' views in developing a curricular framework for physics education. An assumed strength of the Delphi technique is that soliciting a group of experts' views increases the likelihood of *honing in* on the identified problem with greater validity (cf. Osborne et al., 2003).

Research Questions

In pursuit of further investigating experts' views on translation across MERs in acquiring biological knowledge in the domains of ecology, genetics, and evolution, the following three research questions were formulated:

1. To what extent do experts agree that the biological knowledge framework (see Fig. 7.1) can be applied to each of the knowledge domains?
2. What do experts view as the challenges associated with horizontal and vertical translation in the construction of knowledge in each domain?
3. What are experts' overarching requirements for students' effective translation in developing biological knowledge about each domain?

Methods

As part of the *second round* of a Delphi approach, this study elicited and analyzed an expert panel's responses to a written questionnaire.

Expert Sample

The ten experts from *Round I* (Schönborn & Bögeholz, 2009) were invited to participate in *Round II* 3 years later in July 2010. A questionnaire (see online Appendix II[2]) was electronically mailed to them together with a summary of experts' views obtained from Round I (see Appendix I). Seven experts responded

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[2] Expert responses are presented verbatim. Words between square brackets were inserted to improve readability. An ellipsis denotes the exclusion of four words or less of response text. An ellipsis between square brackets designates the exclusion of five or more words. Each expert was assigned an anonymous identification (*E.a* through *E.e*). The expert and respective question item (see Appendix II) associated with a response follow each datum.

to the questionnaire. Of these, one expert's responses were incomplete, and another stated that s/he was uncertain of how to interpret certain items. Thus, the expert panel for Round II consisted of five experts. Threats to internal validity (for $n = 5$) were minimized in light of considering other Delphi approaches in the literature. For example, Bourrée, Michel, and Salmi (2008) demonstrated that groups of four experts can render valid Delphi results, whereas Yousuf (2007) asserted that a Delphi study is only as good as the quality of the expert participants. The five experts in our study were leading biology education specialists all with a deep understanding of competency-based curriculum reform. Expert validity was reinforced by the following self-ratings. First, the average rating of experts' biological content knowledge was 76% for ecology, 84% for genetics, and 80% for evolution. Second, experts rated their knowledge about different ER types as 87% on average and their knowledge of the communication competence as defined in the *Bildungsstandards* as 84%. Lastly, experts rated their expertise in each of *horizontal* and *vertical* translation as 90% on average, respectively.

Design and Implementation of the Expert Questionnaire

A questionnaire focused on the nature of biological knowledge and translation across MERs served as the data-collection instrument for Round II. A preliminary version was piloted with six biology education colleagues to validate item syntax and clarity. The final questionnaire sent to the expert panel consisted of an electronic form (see Appendix II) and corresponding information booklet (see Appendix I). The questionnaire was divided into a self-rating section (Section 0) and three main sections, namely, *Framework of Biological Knowledge* (Section 1), *Translation Processes and Challenges* (Section 2), and *Designing Translation Situations for Acquiring Knowledge* (Section 3). Sections 1–3 comprised four five-point Likert items ranging from "I completely disagree" to "I completely agree" and 21 open-ended items. The information booklet contained a summary of the results from *Round I* (Schönborn & Bögeholz, 2009). The experts responded in English.

Analysis of Expert Questionnaire Responses

Data were treated with a mixed deductive-inductive analysis (e.g., D'Amour, Goulet, Labadie, San Martín-Rodriguez, & Pineault, 2008). First, the authors used a deductive analysis to code expert responses to the Likert items and sought representative datum examples of expert responses corresponding to each of the domains. In this deductive stage, the authors intended to establish the following: (1) whether the experts agreed that the types of biological knowledge (see Fig. 7.1) could be applied to the domains of ecology, genetics, and evolution; (2) examples of such application in each domain; (3) whether the experts agreed that the nature of the knowledge needed for horizontal versus vertical translation was different; and (4) ways in which the nature of the knowledge required for translation could be different in each domain.

Second, any themes in the data were iteratively developed (e.g., Björnsdóttir, Almarsdóttir, & Traulsen, 2009) during an inductive analysis. This inductive stage intended to uncover experts' views on challenges facing learners in the engagement of (1) horizontal and (2) vertical translation processes and (3) overarching requirements for effective translation in students' acquisition of biological knowledge.

Results

The findings of this study are structured in response to the three research questions posed.

To What Extent Do Experts Agree That the Biological Knowledge Framework (See Fig. 7.1) Can Be Applied to Each of the Knowledge Domains?

