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# Using Knowledge Construction Theory to Evaluate Learning Processes: A Randomized Controlled Trial on Showing Gradually Built-up Concept Maps Alongside a Scientific Text

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## ABSTRACT

Scientific texts convey new and complex information relevant not only to researchers but also to lay audiences. We present a randomized controlled trial that investigated whether showing a concept map, gradually building up as a user reads a scientific text, supports the cognitive processes of knowledge construction. The intervention group ( $n = 44$ ) exhibited significantly more knowledge construction [ $t(89) = 1.94, p = .029, d = 0.41$ ] than the control group ( $n = 47$ ). The intervention supported basic knowledge construction, i.e., *simple processing of information*, but not medium and complex levels. This study makes two contributions: (1) showing interactive concept maps and building them up gradually alongside reading helps make scientific texts cognitively more accessible to a lay audience, e.g., to inform public debate, and (2) knowledge construction theory can be used as a theoretical foundation for measuring specific aspects of learning processes—complementing other metrics for comparative design examinations, e.g., usability, user experience, or performance-based measures.

## KEYWORDS

Predefined concept maps; knowledge construction; learning; experiment; open science

## 1. Introduction

Scientific texts tend to convey complex and, in the case of original publications, new information (Plavén-Sigray et al., 2017; Rowan, 1991). An obvious target audience are experts from the domain in which the text is situated. However, there are good reasons why a wider audience could and should be interested in scientific texts: first, in interdisciplinary academic discourse, it is necessary to integrate knowledge from multiple fields; second, many academic research topics are of interest in public debate and policy-making whether they are on climate change or vaccinations, for instance; and third, business is always looking toward research as the impulse for innovation.

Scientific texts are “informative texts as they provide information for their readers” (Yildiz, 2015, p. 257), their purpose is “to discuss a scientific problem which forms the subject of their study” (Yildiz, 2015, p. 257), and they should “enable readers to get knowledge on a specific scientific issue” (Yildiz, 2015, p. 257). Accessing scientific texts is, in some ways, being made increasingly easy due to ongoing efforts of open science (Vicente-Saez & Martinez-Fuentes, 2018). This means that many scientific texts are now accessible without extra pay, technically accessible in standard formats (e.g., PDF), and further accessibility efforts, such as alternative image descriptions, are gaining traction. Such accessibility, however,

is no guarantee that readers will understand the content, even if the text is well written: simply reading a text does not guarantee comprehension, since constructing knowledge from new information requires substantial cognitive effort (Dole & Sinatra, 1998). Moreover, the “readability of scientific texts is decreasing over time” (Plavén-Sigray et al., 2017, p. 1); due to the growing complexity of formulations and content (Rowan, 1991). Consequently, it becomes more difficult for a lay audience to understand such content (Flemming et al., 2020; Rowan, 1991; Salita, 2015). Complementing the discourse on accessibility in human-computer interaction (HCI) that targets accessibility of content toward an audience with special perceptual or motor-skills-based needs, we consider this a cognitive accessibility issue. The fundamental question that motivates our research is how interface and information design can support such cognitive accessibility and thereby help that knowledge encoded in a scientific text can be taken up by lay audiences.

## 2. Background

### 2.1. Knowledge construction

Knowledge construction refers to the process of actively acquiring and developing new knowledge and new

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understanding (van Aalst, 2009). Literature on knowledge construction differentiates between individual knowledge construction as a cognitive process and collaborative knowledge construction as a socio-cognitive process. Individual knowledge construction is based on notions of constructivism (Castle, 1997; Cress & Kimmerle, 2008; Novak, 1993; van Aalst, 2009), which postulate that information from the environment is not simply adopted as is. Instead, the newly acquired information is cognitively processed in the sense that it is adapted, assimilated, and reflected upon; prior knowledge must be consolidated accordingly. Thus, knowledge is actively constructed in relation to learners' prior knowledge, such that existing knowledge influences what is learned as new concepts need to be integrated into prior knowledge (van Aalst, 2009). Collaborative knowledge construction refers to a socio-cognitive process in which individual knowledge is made available to others (externalized) and collaboratively negotiated. An essential element in this process is consensus building, typically enabled by an initial dissonance of ideas within the group, integration of these ideas, and subsequent co-construction of knowledge available in the group as a whole (Fischer et al., 2002; Gunawardena et al., 1997; Hmelo-Silver, 2003; Stahl, 2000).

Moreover, prior literature understands both individual and collaborative knowledge construction as multi-level processes in which basic knowledge construction levels are necessary prerequisites for more complex levels. While works in educational technology use the concept of knowledge construction to denote a particular type of learning (e.g., Harbarth et al., 2018; Liaw & Huang, 2006), most do not consider knowledge construction theory (including distinct levels) to study this process and thereby miss access to understanding the fine-granular underlying processes. In this work, we address individual knowledge construction and understand its constituent levels as described by Dole and Sinatra (1998): *simple processing* (I), *assimilation* (II), *deeper processing/reflection* (III), *knowledge restructuring* (IV), and *meta-cognitive processing* (V). Dole and Sinatra (1998) have grouped these levels into categories, classifying the first two levels, *simple processing* and *assimilation*, as *low levels*, *deeper processing/reflection* as *medium level*, and *knowledge restructuring* and *meta-cognitive processing* as *high levels*. Table 1 summarizes these levels and respective categories.

