Journal of Science Education and Technology (2021) 30:125–138
https://doi.org/10.1007/s10956-020-09893-x

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Zooming in Time—Exploring Students' Interpretations of a Dynamic Tree of Life

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Accepted: 19 December 2020 / Published online: 26 December 2020
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Abstract
Central to evolution is the concept of a common ancestry from which all life has emerged over immense time scales, but learning and teaching temporal aspects of evolution remain challenging. This study investigated students' interpretation of evolutionary time when engaging with a multi-touch tabletop application called DeepTree, a dynamic visualization of a phylogenetic tree. Specifically, we explored how interactive finger-based zooming (zooming "in" and "out") influenced students' interpretation of evolutionary time, and how temporal information and relationships were conceptualized during interaction. Transcript analysis of videotaped interview data from ten secondary school students while they interacted with DeepTree revealed that zooming was interpreted in two ways: as spatially orientated (movement within the tree itself), or as time-orientated (movement in time). Identified misinterpretations included perceiving an implicit coherent timeline along the y-axis of the tree, that the zooming time duration in the virtual tree was linearly correlated to real time, and that more branch nodes correspond to a longer time. Sources for erroneous interpretations may lie in transferring everyday sensory experiences (e.g., physical movements and observing tree growth) to understanding abstract evolution concepts. Apart from estimating the occurrence of dinosaurs, DeepTree was associated with an improvement in interpretation of relative order of evolutionary events. Although highly promising, zooming interaction in DeepTree does not facilitate an intuitive understanding of evolutionary time. However, the opportunity to combine visual and bodily action in emerging technologies such as Deep Tree suggests a high pedagogical potential of further development of zooming features for optimal scientific understanding.

Keywords DeepTree · Evolutionary time scales · Interactive visualization · Conceptual understanding · Zooming · Interactive touch table

Introduction

A central tenet of evolution is the notion of a common ancestry from which biological diversity has emerged over immense time scales often depicted as a *tree*. Darwin realized the necessity of deep time for evolution and emphasized that anyone who could not "admit how vast have been the past periods of time, may at once close this volume" (Darwin 1859, p. 282). Interpreting the temporal scales involved is a fundamental reason why evolution education remains challenging (Smith 2010). Concepts associated with evolutionary time scales and the visual representations used to convey them are abstract and difficult to comprehend yet pivotal for understanding evolution (Catley and Novick 2009). Tree metaphors for relatedness are often constructed and used by experts but prove troublesome for novices (e.g., Gregory 2008; Meir et al. 2007). Thus, it is important to complement students' conceptual knowledge with an appreciation of how different representations relate to different evolutionary phenomena (Matuk and Uttal 2018).

Emerging digital technologies provide new opportunities to interact with tree representations through touch-based gestural actions (Hornecker et al. 2008; Block et al. 2012b). In contrast with textbook images, immersive interfaces offer

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dynamic avenues to perceive tree metaphors in terms of evolutionary time scales through interactive features such as *zooming*, enabling users to move in both space and time. Such features can potentially enhance students' interpretation of relatedness and temporal aspects of evolution. The latter serves as the focus of the present study, where we investigate how the zooming features of *DeepTree*—an interactive touch table visualization of the "Tree of Life" (Block et al. 2012a)—influences students' understanding of evolutionary time.

Theoretical Background

Interpreting Time and Temporal Representations for Conceptualizing Evolution

Several studies have explored obstacles in students' interpretation of time in the geosciences and biosciences (e.g., Jaimes et al. 2020). Challenges include the ability to find events at specific times (Hidalgo et al. 2004), comprehend relative order of events (Trend 1998, 2000, 2001; Libarkin et al. 2007; Catley and Novick 2009), estimate the duration of a time interval (Dodick and Orion 2003; Cheek 2013a), compare different temporal durations (Hidalgo et al. 2004; Cheek 2013b), and comprehend the concurrency of events (Mayer and Moreno 2003).

Since time is often conceptualized metaphorically in terms of space (Boroditsky 2000), interpreting size and scale is important for comprehending temporal aspects of evolution. When comparing novice and advanced tertiary students' evolution knowledge, Athanasiou and Mavrikaki (2014) found that grasping deep time is a more advanced assignment than understanding individual variation and inheritance. Swarat et al. (2011) identified four ways that students conceive scale: as fragmented, linear, proportional and logarithmic. The most difficult to grasp was the logarithmic scale and the ability to connect timeframes. Delgado and Lucero (2015) investigated students' ability to generate spatial and temporal scales covering several orders of magnitude. They found that students spaced all timeline events to present all the temporal information, even at the cost of accuracy. This supports other research revealing a tendency for children to use inconsistent scales to enhance the narrative of a timeline by omitting "absent" data (e.g., unknown values) from the representation (Nemirovsky and Tierney 2001). Furthermore, Lee et al. (2011) showed that students tend to underestimate long durations (e.g., mountain formation) and overestimate short durations (e.g., an eye blink) in temporal scales.

Visual representations can benefit the learning and teaching of temporal scales provided they are well designed and align with intended learning outcomes (Phillips et al. 2010). One popular strategy is to employ multiple visual representations (Ainsworth 2006) such as combining geological time spirals with deep time clocks. Another strategy is to use multimodal representations (Moreno and Mayer 2007), by combining evolutionary diagrams with narrated explanations of temporal aspects. An integrated framework developed by Tang et al. (2014) that combines multiple and multimodal representations emphasizes students' active engagement in constructing and "re-representing" abstract concepts to develop scientific understanding. Research comparing paper-based with virtual timelines (Foreman 2008; Korallo et al. 2012) shows that virtual timelines are advantageous when the user has an opportunity to control the presented information.