The first result section presents experts' application of the types of biological knowledge framework (see Fig. 7.1) to the domains of ecology, genetics, and evolution.

Ecology Domain

All five participants agreed (3/5 completely and 2/5 partially) that the structure and components of the framework (see Fig. 7.1) could be applied to ecology. Consider the following response[2] obtained from one of the two partially agreeing participants:

> From a pedagogical point of view you have to regard ecology as an applied science. As a consequence you have to consider ethical principles like sustainability, common wealth, utility. So, the 4 types of knowledge are necessary but not enough [. . .] (E.a., 1.1.2.).

The response above suggests that ecological understanding also requires incorporation of other knowledge forms (e.g., Kuechle, 1995). In conjunction with the revealed agreement, all five experts (5/5) demonstrated application of the framework in identifying examples of ecological knowledge corresponding to each knowledge type (see Fig. 7.1), as represented by the example below:

> The biological terms *predator* and *prey* together form the biological concept of *predator-prey relationship*. This concept, together with *competition* (e.g., for food) and *symbiosis*, conveys the principle of *interaction of organisms*. Furthermore, to understand *system* as a biological fundamental in the context of ecology, students need to have knowledge of some more examples for ecological principles [. . .] (E.d., 1.1.3.).

The expert's opinion quoted above also clearly elucidates potential interrelationships between different knowledge components of the framework (see Fig. 7.1).

Genetics Domain

Agreement on application of the framework (see Fig. 7.1) to a genetics domain was reached among four (4/5) experts (two completely and two partially agreeing), whereas one expert was undecided. The response from one of the partially agreeing experts was as follows:

> In addition to these principles [mentioned in response to 1.1.2.] you have to regard the principle of dignity (e.g., genetic fingerprinting, prenatal diagnosis, newborn screening. . .). (E.a., 1.2.2.)

The response expresses the need to include other ideas into the notion of genetics knowledge (e.g., France, 2007). Coupled to the observed agreement in the panel as a whole, the following expert's formulation of examples was related to types of genetics knowledge (see Fig. 7.1):

> Example: sickle cell anemia on the level of molecules
> Type 1/biological term[s]: DNA triplet. . . characteristics of amino acids, amino acid sequences. . .
> Type 2/biological concept: point mutation and molecular structure of proteins (primary to quaternary structure)
> Type 3/underlying biological principle: genetic code determines the molecular structure of proteins
> Type 4/biological fundamental: structure and function (E.b., 1.2.3.)

Evolution Domain

Of all participants (5/5) showing consensus, two experts (2/5) completely agreed, whereas three (3/5) partially agreed that the framework (see Fig. 7.1) can be applied to evolution. A response that represented partial agreement was as follows:

> . . .there are subjects/issues to be regarded in education which are not included in the four types [of knowledge]: [e.g.] epistemology in connection with the dispute on evolution/creation; cultural evolution. (E.a., 1.3.1.).

This same expert mirrored his/her response to the previous domains by suggesting that certain epistemological ideas need to be considered in evolution knowledge. All five experts provided application of the framework in an evolution context, as represented by the following two examples (*1* and *2*) obtained from one expert:

> Fundamental: development (of populations and species)
> Principle *1*: variability and adaptation
> Concepts *1*: mutation
> Terms *1:* DNA, gene, genotype
> Principle *2*: reproduction
> Concepts *2*: selection
> Terms *2*: phenotype, offspring (E.d., 1.3.2.)

In addition to mapping evolutionary knowledge onto the four framework components (see Fig. 7.1), this response provides an example of how different principles can mutually contribute to the same biological fundamental.

What Do Experts View as the Challenges Associated with Horizontal and Vertical Translation in the Construction of Knowledge in Each Domain?

Experts' views on translation processes and challenges facing students' construction of knowledge in ecology, genetics, and evolution are structured in three subsections: (1) the *nature* of the knowledge engaged in *horizontal and vertical translation*, (2) the challenges inherent in *horizontal* translation processes, and (3) the challenges inherent in *vertical* translation processes.