## 2.2. Designing for knowledge construction

A considerable amount of research in HCI and the adjacent field of educational technology has been carried out on technological support for knowledge construction on the

one hand (see Disch et al., 2022 for a recent overview) and reading on the other (e.g., McNamara, 2007). At the intersection of such research, it has been investigated how to support knowledge construction during reading (e.g., Harbarth et al., 2018; Liaw et al., 2010) with adaptive and intelligent systems for learning being a salient type of technological approach (e.g., Alevan et al., 2016; D'Mello & Graesser, 2013). Another approach to supporting knowledge construction during reading is to present content in a multi-modal way, the underlying rationale being that multimodal presentation facilitates the comprehension of complex texts (Burton-Jones & Meso, 2008; Serafini, 2015). Based on this fundamental principle, research has explored a plethora of ways to visually augment text (Shams & Seitz, 2008), such as using data visualization (Sultanum et al., 2018), animated transitions between different parts of text (Chevalier et al., 2010), or text integrated into videos and 3D graphics (Jankowski et al., 2010). In this context, concept maps are a way to visualize knowledge in a way that reflects the human cognitive representation of knowledge (Medin, 1989; Novak, 1993). As knowledge construction theory points out the importance of connecting and integrating new concepts into existing knowledge during the learning process, we consider concept maps a particularly interesting intervention for making complex scientific texts cognitively more accessible. Below we discuss in detail extant literature regarding concept maps visualization (Cañas et al., 2005; Eppler, 2006; Nesbit & Adesope, 2006; Novak, 1993; Novak & Gowin, 1984; Padilla et al., 2017), concept map authoring and generation (Falke, 2019; Kowata et al., 2010; Presch, 2020; Valerio et al., 2012; Zouaq & Nkambou, 2008, 2009), and how concept maps support knowledge construction and learning (Chang et al., 1997; Collins & Nyenhuis, 2021; Eppler, 2006; Morsi et al., 2007; Novak, 1993; O'Donnell et al., 2002; Sun et al., 2004).

## 2.3. Concept maps

A concept map (Novak & Gowin, 1984) is a visual representation of information that is structured as consisting of concepts and their connections and is visualized in the form of a node-link assembly (Nesbit & Adesope, 2006). In this, nodes represent concepts, and links between nodes represent the conceptual connections between concepts.

### 2.3.1. Concept map visualization

Various works suggest design rationales for concept map visualizations (e.g., Cañas et al., 2005; Novak, 1993; Padilla et al., 2017), such as to word concept labels as short as

**Table 1.** Descriptions and categories of individual knowledge construction levels along Dole and Sinatra (1998).

Level	Description	Category
Simple processing	Simple processing of information	Low level
Assimilation	Assessing extent to which information fits to prior knowledge	Low level
Deeper processing/reflection	Attempt to make meaningful connections of new information to existing concepts through reflection/internal questions	Medium level
Knowledge restructuring	Reconstruction of prior knowledge concepts—new information can be integrated into existing concepts	High level
Meta-cognitive processing	Creating meta-concepts that combine new information with existing concepts	High level

possible (Cañas et al., 2005), and to allow blank spaces between (groups of) concepts (Padilla et al., 2017) in the map. However, concrete design rationales depend on the context in which the concept map is used (Padilla et al., 2017); hence, more general visualization principles need to be relied on (e.g., Chen, 2013; Hicks, 2009).

### 2.3.2. Concept map authoring

Before visualizing a concept map, someone needs to create its content, i.e., define concepts and relations between concepts. This authoring can be done manually, semi-automatically, or fully automated. Substantial research has been directed at extracting concepts and their relations from unstructured texts using methods from natural language processing (e.g., Falke, 2019; Kowata et al., 2010; Valerio et al., 2012; Zouaq & Nkambou, 2008, 2009). In a review of such approaches, Kowata et al. (2010) highlight exciting results on automatically authored concept maps and learning (Zouaq & Nkambou, 2008, 2009). Also, Valerio et al. (2012) show that an automatically generated concept map can support a user in understanding key points made in a document to assess its relevance. Overall, however, automatically generated concept maps may fail to fully convey the mental knowledge model of an expert (Presch, 2020), and it seems more realistic to assume that automatically generated concept maps are the input to human (manual) post-editing if the quality of the concept map is relevant (Falke, 2019; Kowata et al., 2010).

Concept maps can also be manually created. In this article, we distinguish two possibilities of manual creation. First, users can create concept maps as part of the reading and learning process—we refer to these as self-created concept maps. The creator and user of the map are the same person. Second, concept maps can be created by someone other than the user of the map—we refer to these as predefined concept maps because they are defined before they are used. The creator and user of the map are different entities. In the case of manual generation, this instance is a human, e.g., the document authors, an expert, or a teacher who creates the concept map specifically for a text. In the case of fully automated concept map generation, the predefining instance is a computer. In the case of semi-automatic concept map generation, a human defines the concept map with the help of a concept mining algorithm. Concept map quality and process efficiency (time spent on authoring *vs.* quality of concept map) are of concern for predefined concept maps. Below we discuss the literature on concept maps and their impact on learning and knowledge construction separately, as the involved learning mechanisms are different.