Affordances and Constraints of Digital Tools for Portraying Time

In a recent study on the affordances and limitations of digital tools for communicating time, Stenlund and Tibell (2019) showed that an animated timeline which purposefully slowed down when approaching present time proved superior over other timelines for comprehending human evolution. However, the same study showed that altering animated time may impede the comparison of time durations. This is in line with Lee et al. (2011) who have cautioned against adjusting the pace of temporal information in dynamic visualizations. Therefore, hands-on interactive technologies that allow users to control presented information provide novel opportunities for learning (Johnson-Glenberg et al. 2014). Touch-based interfaces also offer possibilities for an increased sense of immersion with scientific content through finger-based zooming features (Bederson 2011). Zooming provides users with an opportunity to navigate and "travel" in time and/or space. However, little research has explored the constraints of interactive digital tools for learning and teaching temporal scales, and there is a need for more investigation on how temporal scales are perceived when accompanied by technological affordances such as zooming (Bederson 2011; Lee et al. 2014).

Tree Representations for Conceptualizing Evolutionary Time

A common diagram for representing evolutionary relationships is the phylogenetic tree. The "Tree of Life" wields significant metaphorical power for understanding evolution (O'Malley and Koonin 2011): the visual perception of a branching tree is mapped onto conceptualizing speciation and relatedness. Since metaphors illuminate certain aspects of a phenomenon while suppressing others, interpreting phylogenetic trees requires understanding both the visual features and the intended mappings (Baum et al. 2005; Marcelos and Nagem 2010). Herein, phylogenetic trees that incorporate temporal information combine at least two abstract entities: the concept of evolutionary time and the tree metaphor for relatedness. The notion of the *most recent common ancestor* is crucial for interpreting phylogenetic trees—two species or taxa are more closely related if they have a more recent common ancestor (Baum et al. 2005). Temporal information is only implied in many phylogenetic trees, which can induce misinterpretations about evolutionary time.

Interactive Features of DeepTree and Previous Studies

From 2011 to 2012, an interactive touch table application called *DeepTree*[1] was developed and evaluated at the Harvard Museum of Natural History as a part of the "Life on Earth" project (Block et al. 2012a). One central feature of DeepTree is *zooming*—enabling finger-based gestures to "zoom in and out"—in exploring, navigating, and controlling visualized content (Börner et al. 2005). Previous studies investigated how DeepTree enables collaborative exploration (e.g., Davis et al. 2015) and showed that interaction is associated with an improved interpretation of common descent, and an increased engagement with evolutionary content (Horn et al. 2016).

To date, research on DeepTree has made several inroads into the role of collaborative learning about evolution in public settings but not so much about individual learning about evolutionary time.

Aim

This study investigates how an interactive touch table visualization of the "Tree of Life" (Block et al. 2012a) influences students' interpretation of evolutionary time associated with this particular phylogenetic representation. The following research questions were posed:

- How do students perceive and conceptualize zooming in DeepTree?
- How do students interpret temporal information and temporal relationships in DeepTree?
- Are there any student misinterpretations concerning the temporal aspects communicated by DeepTree? If so, can they be identified?

[1] See https://www.youtube.com/watch?v=dpo9iK26el8. DeepTree development is detailed in Block et al. (2012a, 2012b)

Methods

DeepTree: an Interactive Digital Tabletop Visualization of the Tree of Life

DeepTree visualizes phylogenetic relationships between living and extinct organisms through an interactive multi-touch interface (Block et al. 2012a). Approximately 70,000 species are embedded, with 8000 species presented with accompanying images (Horn et al. 2016). Time is expressed explicitly at 200 internal nodes that are numerically labeled with corresponding evolutionary events (Block et al. 2012a). Time is not mapped onto any clear axis, which means that different branches appearing at the same vertical tree level do not necessarily infer a simultaneous occurrence.

The main visual components of DeepTree comprise the main tree, a scrolling "image wheel" containing 200 species and an "action" button (Block et al. 2012a). Tapping the action button unveils options for relating different species pairs that include discerning the pair's most recent common ancestor and navigating to other species.

This study specifically investigates individuals' use of the "zoom" feature, where users can move virtually from the origin of life to present day species. This zooming feature represents a unique interactive visual experience in comparison with static images. Zooming is achieved by moving one's finger downward while in contact with the table surface. This causes the tree to move downward while more details in the tree canopy become visible, which provides a "zooming in" effect (see 1 in Fig. 1). Moving one's finger upward on the table causes the tree to move upward, which reveals new nodes below, while details at the top fade away, thus providing a "zooming out" effect (see 2 in Fig. 1). It is also possible to pan horizontally by dragging one's finger left or right (see 3 in Fig. 1) (Block et al. 2012a).

The first (and most accurate) way to infer temporal information from DeepTree is to perceive the time numerals at the nodes (e.g., a in Fig. 1). A second way is to interpret an implied temporal y-axis from the tree root to the tree tips (b in Fig. 1). A third way is to perceive the "zooming time" in proportion to real time. This zooming direction could be viewed as being directed inward and upward along such an axis (c in Fig. 1).

Interview Protocol Development

Interview questions were designed to target how the zoom feature is experienced, and its influence on students' interpretation of temporal information and time relationships. A pilot study with 21 volunteers was performed before the