The Nature of the Knowledge in Horizontal Versus Vertical Translation Processes

A split in experts' agreement was revealed as to whether the *nature* of the biological knowledge—which students needed to access in horizontal versus vertical translation across MERs—is fundamentally different. One (1/5) expert completely disagreed, two (2/5) partially disagreed, whereas the remaining two (2/5) completely and partially agreed, respectively. With respect to ecology, the response from the expert who partially agreed was as follows:

> *Horizontal translation* means just [being able] to *apply* a concept, principle, or fundamental to *different examples* (e.g., predator-prey relationship to different species). The idea (model) remains the same, the context changes. With regard to MERs, this means [being able] to recognize the core idea in different ERs. *Vertical transfer [translation]* requires knowledge of new characteristics, that is, there is a *new quality* or a new idea (model), if you go 'level-up'..., for example, the relationship between predator and prey could not be predicted from the characteristics of a predator and of prey alone. [...] (E.d., 2.1.2.a.)

Regarding genetics, the opinion from the expert who completely agreed that the nature of knowledge is fundamentally different in horizontal and vertical translation was as follows:

> I (as a student) acquire factual knowledge about the terms homo- and heterozygosity by analyzing monohybrid crosses of peas. Thus, I acquire knowledge at the organismic level (e.g., by comparing attributes of pea seeds). For horizontal transfer [translation] to other crosses [...] I do not need any new knowledge. I just have to identify the known attributes of those terms [...]. However, for explaining the phenotypic differences between the pea seeds, I need additional knowledge, because I have to change to other levels, for instance, the cellular level (comparing homologous chromosome pairs and its [their] distribution during meiosis) or the molecular level (comparing DNA molecules and its [their] distribution during meiosis). Thus, vertical translation again requires that [...] a student has to connect those knowledge items [...]. (E.e., 2.1.2.b.)

The opinions above drawn from the ecology and genetics domains demonstrate that horizontal translation does not involve *any new knowledge* during linking knowledge to the new context, but vertical translation requires *additional* and a *new quality* of knowledge when changing levels of biological organization, as well as bridging knowledge between the levels. Lastly, with respect to evolution, the following response is from the expert who completely disagreed that the nature of biological knowledge accessed in horizontal versus vertical translation is different:

> [. . .] if we change e.g., [for example] from homologies on [at] the organ level to molecular homologies, we change the level of organization but not the nature of the knowledge. Furthermore, in a phylogenetic tree you make [perform] a vertical transfer [translation] in quite [an]other sense than explained in [Appendix I]. (E.a., 2.1.2.c.)

The view above suggests that the *nature* of biological knowledge can sometimes remain constant—even when the level of organization changes in that *vertical* translation *within* a phylogenetic tree ER, as interpreted by the expert in this context—does not necessarily entail switching *levels* of biological organization.

Challenges Inherent in Horizontal Translation Processes

In responding to a request—to apply their examples of knowledge in each domain for considering the core challenges that learners face in engaging horizontal translation in building such knowledge—two experts had the following responses regarding the domain of ecology:

> The most important challenge in ecology is the fact that ecological systems are constructs (models) and not reality itself, that is, to distinguish between objects (reality) and systems (constructs) [. . .]. (E.c., 2.2.1.a.)

> Biological phenomena. . . in the domain of ecology in biology classes are represented by visualizations that are often very concrete, i.e. they are vivid and taken from the macro world (e.g., prey, predator). To get the idea behind the phenomena (What is prey? What is a predator?) learners have to think on a more abstract level. (E.d., 2.2.1.a.)

In view of the above, one challenge that learners may face in engaging horizontal translation in building ecological knowledge is to discriminate between ecological systems represented in external models and the ecological *reality* itself (e.g., Westra, Boersma, Waarlo, & Savelsbergh, 2007). Another challenge is being able to access the knowledge residing *behind* realistically visualized ecological ideas. With respect to translating horizontally across MERs in the acquisition of genetics knowledge, one expert view was as follows:

> For building up an internal representation of the term DNA [type 1 knowledge], students have to use external representations of different modes. For instance, learners [may] have acquired knowledge about DNA structure by analyzing. . . a schematic drawing. For a horizontal transfer [translation] of their knowledge they are [could be] prompted to build a model of the DNA structure (e.g., 2-D or 3-D). (E.e., 2.2.1.b.)

With regard to evolution, the following expert suggested that one main challenge for learners is to horizontally move across depictions of different evolutionary processes in a manner where underlying principles can be clearly interpreted:

> A major challenge for horizontal transfer [translation] in the domain of evolution lies in the very different examples for evolutionary processes. A huge amount of morphological, physiological, and behavioral features can serve as examples for evolutionary processes. (E.d., 2.2.1.c.)