### 2.3.3. Self-Generated concept maps, learning, and knowledge construction

Concept maps that are self-generated serve as a tool for active learning (Collins & Nyenhuis, 2021; Morsi et al., 2007; O'Donnell et al., 2002). Typically, self-generated concept maps are used in contexts where there is a corrective instance, such as a teacher. Prior literature provides some if not ample, evidence that self-generated concept maps

support understanding of information (Burton-Jones & Meso, 2008; Edmondson, 2005) and knowledge construction (Harbarth et al., 2018; Liu et al., 2020; Suthers et al., 2007); and further evidence that all individual knowledge construction levels are supported (*deeper processing/reflection, knowledge restructuring, and meta-cognitive processing* by Harbarth et al. (2018); and all collaborative levels (Liu et al., 2020). Chang et al. (2001) went one step further and investigated how different variants of concept maps (e.g., predefined *vs.* self-generated concept maps) can support the understanding of information in an online learning environment. They showed that a partially predefined concept map, which needs to be completed, supported the understanding of information more than a concept map that has to be created by users from scratch.

### 2.3.4. Predefined concept maps, learning, and knowledge construction

Typically predefined concept maps are investigated as complementing textually encoded knowledge (Burton-Jones & Meso, 2008; Chang et al., 2001), described as a “systematic, proven approach to provide overview” (Eppler, 2006) that enable “rapid information provision” (Eppler, 2006). Used that way, concept maps serve as a tool for receptive learning (O'Donnell et al., 2002) and support “the direction of learning [...] from written or spoken form to meaning” (Webb, 2012). Predefined concept maps (e.g., by experts) are assumed to represent correct knowledge. Prior work focused on assessing the impact of concept maps on learning outcomes (Chang et al., 1997; Novak, 1993; Valerio et al., 2012) and knowledge construction (Sun et al., 2004) in e-learning settings. Novak and Cañas (2006) investigated the influence of predefined concept maps on the learning outcome in an online learning environment. Their results show that such concept maps help users to build a solid knowledge foundation and serve as a complementary instrument for learning complex topics. In a study on predefined automatic concept maps, Valerio et al. (2012) showed that automatically generated predefined concept maps supported reading and comprehension of texts from different areas (e.g., an article about a suspension bridge). Sun et al. (2004) show that concept maps that visualize learning goal definitions, expected learning outcomes, and relevant skills in an online e-learning environment support individual knowledge construction. Contrary to research on concept maps as a tool for active learning, *prior research on predefined concept maps has not carried out assessments with respect to the kind of learning or the level of knowledge construction that is facilitated* in relation to understanding complex texts. In this work, we ask how effective human-generated, predefined concept maps are in supporting knowledge construction, knowing that they require less cognitive effort and activity from users than self-generated concept maps and in settings where no interaction among learners or between learners and teachers can be expected.

## 2.4. Research question and hypotheses

The goal and question of our research was to investigate *to what extent predefined concept maps as a complement for scientific texts support learning and knowledge construction, and in particular, which levels of knowledge construction are supported* (RQ). As an intervention, we developed an interactive concept map that gradually builds up per paragraph as the users read through a scientific text. Based on the prior literature discussed above, we formulated the following directed hypotheses:

- First Hypothesis (H1)—knowledge construction: The use of a gradually built-up concept map leads to more knowledge construction regarding a scientific text compared to simply reading the scientific text without a concept map. This hypothesis was directed toward the cognitive process of knowledge construction.
- Second Hypothesis (H2)—learning outcome: The use of a gradually built-up concept map leads to more gain in factual knowledge about the content of the scientific text compared to simply reading the scientific text without a concept map. This hypothesis was directed toward the learning outcome.

We preregistered our study on AsPredicted.org to specify and record our research plan, including the formulated research questions and hypotheses in advance. In the present article, we investigated individual knowledge construction, while the preregistration also describes our future study plan to investigate the influence of the intervention on collaborative knowledge construction. Further, we conducted exploratory data analyses, in particular, to identify which knowledge construction levels were facilitated.

## 3. Methodology

### 3.1. Procedure

To answer the research question and test the hypotheses, we conducted an experimental study in a web environment. The study procedure is depicted in Figure 1. First, study participants were asked to read the participant information sheet and fill in an informed consent form. After their agreement, they were randomly assigned to either the intervention or the control condition. In the second step, all participants answered a factual knowledge test on topics they would get to know during the study. In step three, every participant was asked to read the abstract of the scientific text we used in the study to determine whether the

participants knew the publication. If a participant had known the publication, the participant would have been excluded from the rest of the study. In step four, the participants were asked to read the scientific text and take notes about its content. Participants had up to 45 min to accomplish this task but could continue before the time expired. Next, they were asked to summarize the publication along predefined criteria in their own words without having the scientific text available. In this step, they could use the notes they had previously taken. Participants were given 30 min for this task but could move on at any time before the given time expired. Afterward, the participants were asked to again fill in the same factual knowledge test. Finally, participants were tested for their competence in English (as the text was in English and most participants were not English native speakers) and provided some demographic information. While in the control condition, the participants followed precisely the procedure described above, in the intervention condition, the participants were shown an interactive, gradually built-up concept map alongside the scientific text. The intervention (CoMap tool) is described below in more detail. Overall, the participants took  $M = 1.28$  ( $SD = 0.17$ ) hours to complete the whole study procedure. As a reward for their participation, the study participants received bonus points for the respective university course.