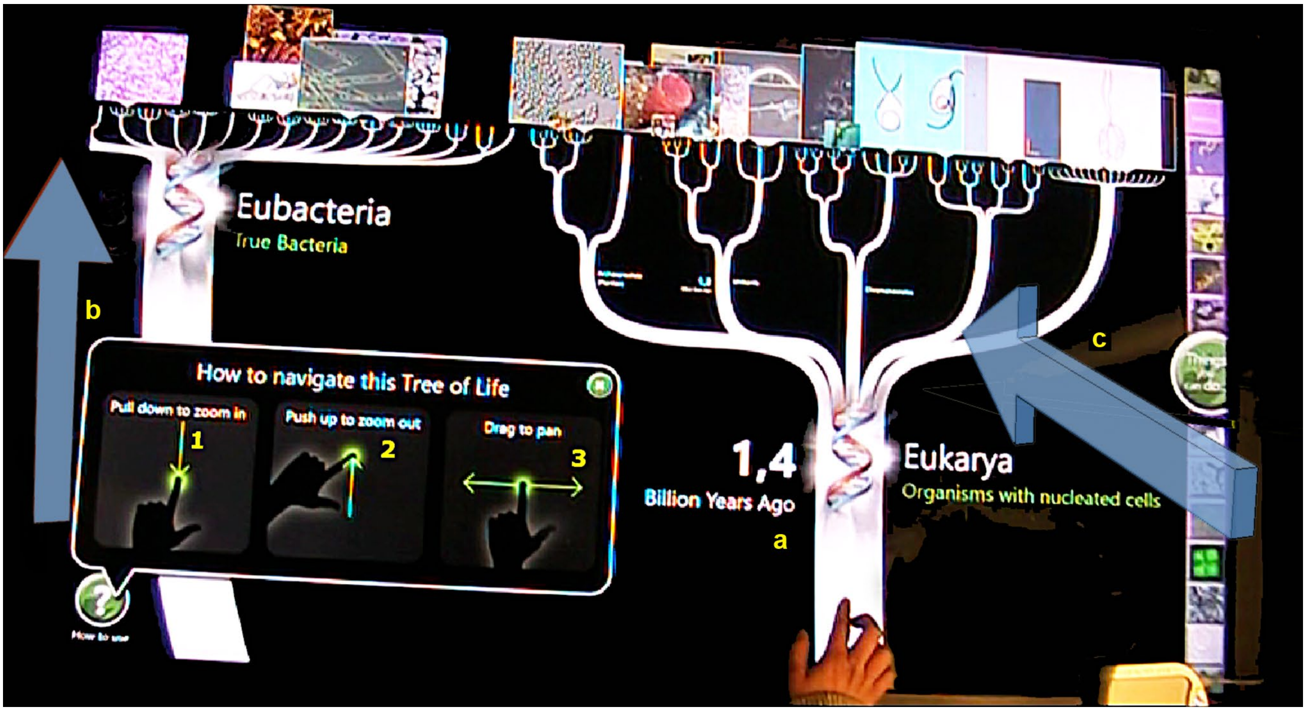

Fig. 1 Navigation and perception of the phylogenetic tree in DeepTree. The yellow numerals indicate how one-finger touch gestures can be used to navigate the tree. The yellow letters and corresponding blue arrows represent different temporal cues (Permission to reproduce an image from the DeepTree interface obtained from C. Shen and F. Block)

main study to explore individuals' initial encounters with DeepTree[2] and their use of the zooming feature to help inform the semi-structured interview protocol (see Table 4).

Interview questions were also inspired by five time-related facets described in Stenlund and Tibell (2019) and by kinship questions reported in Catley et al. (2013). Questions targeting potential misinterpretations were informed by Gregory (2008) and Meir et al. (2007), while questions related to zooming were stimulated by Bederson (2011). Organism choice in the protocol was based on students' expected species knowledge in combination with how easy they were to locate in DeepTree.

Participants and Data Collection

Ten upper secondary school students (8 females and 2 males) aged 16–18 years (mean 17.3 years) in Sweden voluntarily participated in the study. All students previously studied the national elementary school curriculum and were all enrolled in the same school in the same national social science program.

At the commencement of each interview, the participant was informed about the study and the right to withdraw. Next, and prior to exposure to DeepTree, the participant completed a pre-questionnaire on age and gender. The pre-questionnaire also included a task requiring marking six evolutionary events on a timeline (hereafter termed the "time line task"). A similar task was also administered during the interview. The aim of these tasks was to compare students' perceptions of the occurrence of evolutionary events prior to and during interaction with DeepTree.

Following the pre-questionnaire, students had an opportunity to gain familiarity with the navigational features of DeepTree. Then, a 35–45-min semi-structured interview (Table 4) was conducted while each participant interacted with DeepTree. The interview probes focused on use and interpretation of the *zooming* feature and *time*, and also explored any reasoning that emerged unexpectedly (e.g., Schönborn and Anderson 2009). Sessions were video recorded with a camera mounted above the tabletop that captured audio, gestural interaction, and the tabletop screen.

Probing Students' Engagement of the Zooming Feature and Probing Aspects of Time

While each student explored how to navigate DeepTree, they were asked in what direction the zooming was experienced. Each

[2] Pilot participants and participants in this study found DeepTree engaging and compelling, findings that are the subject of a separate report

participant was also asked questions that included, "When is 'now'? and "How do you know?". Interpretation of the zooming feature was also explored through questions that probed species comparisons. Each participant was probed about five aspects of time (Stenlund and Tibell 2019), namely, the ability to (I) find events at specific times, (II) comprehend relative order of events, (III) estimate the duration of a time interval, IV) compare different temporal durations, and (V) comprehend the concurrency of events (see Table 4 for interview question and task content).

Table 1 Suspected misinterpretations identified by the deductive component of the analytical process

Misinterpretation	From visual content analysis	From pilot study
i. Y-axis perceived as coherent	X	
ii. Zooming time perceived as linearly related to real time	X	X

Data Analysis

Video-recorded speech was transcribed verbatim and complemented with information about the nature and occurrence of interactions with the interface (e.g., zooming), and/or other gestures (e.g., pointing at the interface). A combined inductive and deductive approach (e.g., see Bos and Tarnai 1999; Fereday and Muir-Cochrane 2006; Höst and Anward 2017) was employed to analyze the ten transcripts.