In addition to considering each of the knowledge domains alone, the experts also provided views on the *overall* challenges faced by learners for performing horizontal translation in the construction of biological knowledge:

> The differences between the three biological domains are: ecology is a describing [descriptive] biological area; genetics is more abstract and with a lot of chemical aspects, and evolution is extremely analytical. The way of thinking differs a lot [between these three domains] [. . .]. (E.b., 2.2.2.)

The datum above implies that genetics knowledge is often communicated at the submicroscopic level, which in turn, requires interpreting ERs that are abstract, whereas ecology often necessitates descriptively interpreting (more) realistic ERs. Overall, core challenges which learners face in *horizontal* translation processes are to:

- Access the underlying knowledge, or *biological reality*, that lies embedded across ERs, which are only models of the represented phenomenon (4/5 experts).
- Appropriately apply the necessary knowledge when interpreting a different ER at the same level of organization and/or map the interpretation of one ER to another that represents the same concept or principle being represented at the same level of organization (3/5 experts).
- Realize the different communicative goals associated with ER interpretation in each domain, where the representation mode is often a function of the qualities of that domain (e.g., abstract ERs in genetics vs. realistic ERs in ecology) (2/5 experts).

Challenges Inherent in Vertical Translation Processes

Experts' opinions concerning challenges in engaging vertical translation in the construction of biological knowledge were also divulged. With regard to ecology, the following is an example of an expert's viewpoint:

> In ecology, the learner must be aware that he or she has to [often] go down to another biosystem with its own relations, which are different from ecological relations, for example, physiological relations of [within] the organism. (E.c., 2.3.1.a.)

The aforementioned expert viewed one challenge in vertical translation as the ability to consider the biosystem *relations* specific to a particular level of ecological organization (e.g., Westra et al., 2007). For the acquisition of genetics knowledge, the following expert's opinion can be considered:

> In genetics, the fundamental processes take place on the molecular level. Visualizations of these have to be schematic, compared to photo-realistic pictures. There is a cognitive distance that has to be bridged in order to connect the abstract molecular level with the real world phenomena on the level of organisms and individuals. [It is hard to connect] an illustration of a gene mutation… directly with the phenotype of, for example, albinism. (E.d., 2.3.1.b.)

The datum above highlights the linking between levels and suggests that this often requires bridging across a great *cognitive distance*. The following two responses were examples of vertical translation challenges facing learners in the evolution domain:

> Learners will often mingle the individual and populational level. (E.c., 2.3.1.c.)

> In the domain of evolution, there might be a problem [for students] with [interpreting] the time evolutionary processes typically span […]; to reason [about] phylogenetic development from single mutations on the organismic level is not easy. Regarding MERs, different hominid species can be depicted very vividly… by photo-realistic illustrations. But the diagrammatic visualization of mutations underlying the phylogenetic development of hominids might appear unsatisfying and insufficient for learners to make a connection between the two levels of biological organization. (E.d., 2.3.1.c.)

The experts' opinions quoted above both point to the challenge of making appropriate vertical connections between biological properties specific to the individual level with those for the population level. The second expert described this difficulty relative to conceptualizing the time involved in evolutionary processes, such as visualizing the concept of phylogenetic development based on ERs describing micro- and macroevolutionary processes (e.g., Catley & Novick, 2008).

Further to their viewpoints about each domain, the expert panel also offered opinions on the *overall* challenges faced by students for executing vertical translation in constructing knowledge. An example of an expert's view about such challenges was as follows:

> Common challenges [across the three domains]: the way of visualizing (pictures, micrographs, tables, diagrams, symbols, and so on) [in] ecology and evolution are [for] visualizing long-time[term]-processes, vertical transfer [translation] seems to be more seldom[ly represented], not a lot of examples [are available] in [at] different levels. Differences [between the three domains]: Genetics has a lot of in-between-levels, more thinking in short processes and needs more linking of facts (E.b., 2.3.2.).

The response above suggests that there is limited MER support for visualizing different levels of biological organization for expressing time-based phenomena to learners. In summary, experts' opinions on the core challenges facing learners (and teachers) in engaging *vertical translation* in the building of knowledge were to:

- Engage the *abstract* thinking necessary for connecting knowledge represented by an ER at one level of biological organization with knowledge represented at a different level (5/5 experts).

- Provide teaching methods that initiate the shifting between levels of biological organization and corresponding MERs in the construction of knowledge (3/5 experts).
- Gain access to ERs that have been purposefully designed around facilitating links between different biological levels, and relative magnitudes of size, scale, and time (3/5 experts).

What Are Experts' Overarching Requirements for Students' Effective Translation in Developing Biological Knowledge About Each Domain?