### 3.2. Participants

We recruited study participants in a computer science course at the bachelor level at TU Graz (“Introduction to Data Science and AI,” year of course withheld to support continued anonymity of participating students). Students who met minimum criteria, like completing the study and submitting a very basic reasonable summary, received bonus points for the course. The assignment of points in the course context was independent of the points a participant scored in the factual knowledge tests and the knowledge construction score their summary received during data analysis for our research purposes.<sup>1</sup> To estimate the appropriate number of participants per group, we performed a power analysis using the *G\*Power* 3 software (Faul et al., 2007, 2009). Based on previous literature on concept maps (see Background above), we expected a medium to strong effect (approx. Cohen’s  $d \approx 0.5$ – $0.8$ ) for our hypotheses, resulting in a recommended sample size of  $n = 35$ – $88$  per group. Out of 431 students enrolled in this course, 97 students participated and completed the study. However, we had to exclude the data of six participants. Four participants were excluded because their English level was below A2 on the Cambridge general English short test. Two participants were excluded

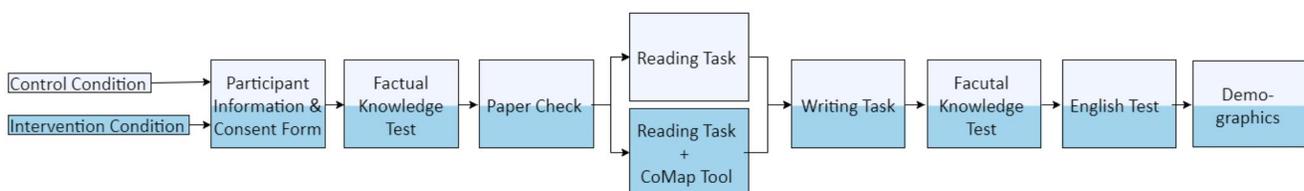


Figure 1. Overall experimental procedure.

because their summary contained <200 words, resulting in  $n=47$  participants in the control and  $n=44$  participants in the intervention condition. Given our a priori power analysis described above, we consider the group sample sizes to be sufficiently large.

### 3.3. Materials

#### 3.3.1. Reading material: Peer-reviewed scientific article

The scientific text that study participants were asked to read and summarize was an original research publication with the title “Leaning to the Left Makes the Eiffel Tower Appear Smaller: Posture-Modulated Estimation” by Eerland et al. (2011). We selected this publication as the text is concise, rather short, and easy to understand (2, 015 words, estimated reading time: 8.47 min on average (reading time calculated according to Brysbaert, 2019)). This was necessary to have an overall reasonable time for the experiment (if the experiment had taken too long, participants’ attention would have become an issue). Nonetheless, the article contains theories, such as “mental-number line theory” (Restle, 1970) and “anchoring-and-adjustment heuristic” (Tversky & Kahneman, 1974) that are not commonly known. Moreover, the article comes from the field of psychology and therefore did not relate to most participants’ primary field of study. This means that we could expect most participants not to know the article beforehand (which was an exclusion criterion). Further, this approximates our research’s underlying motivation, which is that of a general readership being interested in scientific texts outside their core area of expertise.

#### 3.3.2. Computational environment for the experiment

The experiment was carried out *via* an interactive website which we implemented specifically for this purpose. The website consisted of four different views: an *information view*, a *survey view*, a *reading view*, and a *writing view*. The *information view* presented the text to participants without requiring any further action (e.g., presenting information on the landing page at the beginning of the study). The *survey view* presented questions in the form of a questionnaire. This view was used, for instance, to test study participants for factual knowledge, for their proficiency in English, and for demographic information.

The *reading view* (see Figure 2) was the central part of the experiment. It consisted of five areas. The first area was located on top of the window and showed the description of the current task and a short summary about how to use the interface (see Figure 2, point 1). The upper right corner shows how much time is left to perform the task. The reading task was scheduled for 45 min (see Figure 2, point 2). This timing was deemed more than sufficient because the estimated reading time was much shorter (see above). Participants who did not complete the task in time were forced to proceed to the subsequent task. The third area in the reading view showed the scientific text (see Figure 2, point 3). A checkbox was displayed below each text

paragraph. When a study participant had finished reading a paragraph and ticked the checkbox below the paragraph, the concepts and their connections that correspond to the just-read paragraph were added to the concept map (CoMap tool), which was presented in the fourth area (see Figure 2, point 4). The CoMap tool is described in more detail in the next subsection (Section 3.3.3). The fifth area in the *reading view* was the notes area in the bottom right corner (see Figure 2, point 5). This area was a plain text field in which the study participants could take notes. These notes were saved on the server side to be used later during the writing task. The fourth area with the CoMap tool was only visible in the intervention group; thus, the notes area had to be extended for the control group and covered the whole right part of the *reading view*.

The *writing view* (see Figure 3) consisted of four areas. The first area (see Figure 3, point 1) contained the information about the current task (a repetition of the information given to participants at the beginning of the experiment). Again, a timer was presented in the upper right corner (see Figure 3, point 2). The writing task was scheduled for 30 min. Like in the reading task, the participants were forced to continue with the subsequent task after the foreseen time was elapsed. The third area was the summary writing area, where the participants had to write the summary of the article (see Figure 3, point 3). The summary writing area was an editable text field whose content was saved in the database of the server every 2 s. The summary was finally saved when the participant left the *writing view*. The reasoning behind the periodical savings was to avoid data losses in the case of unexpected circumstances, such as disconnections or server crashes. The fourth area was the notes area (see Figure 3, point 4), showing the notes that the study participant had taken during the reading task in the notes area. The notes were again editable and saved inside the database.