Inductive Analysis of the Transcripts

Inductive analysis pursued the natural discovery of themes of reasoning and interpretation. Emergence of a theme could be expressed in one or multiple utterances (Amundsen et al. 2008), while multiple themes could also relate to a single utterance. Each author initially perused the same six randomly selected transcripts, followed by collectively discussing any emerging themes related to evolutionary time. The remaining four transcripts were then analyzed by two of the authors. Students' utterances concerning zooming emerged as referring to movement within the tree itself, i.e., along the *spatial space* of the stem and branch structures that would map onto the idea of relatedness (labeled "S") and/or referring to movement in time, i.e., in a virtual *temporal space* that would map onto the history of evolution (labeled "T"). After the S and T themes emerged, two of the authors compared their respective appraisal of the utterances as representative of

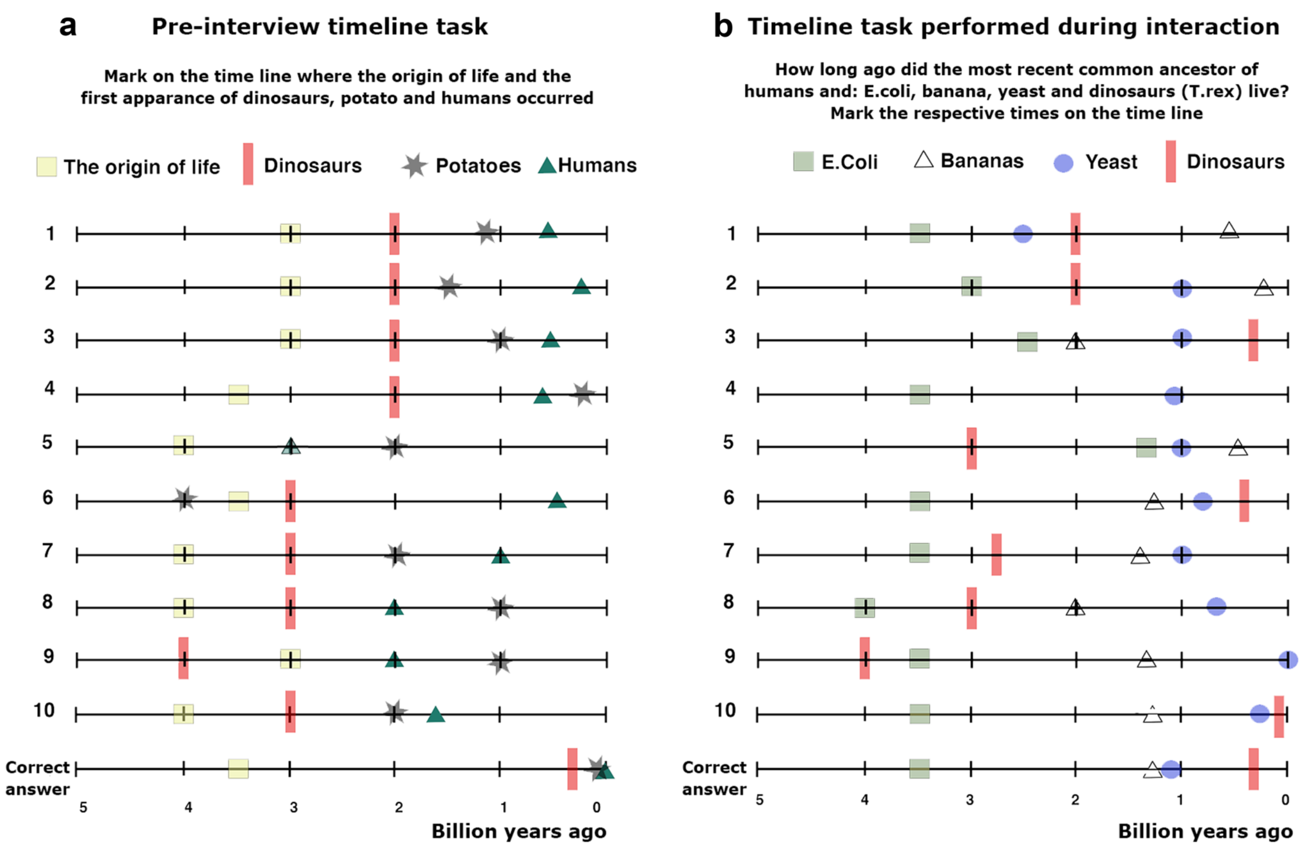

Fig. 2 Responses from all ten (1–10) students on the time line task before the interview **a** and from the task during the interview **b**. Correct answers are provided for readers' comparison

the S and T themes. In 3 of 70 utterances the authors initially disagreed, but reached agreement after discussion.

Deductive Analysis of the Transcripts

Deductive analysis (e.g., Mayring 2000) was based on hypothesized misinterpretations and reasoning difficulties deduced from a visual content analysis (e.g., Bell 2001) of the visual and interactive features of DeepTree, the pilot studies, and from the literature (Gregory 2008). Suspected conceptual difficulties (Tables 1 and 4) comprised misinterpreting (i) the Y-axis as coherent and (ii) zooming time as linearly related to real time. Two authors performed the analysis in parallel, which resulted in a full agreement on prevalence of the suspected misinterpretations.

Results

Students' Responses to the Time Line Tasks

Paper-based "time line tasks" asked students to indicate respective times when specific organisms emerged (from the origin of earth to present). Before the interview, the participants (numbered 1–10) were asked to mark where the *origin of life* and the emergence of each of the respective taxa *dinosaurs*, *potatoes*, and *human*s were located on the time line (Fig. 2a). Then, while engaging with DeepTree, a further time-line task (Fig. 2b) asked students to depict how long ago the most recent common ancestor of *H. sapiens* and *E. coli*, *bananas*, *yeast*, and dinosaurs (*T. rex*) lived, respectively.

Prior to the interview five students correctly indicated the order of evolutionary events (Fig. 2a). However, answer accuracy varied greatly. For example, for *potatoes* and *humans*, both the order and indicated times deviated considerably from correct times.

Responses to the task administered during the interview were more accurate (Fig. 2b). Albeit so, a notable result was that only three students altered their perception of the occurrence of the most recent common ancestor of dinosaurs and humans compared with actual evolutionary time, while six remained inaccurate. Overall, six of ten students accurately marked the time of the most recent common ancestor of Humans and *E. coli* and seven provided an approximately correct time point for the most common ancestor of yeast and Humans.