Upon revisiting their examples of knowledge they had provided for each domain, the experts described examples of MERs they would employ to develop students' biological understanding. These examples ranged from references to ERs in textbooks and to ERs designed by the experts themselves. The following is one expert's authentic example for the genetics domain (cf. Response E.b., 1.2.3. above):

> I take some pipe cleaners and [...] different [colored] beads are representative for [of] different amino acids [see Fig. 7.2, left]... the primary structure of [a] protein. If I roll [twist] the pipe cleaners around my finger I produce an alpha-helical structure [Fig. 7.2, center]. I can fold two parts of the long structure [in]to a beta-sheet structure, I demonstrate what tertiary structure means with this model and point out the quaternary structure [Fig. 7.2, right] [...] In the case of sickle-cell anemia, I can demonstrate... what kind of negative effects the point mutation has in [the] beta-sheet structure of hemoglobin [...] (E.b., 3.1.2.).

As per this expert's description, teachers (and learners) can manipulate the physical ER (see Fig. 7.2, left) to visualize and communicate aspects of primary and secondary protein structure (see Fig. 7.2, center), as well as model the effects of genetic mutations on tertiary and quaternary protein structures (see Fig. 7.2, right).

The expert panel also provided views of overarching critical requirements for effective translation in developing sound biological knowledge, such as the two views below:

> Learners have to recognize, how an idea visualized on one level of biological organization corresponds to the visualization on another level of biological organization. The referential connections have to be stimulated explicitly. If different modes of representation are used to visualize a concept or a principle... on the same level of biological organization or on different levels of biological organization, learners must be able to translate between modes by themselves. Therefore the modes of representation should be chosen carefully and dependent on learners' abilities [...] Learners have to understand how the types of biological knowledge are linked together in a hierarchical way. They have to be able to change between these types of biological knowledge and the corresponding MERs. (E.d., 3.2.)

> ... I think that both the prior knowledge and students' abilities to analyze external representations are required. The latter [abilities] include a competence to communicate scientifically... in an appropriate mode [of representation]. I think that teachers have to

Fig. 7.2 Authentic examples of physical ERs provided by an expert (E.b.) for visualizing amino acids (*left*) and initiating students' translation between primary and alpha-helical secondary (*center*), and tertiary and quaternary levels (*right*) of protein structure with respect to point mutations in genetics

> practice these competencies with their students—they do not arise by themselves. Additionally... designing ERs should consider cognitive load effects known since [for] the last two decades (e.g., split attention effect, redundancy effect). (E.e., 3.2.)

Overarching requirements in the first response above suggest that connections be *stimulated explicitly* for learners to effectively translate between different modes of representation and corresponding biological knowledge. The second response echoes the need of a communicative competence that acknowledges ER-related skills (cf. Lachmayer, 2008) and an alignment of ER design with theoretical information-processing principles. Overall, for effective translation in developing biological knowledge, learners require:

- Explicit visual support for changing levels of biological organization during vertical translation across MERs (3/5 experts)
- Practice in developing the specialized competence of interpreting different modes of representation for communicating biological knowledge (3/5 experts)
- To be overtly taught the skills for translating horizontally and vertically across MERs in the construction of biological knowledge (3/5 experts)

Discussion and Implications

This study has revealed an agreement in experts' application of the biological knowledge framework (see Fig. 7.1) to the domains of ecology, genetics, and evolution. Experts' views on the challenges concerning translation across MERs in the building of biological knowledge were reduced to three viewpoints for horizontal and three for vertical translation processes. Experts' opinions on overarching requirements for effective translation across MERs in the development of biological knowledge were exposed as three overall themes.

With respect to research question (i), the results reflected a consensus that the framework (see Fig. 7.1) can be applied to the knowledge components of ecology, genetics, and evolution. It is important that this stability in agreement served to validate experts' subsequent opinions on translation across MERs because expert viewpoints emanated from a common ground. Although consensus was reached, experts suggested that other dimensions also constitute biological knowledge. For instance, sustainability and citizenship were felt closely related to the ecology domain (e.g., Kuechle, 1995), whereas ethics and morals were deemed a *higher-order* component of genetics knowledge (e.g., France, 2007), and facets of belief and cultural evolution intertwined with evolutionary knowledge (e.g., Kinchin, 2010).