#### 3.3.3. Intervention: CoMap tool

The CoMap tool is an interactive concept map. It visualizes concepts and their connections as a labeled graph. When a concept (=a node) is clicked on, a definition of the concept is shown (Figure 2, point 4). In our experiment, the CoMap tool visualized core concepts and connections between concepts of the scientific text that study participants had to read and summarize as part of the experiment.

In particular, the concept map was built up paragraph by paragraph as participants read the publication. The gradual build-up was chosen based on cognitive load theory (Sweller et al., 1990), which states that processing too many pieces of information at once leads to cognitive overload of the working memory, which in turn hinders the learning process. To implement this functionality, the CoMap tool was linked to the *reading view*, which showed a checkbox that should be ticked after a paragraph of the scientific text had been read. The newly added concepts were colored in a slightly different shade so that users could easily see which new concepts were added to the concept map as a new paragraph had been read (as shown in Figure 2). The design rationale underlying this gradual build-up of the concept map was to

**Reading the Paper** Remaining Time  
0:36 min

1 **Read the paper.** When you are finished reading a paragraph tick the box at the bottom of the paragraph

2 Use the **concept map and concept definitions** to better understand the concepts mentioned in the paper. The concept map shows the important concepts mentioned in the paper and their relationships. When you mark a paragraph as finished, the concept map continues to build up with the important concepts mentioned in the corresponding paragraph

3 **Take notes** on the content of the paper in the text field. You may use these notes later to write a **summary** of the paper (if you move the cursor over the underlined word summary, you will see again the details of what the summary should contain)

**PAPER**

**Leaning to the Left Makes the Eiffel Tower Seem Smaller: Posture-Modulated Estimation**

**Abstract**

In two experiments, we investigated whether body posture influences people's estimation of quantities. According to the mental-number-line theory, people mentally represent numbers along a line with smaller numbers on the left and larger numbers on the right. We hypothesized that surreptitiously making people lean to the right or to the left would affect their quantitative estimates. Participants answered estimation questions while standing on a Wii Balance Board. Posture was manipulated within subjects so that participants answered some questions while they leaned slightly to the left, some questions while they leaned slightly to the right, and some questions while they stood upright. Crucially, participants were not aware of this manipulation. Estimates were significantly smaller when participants leaned to the left than when they leaned to the right.

**CONCEPT MAP**

```

graph TD
    BP[body posture] --- MNL[mental-number-line theory]
    MNL --- EXP[experiment]
    MNL --- P[participants]
    MNL --- RH[right-handed]
    EXP --- MR[memory retrieval]
    MR --- AA[anchoring-and-adjustment heuristic]
    MR --- ME[magnitude estimates]
  
```

4

**NOTES**

Write your notes here

5

**NEXT**

Figure 2. Reading view: reading task with concept map.

avoid overloading study participants with a concept map representing the scientific text's complete content from the beginning of reading the article. Concept map design characteristics followed selected design rationales as introduced in prior literature (Cañas et al., 2005; Padilla et al., 2017), i.e., brief concept labels (Cañas et al., 2005); no duplicated concept labels (Cañas et al., 2005); proximity, similarity, and connectedness in visualization (Padilla et al., 2017); and customizable complexity of visualization (Padilla et al., 2017). As it was implemented, the concepts that appeared in a text paragraph were always shown after the paragraph was read (and the checkbox below was clicked). The concept map, therefore, worked like a *post-hoc* summary of the just-read paragraph.

Technically, the CoMap tool read the concept map from a JSON file that defined nodes (concepts defined by a label and a longer textual description/definition) and connections (connections between nodes, defined by starting and ending points for each connection), and the exact position of the nodes. Node positions are optional, but nodes would be

positioned automatically if missing. In our experiment, node positions were predefined to ensure that the concept map was visualized in precisely the same way to all study participants. A short video of the CoMap tool is available as Supplementary Material to this publication.

The content of the concept map (concepts, connections between concepts, concept labels, and definitions) was hand-crafted by two of this article's authors ("concept map authors" below) based on the selected scientific text for this experiment. The rationale for manual creation was that (i) no concept map for this scientific text existed, and (ii) while tools for automatic concept map creation from text exist, we wanted to ensure a high quality of the content and a per-paragraph concept map. Note that the CoMap tool does not require the predefined concept map to be manually created; however, we needed to assume that the quality of the predefined concept map impacted the support it could give for knowledge construction.

We proceeded similarly as in a coding process: In the first step, the two concept map authors read the article

**Writing a Summary**

Remaining Time  
29:27 min

**2**

**1** Write a summary in the text area.  
The summary should contain brief descriptions of:

- the topic of the paper (what the paper is about)
- the important theories in the paper
- the experiments (and the differences between them)
- the results
- one strength and one weakness of the paper
- an alternative study setup with which one could test the effects mentioned in the paper
- how the results are relevant and have an impact on real life

**3**

**SUMMARY**

You can use 200-500 words for your summary.

Please write your summary here

words: 0

**4**

**NOTES**

Write your notes here

**NEXT**

Figure 3. Writing view: writing task.

independently and extracted a list of concepts per paragraph that were considered important for understanding the publication. Second, the two concept map authors compared the identified concepts and, in a reflective discussion, decided to remove several concepts deemed of lesser importance. In the third step, each concept's occurrence was counted by counting words in the scientific text that referred to this concept. Concepts that occurred less than three times in the publication were also removed from the list of concepts. Finally, 24 concepts and their connections were selected to describe the scientific text. For each concept, the concept map authors created a definition based on reliable online sources in the field of psychology (e.g., APA Dictionary of Psychology American Psychological Association, 2018). This overall concept map consisted of seven subparts. Two more authors of this article reviewed the resulting concept map for understandability. All concepts and respective definitions are listed in the Supplementary Material.