Misinterpretations About Evolutionary Time Associated with Interacting with DeepTree

As presented in Table 2 below, deductive analysis revealed two suspected misinterpretations (1 and 2). Inductive analysis yielded two unanticipated misinterpretations (3 and 4) across the ten participants.

Y-Axis Perceived as Coherent

To investigate the conflicting temporal information provided in the numerical labels and/or the implicit y-axis, we posed the interview question, "Where is one billion years ago located in the tree?" when the entire tree was displayed. Since the different lineages had different time scales along the implicit y-axis (apparent from the numerals), two vertical branching events occurring at the *same* horizontal height of the tree could correspond to very different absolute times. Four students did not observe the difference in the various lineages and misinterpreted the representations of time as coherent and horizontally equivalent regardless of which lineages were compared, as shown by student 4:

> T: Can you point out where one billion years ago is in the tree?
> S4: Approximately here [student points to numeral "1,4 billion years ago"] (…) No, I think it is approximately here, you can imagine, along this line [the student gestures a horizontal straight line].

In contrast, three students observed the contradicting information from the labels and the implicit y-axis (Table 2).

Table 2 Description and prevalence of identified suspected and unanticipated misinterpretations of evolutionary time

Misinterpretation	From deductive analysis	From inductive analysis	Students showing misinterpretation	Students with scientifically acceptable explanations	Students with unclassified interpretations
1. Y-axis perceived as coherent	X		4	3	3
2. Zooming time perceived as linearly related to real time	X		10	0	0
3. Branch tips of all represented species perceived as present time		X	4	6	-
4. More nodes perceived as longer time		X	5	0	-

Zooming Time Perceived as Linearly Related to Real Time

In another question probing estimation of the time interval, we asked students to compare two identical time intervals which required very different zooming times. For example, the time interval between the origin of life and two contemporary organisms, namely, *Homo sapiens* and *Methanopyrus kandleri*, a hyperthermophile archaea. No students could discern that the time between the origin of life and contemporary existence of *H. sapiens* and *M. kandleri* was identical (Table 2), for example:

S1: I perceived it as … when man was created, it took a much longer time because you could see that it took less time to reach the end there [to *M. kandleri*] than it took there [to *H. sapiens*], because there you had to hold down [your finger] much longer.

As was typical when expressing this difficulty, S1 interpreted the relatively short zooming time from the origin of life to *M. kandleri* as equivalent to a relatively short time in evolutionary history.

Branch Tips of All Represented Species Perceived as Present Time

All students orientated their temporal perceptions in terms of the tree root representing the most ancient time and the canopy the closest to present time (Table 2), as shown by student 7:

S7: it starts here [pointing at the root of the tree] and that would be furthest away [in time] I think, and then, it approaches present time the higher up you reach.

Furthermore, when asked to indicate where present time is depicted on the tree, more than half (n = 6) used *H. sapiens* as a signpost. Four of the students expressed that present time is equivalent to the uppermost part of the tree. For example, S1 stated, “It seems like it may develop later or so, because it just ends, or it’s not going to develop anymore.” Here, the branch tips were interpreted as present time and as species endpoints (which are not mutually exclusive).

More Nodes Perceived as Longer Time

Interpretations of how the branching pattern influenced students’ perception of time were also probed. In five cases, an unanticipated misinterpretation emerged when students equated more branches with a longer time span (Table 2). For example, consider this reasoning generated from student 5:

S5: It took less time to come to it [*M. kandleri*] than it did to man. It took quite a long time, there were very many preceding branches.

A factor influencing students’ misinterpretation appears to be the number of branches, which differ by as much as twenty times as many nodes on the lineage ending with *H. sapiens* compared with *M. kandleri.* Several students mentioned branch number as an attribute that they considered when comparing species.

Students’ Utterances About the Direction of Zooming in Time and Space

All students perceived zooming as movement in a virtual space. The touch interface in combination with the visual appearance reinforced the metaphor of moving along a path and being able to control the speed of the movement while organism images “pass by” on either side. Students 6 and 3 provided the following examples portraying this perception, respectively:

S6: …depending on how fast I pull… sometimes when pulling very fast you won’t be able to … see, but if you do it at a slow pace, like this, then you see what is what … and how it divides [refers to a visual display similar to that shown at timestamp 01:05–01:12 in the clip in footnote 1]. And it is nice that you can change the pace too.
S3: they are pulled apart [refers to a visual display similar to that shown at timestamp 01:34–01:37 in the clip in footnote 1]… you can, kind of, see the roads leading to them [the target species].

Overall, movements were perceived as being orientated toward motion in a spatial space (i.e., within the tree metaphor along the branches) or as motion in a temporal space (i.e., as “time travel”). As summarized in Table 3, among the utterances

Table 3 Two ways of perceiving direction of movements when zooming in time and space showing respective prevalence and examples of representative utterances

Utterances	Forward/backward perceptions	Examples of corresponding utterance	Upward/downward perceptions	Examples of corresponding utterance
About time	13	S6: It is more forward in time that humans emerge	0	-
About space	4	S6: We went back from the other branch and then switched branches	5	S5: We *follow the same branch* all the way until we split humans and animals

concerning movements in a temporal space, the most frequent direction was expressed in terms of forward/backward. In contrast, the frequency of upward/downward direction perceptions was only associated with referring to movements in space.

Interpretation of Evolutionary Time in DeepTree

Since DeepTree lacks a coherent time axis, it was difficult for students to *identify specific times*. Inaccurate interpretations were common but some students' realized their mistake, for example:

> S1: it says 1.2 billion years ago. Then you understand that … because it is there and that is where they [the lineages leading to bananas and humans] met. Then you understand that it is not really so close in time.

Apart from interpreting the order within a specific lineage, *comprehending relative order* also proved challenging. Estimating relative order was uncovered specifically by questions 4, 6, 7 and 8 (see Table 4) and the time line task. In addition, *estimating the duration of time intervals* was likely to be misinterpreted, since zooming time was erroneously equated by the students as corresponding to an equivalent time interval (question 2). The probe requiring students to *compare different temporal durations* yielded no correct responses (question 2). Finally, when interacting with DeepTree, students faced difficulties in *comprehending the concurrency of events* probably due to the assumption of a coherent time axis from the root to the canopy.