In response to research question (ii), experts did not converge in agreement as to whether the *nature* of the knowledge—which learners need to deploy in engaging horizontal versus vertical translation—is fundamentally different. It is interesting that this divergence has been carried over from *Round I* (Schönborn & Bögeholz, 2009). Although consensus was not reached in Round II, the expert panel clearly revealed that while the nature of knowledge remains *constant* in horizontal translation, a *new quality*, *additional,* and *combinatorial* knowledge is certainly involved in *connecting* different biological levels during vertical translation.

In terms of specific challenges inherent in *horizontal translation*, one core obstacle facing learners is to be able to *comprehend* the biological idea embedded *behind* ERs pitched at the same level of organization. In support of this in an ecological context, Westra et al. (2007) indicated the importance of students *getting hold* of underlying ecological ideas represented in ERs such as food webs since models will never contain *all the features of reality*, and different ER types serve different communicative goals. With respect to the fact that ecological concepts are often communicated through graphical ERs (e.g., Bayrhuber, Hauber, & Kull, 2010), Roth, Bowen, and McGinn (1999) found that novices often interpret graphs as *obtrusive tools* and struggle to extract the intended ecological ideas.

Given that gaining biological knowledge inevitably involves translating across different representation modes, experts often associated ecology with a pronounced use of macroscopic realistic ERs, whereas the genetics domain was viewed as often being communicated through abstract representations. This view was confirmed in our own informal analysis of MERs in a prominent upper secondary school textbook (Bayrhuber et al., 2010), which demonstrated ecology to be associated with a high frequency of realistic pictures, whereas genetics regularly incorporated abstract ERs of structure and process at the submicroscopic level.

In terms of specific challenges inherent in *vertical translation*, learners need to engage in the necessary level of *abstractness* for connecting knowledge represented at different levels. For example, with respect to evolution, experts felt that a major challenge is for learners to make appropriate vertical connections between biological properties specific to the individual with those of the population. This challenge is emulated in the study of Catley and Novick (2008) who indicated that ERs of evolution must support learners' discrimination between macroevolution processes and changes within populations. By the same token, constructing genetics knowledge regularly requires students to *bridge* the submicroscopic and the macroscopic (Bayrhuber et al., 2010), a process which experts often view as a demanding *cognitive distance*, and this is somewhat synonymous with *high-road* transfer, which requires learners' *mindful abstraction* of the possible connections and bridges between knowledge areas (Salomon & Perkins, 1989).

In order to shorten the *transfer distance*, teaching must actively initiate students' shifting between biological levels. In terms of evolution, a further demand placed on students in vertical translation is conceptualizing the relative time periods of evolutionary change, as well as visualizing how changes at the organism level can be *mapped* onto phylogenetic development. In this regard, Catley and Novick (2008) stated the importance of visualizing a *true sense* of time in evolutionary ERs. The expert data divulged that vertical translation could be facilitated by purposeful ER design that centers on a meaningful visualization of relative scale and time magnitudes.

In light of responding to research question (iii), opportunities for effective translation lie in providing students with explicit *visual support*. For example, deployment of ER forms such as those depicted in Fig. 7.2 could actively stimulate learners' connections between levels of biological organization. Such visual communication is paralleled in Halverson's (2010) visualization of phylogenetic tree knowledge in evolution. Some experts also felt it necessary to consider the nature of visual support in view of contemporary cognitive theory (e.g., Ainsworth, 2006, 1999). A central expert opinion was that learners require *specialized competencies* for interpreting biological ERs. In backing this view, Roth et al. (1999) suggested that experienced ecologists interpret graphs *transparently* and perceive the intended concepts directly. Hence, *graphing* competencies must be viewed as a fundamental component of biological communication and teaching (e.g., Lachmayer, 2008). In a similar direction, Halverson (2011) identified core representational competence skills for reading and constructing phylogenetic trees in the evolution domain.

Overall, learners need to be *taught* the skills for horizontally and vertically translating across MERs in the construction of biological knowledge. On this aspect, Westra et al. (2007) state that ecological literacy must involve teaching specific skills associated with moving between individual, population, and ecosystem levels. Verhoeff, Waarlo, and Boersma (2008) also demonstrated that teaching specific modeling skills can promote students' acquisition of knowledge through the horizontal and vertical *interrelation* of concepts at different levels of organization.

In conclusion, this study has yielded experts' views on the challenges and requirements for effective translation across MERs in acquiring biological knowledge. The results substantiate the assertion that students' construction of knowledge in biology is closely related to an ability to translate across and between MERs represented at various levels of organization. Promoting skill-based translation practices for advancing our students' biological understanding should be viewed as a key enterprise of modern biology teaching.

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