### 3.4. Instruments and data collection

This section summarizes the instruments used for data collection along with the overall experimental procedure (see Figure 1).

#### 3.4.1. Factual knowledge test (pre and post)

We designed a set of single-choice questions to test participants' prior knowledge concerning the content of the reading material. Altogether we developed 12 questions asking about essential concepts, statistics, theories, and their implications, resulting in 12 points (see Supplementary Material).

This test was administered before and after participants read the text. It was used to test the second hypothesis (H2—learning outcome). The pre-factual knowledge score is the score (=number of correct answers given in the test) that participants achieved on the test before the reading and writing tasks. The post-factual knowledge score is the score participants achieved after the reading and writing tasks.

The change in factual knowledge was calculated as the difference between the pre- and post-scores. We examined reliability by determining the internal consistency of the factual knowledge test by applying a split-half reliability analysis (Allen & Yen, 2002). After data collection, the questionnaire was randomly divided into two comparable halves. As a reliability coefficient, we calculated Guttman's  $\lambda$  (Guttman, 1945) by using the *splitHalf()* function of the R package "psych" (Revelle, 2023). Guttman's  $\lambda$  accounts for the potential effects of test shortening in split-half analyses. The calculated split-half reliability coefficient yielded a value of  $\lambda = .81$ , indicating a robust internal consistency within the factual knowledge test.

### 3.4.2. Knowledge construction scores for the summaries

In both the intervention and the control condition, we asked the participants to summarize the publication along the following criteria in the summary task: (i) the topics of the publication (what the publication is about), (ii) the theories mentioned in the publication, (iii) the two experiments presented and their differences, (iv) the results, (v) one strength and one weakness of the article, (vi) an alternative study design that could be used to test the effects mentioned in the publication, and (vii) the relevance of the results and possible real-life implications. The length of the summary was suggested to be between 200 and 500 words. Study participants who wrote shorter summaries were excluded from the data analysis. To enable the participants to keep track of the number of their written words, we implemented a word counter.

Every summary was coded by two members of the research team to calculate a knowledge construction score. The knowledge construction score of a summary expresses for each of the individual knowledge construction levels defined by Dole and Sinatra (1998) to what extent the level is deemed present in a summary. We collaboratively developed a coding schema that operationalized knowledge construction levels described by Dole and Sinatra (1998). The coding schema is summarized in Table 2. We describe the codes and illustrate each with excerpts from an example summary (the respective summary was rated with 16 out of 18 points). For each individual knowledge construction level (Dole & Sinatra, 1998), a summary could receive points: *simple processing*—four points; *assimilation*—six points; *deeper processing/reflection*—four points; *knowledge restructuring*—two points; *meta-cognitive processing*—two points. A summary that exhibited knowledge construction on all levels would receive an overall knowledge construction score of 18 points and respectively less if some levels were not observable in the summary. The overall knowledge construction score (sum of all points given) and the points scored on the single levels were used in the further analysis (see next Section).

Two members of our research team independently rated the knowledge construction levels in the summaries using the developed coding scheme (see Table 2); note that the two raters were not involved in the creation of the coding scheme to ensure impartiality in ratings. To assess the

quality of the coding schema in terms of how clearly it explained how a summary should be scored, interrater reliability between the two researchers' codings was computed. We used the intraclass correlation coefficient (*ICC*) (Koo & Li, 2016). Interrater reliability "reflects the variation between two or more raters who measure the same group of subjects" (Koo & Li, 2016). Our  $ICC = 0.89$  can be considered a good absolute reliability (quality classification along Koo & Li, 2016). For further analyses, we used the average rating of both researchers as knowledge construction level scores of a single summary. The overall knowledge construction score was then built by summing up the level scores. The internal consistency of the knowledge construction score items was assessed by calculating Cronbach's  $\alpha$  coefficient using the *alpha()* function of the R package "psych" (Revelle, 2023). The calculation yielded a coefficient of  $\alpha = .75$ , indicating good reliability (Kline, 2013).

### 3.4.3. English test

To measure the English proficiency of the study participants, we used the Cambridge general English short test (Cambridge University Press & Assessment, 2017b). The test consists of 25 questions that test general English abilities and is scored along the Cambridge English and recommendation scales (Cambridge University Press & Assessment, 2017a) (see Supplementary Material). We measured the participants' English proficiency, as language proficiency influences text understanding (Hammadou, 1991). Participants with a language proficiency below language level A2 were excluded from our further analyses, as we assumed their low language proficiency would interfere with their fundamental ability to understand the text.

### 3.4.4. Demographic questions

We collected demographic data from the participants, namely gender, age, highest educational qualification, field of study, and duration of their studies.

## 3.5. Data analyses

We computed descriptive statistics for the English test, factual knowledge test (pre and post), and knowledge construction scores of the summaries. As primary analyses, we performed comparative statistics testing our two hypotheses:

We tested the first hypothesis (H1—knowledge construction) by conducting a two-sample *t*-test (one-tailed), comparing the intervention and control group's overall individual knowledge construction scores. For fine-granular analyses of individual knowledge construction (Dole & Sinatra, 1998), we conducted two-sample *t*-tests (one-tailed) comparing the scores of the intervention and control group for (i) categories of levels and (ii) each level (overview of categories and levels in Table 1).