Emergence of Two Different Perceptions of Zooming

As shown in Fig. 3, two overall perceptions of zooming emerged from the analysis. In total, a "time oriented (T) group" generated 53 utterances and a "spatial oriented (S) group" 21 utterances, respectively.

Students in the T-group each made six or more utterances about movements in time while the S-group expressed one or two time-orientated utterances and made more space related utterances. An outlier is student 2 who despite making more space-related utterances, still made six utterances about time, which meant assigning her to the T-group.

Individual Student Representative Examples From the Spatial (S) and Temporal (T) Groups

To illustrate how students verbally described the zooming experience in each S- and T-orientated group we compare S1 from group T with S7 from group S (Fig. 3). In response to the question "what kind of movement would you say it is?" (S1), and whilst zooming (S7), students described the following:

> S1: I'm moving *forward in time*[3] as well (…) It seems like you're going on a spacecraft in space, a bit like in the movies.
> S7: That you followed.. like.. the path from the DNA molecule [origin of life] *all the way up* to humans.

The first datum above from S1 includes metaphors that concern a vehicle (e.g., spacecraft or time capsule) that "brings" the student forward and reveals a perceived movement in terms of time where the primary direction is forward in a forward/backward dimension. In contrast, S7 experienced the zooming as movements explicitly referring to spatial space from the bottom to the top of the tree.

Discussion

This study describes how zooming features of modern touch-based technologies influence students' interpretation of evolutionary time. The immersive experiences offered by combined visual and bodily interaction with Deep Tree and other recent touch table applications (e.g., Schuman et al. 2020) yield potential for further development of zooming features with knowledge acquisition. Although highly promising, in its current form, DeepTree does not facilitate an understanding of the represented temporal scales. In this regard, conceptual and representational competence is required for an accurate understanding of abstract science concepts (Matuk and Uttal 2018). The ideas of common origin and most recent common ancestor are fundamental to conceptualizing evolutionary relatedness. Communicating these ideas are challenging for many designers of tree of life representations and additional features such as zooming require an even more enhanced representational knowledge in comparison with "static" phylogenetic representations. Hence, a challenge to confront with emerging technologies like DeepTree is how to engender both an intuitive and realistic interpretation of evolutionary time.

Students' Interpretation of Temporal Information in DeepTree

Students' interpretations of evolutionary time were based on several temporal cues including numerical labels, an implicit y-axis, actual zooming time, and the number of nodes along the "path" to the target species. Our results indicate that conflicting differences between these sources in conjunction with incoherencies within the

[3] Italic font used for emphasis

Table 4 The questions and tasks used in the semi-structured interview protocol complemented with their sources, and conceptual and reasoning rationale. Roman numerals (I–V) refer to the five different aspects of time described in the method section

	Interview question and/or interactive task	Source of developed question/task (from pilot studies, visual content analysis, and/or the literature)	Rationale for posing the interview question/task	Conceptual and reasoning aspects of question/task
1	The pupils are encouraged to investigate zooming and panning What does it mean to pull down (pull down to zoom in)? What does it mean to pull up (push up to zoom out)? What happens when you pull down and sideways (drag to pan) Supplementary questions. What happens? How?	Block et al. 2012a	To explore how the student experiences the movement that the different touch gestures result in	Zooming and time
2	The student explores the function of the tree by zooming from the origin of life towards two species: first *Methanopyrus kandleri*—a type of methane bacteria and then *Homo sapiens*. A question is posed concerning what the student has just observed: compare how long it took for these organisms (*Homo sapiens* vs *Methanopyrus kandleri*) to develop?	Visual content analysis, and observations from the pilot studies Dodick and Orion 2003; Cheek 2013a; Hidalgo et al. 2004; Cheek 2013b	The zoom time represents the same real time span but it is approx. ten times shorter for *Methanopyrus kandleri*. This reveals if the student understands that the timeline is not "equal"—that there are different timelines for different branches	Zooming and time - Estimating a duration (III) - Comparing time intervals (IV)
3	What does the branching represent?	Baum et al. 2005; Gregory 2008; Meir et al. 2007	To investigate whether the concept of most recent common ancestor is perceived by the student, and to be able to expose students to it if it is not revealed. This is to provide all participants with the same background knowledge prior to the subsequent questions	Relatedness
4	Compare the following pairs and write down: How long ago did the most recent common ancestor to… - bananas and humans live? (recent joint ancestors lived 1.4 billion years ago) - yeast and man live? (recent joint ancestors lived 1 billion years ago) - *E. coli* and human live? (recent joint ancestors lived 3.5 billion years ago) - *Tyrannosaurus* and human live? (recent common ancestors lived 302 million years ago) Then, transfer the information to a timeline. Did you expect this or not? Why?	Visual content analysis and observations from the pilot studies Hidalgo et al. 2004; Trend 1998, 2000, 2001; Libarkin et al. 2007; Catley and Novick 2009	To investigate how well the students were able to re-represent the temporal information on a timeline	Time - Finding events at specific times (I) - Relative order (II)

Table 4 (continued)