We tested the second hypothesis (H2—learning) by conducting a two-sample *t*-test (one-tailed), comparing the pre- and post-factual knowledge scores and the factual knowledge

**Table 2.** Coding schema developed for the summaries written in the writing task, schema is based on individual knowledge construction levels along Dole and Sinatra (1998).

KC coding scheme	Examples from a participant's summary
<p>Level 1: Simple processing (low level)</p> <ul style="list-style-type: none"> <li>- An explanation of the mental-number-line theory</li> <li>- Mentioning the Wii balance board</li> <li>- A brief description of the center of pressure (COP)</li> <li>- A brief description of the procedure of the first experiment</li> </ul>	<p><i>"The theory of the mental-number-line suggests that people associate smaller numbers on the left side of an imaginary line and larger numbers on the right side of this imaginary line."</i></p> <p>–</p> <p><i>"The study contained two similar experiments. In the first experiment 33 psychology students (9 male, 24 female) all between the age of 18 and 27 and all right handed, were presented 39 randomly assigned questions of estimations [...]"</i></p>
<p>Level 2: Assimilation (low level)</p> <ul style="list-style-type: none"> <li>- A brief description of the analysis of the first experiment.</li> <li>- A brief description of the results of the first experiment.</li> <li>- A brief description of the analysis of the second experiment.</li> <li>- A brief description of the results of the second experiment.</li> <li>- A brief description of the difference between the set-up of the first and the second experiment.</li> <li>- A brief description of the general results of the study.</li> </ul>	<p><i>"The mean z-score was calculated for each participant and then a mixed analysis of variance (ANOVA) was conducted."</i></p> <p><i>"The results of the first experiment were the following: there was a small significant difference between leaning left and right but there was no difference between leaning right and standing upright."</i></p> <p><i>"Then a similar analysis was conducted like in experiment 1."</i></p> <p><i>"The results were the same: there was a small significant difference between leaning left and right but there was no difference between leaning right and standing upright."</i></p> <p><i>"The only difference was that the estimation scale was reduced to numbers between 1 and 10."</i></p> <p><i>"[...] significant difference between leaning left and right but there was no difference between leaning right and standing upright." &amp; "[...] in the results of the experiments there was no difference between standing upright and leaning to the right."</i></p>
<p>Level 3: Deeper processing (medium level)</p> <ul style="list-style-type: none"> <li>- One strength of the article was mentioned and is inherently logical.</li> <li>- One strength of the article was mentioned and is valid/plausible.</li> <li>- One weakness/limitation of the article was mentioned and is inherently logical.</li> <li>- One weakness/limitation of the article was mentioned and is valid/plausible.</li> </ul>	<p><i>"A strength of the article is that two experiments were conducted with different scales. This contributes to a more robust result."</i></p> <p><i>"A weakness of the article was the fact only right handed people were participating."</i></p>
<p>Level 4: Knowledge restructuring (high level)</p> <ul style="list-style-type: none"> <li>- What could be another experiment with a similar setting? Another setting was mentioned and is inherently logical.</li> <li>- What could be another experiment with a similar setting? Another setting was mentioned and is valid/plausible</li> </ul>	<p><i>"An alternative study setup could be with different groups of dominate hands to examine further if that would have an influence."</i></p>
<p>Level 5: Meta-cognitive processing (high level)</p> <ul style="list-style-type: none"> <li>- The everyday relevance/impact on everyday life/real life was mentioned and is inherently logical.</li> <li>- The everyday relevance/impact on everyday life/real life was mentioned and is valid/plausible.</li> </ul>	<p><i>"The results of this article are important in real life as this could affect the decision making. For example in business when a manager has to estimate revenue streams or in personal finances. With the results of the article it would be important to be aware of the possible affect on the personal and others decision making."</i></p>

The table defines the coding schema and gives examples from a selected summary written by a participant.

gain (difference between the pre- and post-scores) of the intervention and control group.

## 4. Results

### 4.1. Demographic information, prior knowledge, and English proficiency

All study participants ( $N=91$ ) were university students. They were aged between 18 and 40 years ( $M=22.53$ ,  $SD=4.26$ ). 22 (24.18%) were female and 69 (75.82%) were male. The gender distribution in our study was slightly more balanced than the overall gender distribution in the university's computer science bachelor degree course (females: 14.52%, males: 85.58%—% extracted from student statistics). In the intervention group ( $n=43$ ), 14 participants (31.82%) were female and 30 (68.18%) were male; in the control group ( $n=47$ ), 8 participants (17.02%) were female and 39 (82.98%) were male. A Chi-Square Test of

Independence showed that these frequencies did not differ significantly [ $X^2(1, N=89)=2.71, p=.099$ ]. On average, participants had studied for  $M=2.46$  ( $SD=1.46$ ) semesters and had the following main fields of study<sup>2</sup> (relative frequencies in %): engineering (72.53%), social sciences (5.49%), human sciences (5.49%), natural sciences (3.30%), theology (2.20%), and economics (1.10%). The distribution of disciplines is in line with the fact that the selected course is also promoted to students of non-computer science studies. The participants' prior knowledge of the content of the scientific text was tested using the factual knowledge test described above. Overall, participants scored  $M=5.47$  ( $SD=2.10$ ) out of 12 possible points in the pre-knowledge test. Regarding English proficiency, participants scored  $M=20.61$  out of 25 possible points ( $SD=2.13$ ). This score corresponds—based on the Cambridge scale—to an independent (B1/B2) level of English [following the Common European Framework of Reference for Languages (CEFR) (Council of Europe, Council for Cultural Co-operation,