	Interview question and/or interactive task	Source of developed question/task (from pilot studies, visual content analysis, and/or the literature)	Rationale for posing the interview question/task	Conceptual and reasoning aspects of question/task
5	The pupils are then asked to compare two pairs of species First *tyrannosaurus* and *velociraptor* then *velociraptor* and the house sparrow. Which species are more closely related? Probe students' reflections	Visual content analysis Observations from the pilot studies	To purposefully investigate whether the student understands that the tree metaphor representsrelatedness	Relatedness
6	Zoom in to *Homo sapiens*. Then zoom out "bit by bit" and indicate how long ago our most recent common ancestors with a) Chimpanzees lived b) Gorillas lived c) Orangutans lived	Observations from the pilotstudies Hidalgo et al. 2004; Trend 1998, 2000, 2001; Libarkin et al. 2007; Catley and Novick 2009	The purpose of this question is to probe if time, i.e., order (time represented vertically) is perceived correctly and how easy it is to locate explicit dates	Zooming and time -Finding events at specific times (I) - Relative order (II)
7	Compare when the most recent common ancestor of orangutans and humans lived with when the most recent common ancestor of human and chimpanzees lived	Observations from the pilot studies Hidalgo et al. 2004; Trend 1998, 2000, 2001; Libarkin et al. 2007; Catley and Novick 2009; Mayer and Moreno 2003	To investigate the perception of simultaneity, to what extent the inconsistent visualization of the time axis of the tree gives rise to misconceptions (time represented horizontally)	Time - Finding events at specific times (I) - Relative order (II) - Concurrency (V)
8	Compare when the most recent common ancestor of the tomato and potato lived (2 million years), with the tomato and sundew, respectively (118 million years)	Observations from the pilot studies Hidalgo et al. 2004; Trend 1998, 2000, 2001; Libarkin et al. 2007; Catley and Novick 2009	To investigate how temporal aspects of relatedness between different plants were perceived	Relatedness and time - Finding events at specific times (I) - Relative order (II)
9	Where in the tree is a billion years ago?	Visual content analysis and observations from the pilot studies Hidalgo et al. 2004; Mayer and Moreno 2003	Probe whether the student understands that the tree is temporally inconsistent	Time - Finding events at specific times (I) - Concurrency (V)
10	Additional questions that could be posed if required - Where is present time in the tree? - Where are living and extinct species in the tree? - The tree shows different aspects of life. What aspects do you think of when you see the tree? (e.g., unity and diversity) - What was the most striking feature of the application?	Visual content analysis, observations from the pilot studies and Block et al. 2012a; Hidalgo et al. 2004	To investigate additional aspects of how time is perceived as well as supplementary aspects	Time - Finding events at specific times (I)

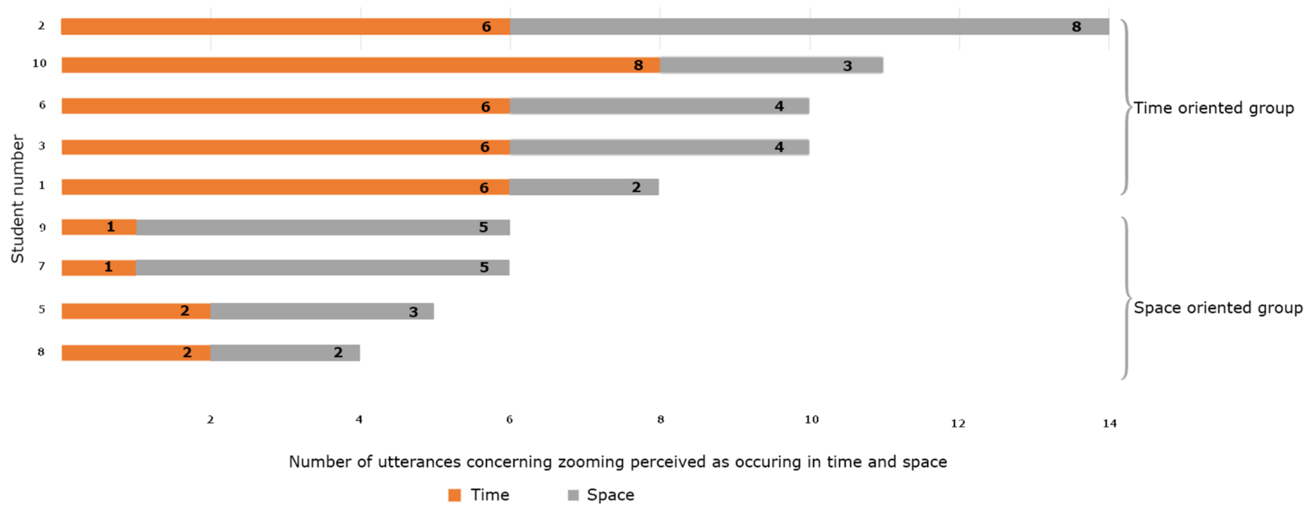

Fig. 3 Two groupings of zooming as a movement in time (time orientated group) or space (space orientated group) displayed according to the number of individual utterances made about time (orange) or space (gray) (Student 4 did not make any utterances about perceived movements.)

implicit y-axis, and the lack of correspondence between zooming time and real time, made it demanding to grasp various temporal aspects related to evolution. The ability to estimate concurrency of events and order of events occurring on different lineages and compare durations was influenced largely by the incoherent temporal information represented by the y-axis and zooming time.

Responses to the interview time line tasks (Fig. 2b) indicate that students are able to locate specific evolutionary events with relative ease when temporal information is explicitly expressed numerically. Interestingly, although the time points in the task were rather straightforward to identify in the tree (appearing as numerals), transferring these to the interview time line task remained challenging. One clear example was the erroneous responses for dinosaurs (Fig. 2b), a finding that might emanate from the counterintuitive proximity in time for the most recent common ancestor of humans and dinosaurs that is often thought to be located further in the distant past (Catley and Novick 2009; Hecht et al. 2020). Overall, the version of DeepTree investigated here may not help students gain an intuitive sense of evolutionary time.

Misinterpretations Concerning Temporal Aspects in DeepTree

Given that several temporal-related misinterpretations in the literature are associated with 2D static tree of life representations (Meir et al. 2007; Gregory 2008) it is not surprising that DeepTree, which also combines additional features such as zooming, also presents new potential sources of misinterpretation. For example, our observation that students associated more branching events (nodes) with longer times supports results from Meir et al. (2007) and Gregory (2008), who found that more nodes between species were interpreted as more distant relationships. The source of this difficulty might be that human metaphorical thinking about time often occurs in terms of *space* (Lakoff and Johnson 1999; Boroditsky 2000). Thus, although the branching pattern is not linearly correlated with time, more nodes indicate a longer *path*, which some students correlated with a longer *time*. Furthermore, since the same "real" time interval (e.g., between two existing species and the origin of life) can be represented with different zooming times, without any information communicating the non-correspondence between zooming time and real time, most learners might erroneously assume a linear correlation.

A likely source of temporal misinterpretations was students' assumptions that the root-to-canopy direction (arrow B, Fig. 1) represented a coherent time axis, which erroneously implies that the same "level" in the tree represents an equivalent evolutionary age. Since tree growth is actually observed to proceed from root to treetop in reality, a mapping between age and height would be an intuitive deduction (Omland et al. 2008). Unfortunately, transferring this assumption to the application may lead to other temporal misinterpretations including perceiving concurrency of events occurring on different lineages with various ages and that branch tips only represent current time.

Students' Perception and Conceptualization of Zooming

DeepTree communicates an abstract visual metaphor of the same source domain—a *tree* that maps onto two different, yet combined target domains—*relatedness* and *time*. The fact that these two mappings are also reflected in the results suggests that zooming induces certain "dual perceptual" experiences (Nemirovsky and Tierney 2001). Herein, zooming is sometimes perceived as movement in a temporal space and sometimes as movement in a "spatial space," i.e., a "spatial" lineage that traces connections between ancestors and descendants. The latter case is usually the main reason for engaging a tree of life representation.

Several students perceived zooming as movement along a path. Some students' experienced interacting with the DeepTree touch interface in the same sense as controlling a vehicle throttle. The "movement" while zooming "to" an organism makes the evolutionary "path" immediately tangible, like travelling along a road, where a longer distance corresponds to a longer time. In support of this experience, most students spoke about the past as "backward" and the future as "forward." While all (but one) students blended both "space" (S) and "time" (T) orientations to perceive zooming, the T-group delivered more utterances overall, and more in terms of time. The T-group's ability to perform both mappings—from relationships to the tree and from time to the tree—might be indicative of a more advanced and nuanced appreciation of the depicted information. Such results in combination with a "resource perspective" (Delgado and Lucero 2015) and reinforcing multimodality (e.g., integrating audition) could further optimize the zooming feature.

Conclusions and Implications

Conclusions yielded by the study are as follows:

- Even if the primary objective of DeepTree is to communicate evolutionary relatedness, the zooming feature offers a powerful interactive opportunity for communicating evolutionary time. Although highly promising, the zooming is not optimized for a full understanding of temporal aspects.
- Potential power of the zooming feature lies in the intuitive, immersive, and seamless possibility provided to the user to control movements in evolutionary time. The findings demonstrate that zooming evokes multiple temporal experiences (which static representations cannot afford).
- DeepTree introduces both suspected (y-axis perceived as linear, zooming time perceived as linearly related to real time) and unanticipated (branch tips of represented species perceived as present time, more nodes perceived as longer time) misinterpretations related to evolutionary time.
- The time-orientated group displayed salient temporal experiences while zooming, which suggests that the zooming feature could be further enhanced to exploit such temporal reasoning for communicating of evolutionary time.

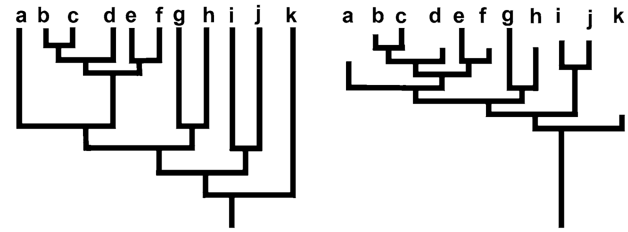

Fig. 4 Two ways of visualizing the same evolutionary history of organisms a–k. Left: evolutionary relatedness between organisms. Right: inclusion of temporal aspects showing that only species c, e, and g currently exist

The conclusions raise several implications for teaching about evolutionary time with tree representations, and for the use and design of educational technologies such as DeepTree. Firstly, while employing visual metaphors to learn abstract topics, it is essential that students have the appropriate representational knowledge to gauge which aspects of a phenomenon a metaphor illuminates or suppresses. In the case of phylogenetic trees, students have to be aware of what evolutionary aspect (e.g., time, relatedness, or both) is in focus (Gregory 2008; Omland et al. 2008). Consequently, potential misinterpretations must be addressed, such as realizing that the branching pattern in the tree is inferred from what is currently known, i.e., reconstructing the lineage leading to bacteria is impossible due to the number of generations that would be required to do so, with no direct traces of these today.

Secondly, teachers should use multiple representations in combination with acknowledging students' prior experiences (Delgado and Lucero 2015) to communicate temporal and relational aspects (Ainsworth and VanLabeke 2004). Consider Fig. 4 which illustrates two complementary visual representations of evolution.

Thirdly, it is important that dynamic interfaces such as DeepTree clearly depict the relation between represented time and real time, and also communicate a coherent relationship between zooming time and real time. A complement to this could be in integrating further touch based options for controlling the "speed" of passing time during zooming. Finally, we propose that users should be able to distinguish extinct from present species.

Lastly, we are currently analyzing students' affective experiences of evolutionary time and relatedness while interacting with DeepTree, an influential factor in considering the role of emerging interactive technologies in science education.

Acknowledgments We are grateful to all the students who participated in the study, Jennica Petré for her support, Henry Fröcklin for technical support, and our colleagues in the EvoVis research group. We thank Dr. Chia Shen, Harvard University, and Dr. Florian Block, University of York, for providing us with the opportunity to conduct research on the DeepTree application.

Funding Open Access funding provided by Linköping University. The research was funded by the Swedish Research Council (Vetenskapsrådet) (grant number 2012-5344) (EvoVis) and the Swedish National School in Science and Technology Education Research (FontD) (Vetenskapsrådet grant number 729-2013-6871) and Örebro University.

Compliance with Ethical Standards

Ethical Approval All procedures that involved human participants were conducted in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all participants.

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