Education Committee, Modern Languages Division, 2001)]. This indicates that the study participants had a reasonably good language proficiency overall, which is the prerequisite for understanding any text. We conducted two-sample *t*-tests to compare the age, semester of study, prior factual knowledge, and English proficiency of the intervention and control groups. The individual results are listed in Table 3 and reveal no significant differences. Thus, the intervention and control groups can be considered equivalent in terms of gender (see Chi-Square Test above), age, semester of study, prior knowledge, and English proficiency.

#### 4.2. First hypothesis (H1)—Knowledge construction

Across both groups, participants ( $N = 91$ ) reached  $M = 11.29$  ( $SD = 3.20$ ) out of 18 points as the overall knowledge construction score. Per level, the results were as follows: low levels score (combined):  $M = 6.10$ ,  $SD = 1.30$  (simple processing score:  $M = 2.64$ ,  $SD = 0.59$ ; assimilation score:  $M = 3.46$ ,  $SD = 0.85$ ); medium level score (deeper processing/reflection score):  $M = 2.63$ ,  $SD = 1.38$ ; high levels score (combined):  $M = 2.06$ ,  $SD = 1.64$  (knowledge restructuring score:  $M = 1.12$ ,  $SD = 0.89$ ; meta-cognitive processing score:  $M = 0.95$ ,  $SD = 0.86$ ).

To test our first hypothesis (H1) on knowledge construction, we compared the intervention and control group using a two-sample *t*-test one-tailed; statistical results are shown in Table 4. The analysis shows, with a small to medium effect, that the intervention group achieved a higher total score in knowledge construction than the control group, thus, supporting H1. To investigate in more detail which knowledge construction levels were facilitated by our intervention, we carried out exploratory analyses; however, they were not preregistered. We conducted two-sample *t*-tests

**Table 3.** Two-sample *t*-tests comparing age, English proficiency, and semester of study of intervention and control group.

	<i>t</i>	<i>df</i>	<i>p</i>	Intervention <i>M</i> ( <i>SD</i> )	Control <i>M</i> ( <i>SD</i> )
Age	0.84	89	.402	22.14 (4.39)	22.89 (4.19)
Semester of study	−0.54	80	.722	2.53 (1.7)	2.40 (1.26)
Pre-knowledge	−0.58	89	.565	5.34 (2.12)	5.60 (2.09)
English proficiency	1.18	89	.242	20.89 (2.06)	20.36 (2.18)

*t*: *t*-value; *df*: degrees of freedom; *p*: *p*-value; *M*: mean; *SD*: standard deviation.

(two-tailed) comparing the scores of the individual knowledge construction level categories (*low levels*, *medium level*, *high levels*) that combined single levels as shown in Table 4, as well as two-sample *t*-tests that compared the intervention and control group concerning each knowledge construction level (*simple processing*, *assimilation*, *deeper processing/reflection*, *knowledge restructuring*, *meta-cognitive processing*). Respective statistical results are shown in Table 4. The results show that the intervention group had higher scores in *low knowledge construction levels* compared to the control group, with a medium-sized effect. More detailed analyses of the individual knowledge construction levels further revealed that the intervention group achieved a higher score on *simple processing* than the control group, with a medium-sized effect. Yet, analyses revealed no significant differences between the two groups with regard to the *assimilation* level. Further, there were no differences between the two groups at *medium* or *high levels* of knowledge construction, namely *deeper processing/reflection*, *knowledge restructuring*, and *meta-cognitive processing*. This shows that our intervention—a gradually built-up concept map—supported knowledge construction at the low level, i.e., *simple processing of information*, but did not explicitly facilitate more complex knowledge construction.

#### 4.3. Second hypothesis (H2)—Learning outcome

Descriptive statistics for pre-, and post-factual knowledge scores and factual knowledge gains of participants overall, intervention, and control groups are shown in Table 5. Regarding our second hypothesis (H2), we compared each participant to the difference in their pre- and post-test scores (delta between pre- and post-scores), representing the factual knowledge gained per participant. We compared factual knowledge gains of intervention and control groups using a two-sample *t*-test (one-tailed) that revealed no significant difference between groups [ $t(89) = 0.79$ ,  $p = .450$ ]. This result does not support H2.

We conducted further analyses to gain more insights into the factual knowledge scores: First, regarding differences in pre-factual knowledge scores, a two-sample *t*-test (two-tailed) revealed no significant difference [ $t(89) = -0.58$ ,  $p = .565$ ] between intervention and control group. Further,

**Table 4.** Two-sample *t*-tests comparing knowledge construction (KC) scores (overall and subscores of individual knowledge construction levels and categories along Dole and Sinatra (1998) with respective maximum scores in brackets) of intervention and control group.

KC scores	<i>t</i>	<i>df</i>	<i>p</i>	Intervention <i>M</i> ( <i>SD</i> )	Control <i>M</i> ( <i>SD</i> )	Cohen's <i>d</i>
Overall KC score (18 points)	1.94	89	.029*	11.95 (3.05)	10.67 (3.25)	0.41
Low levels score (combined—10 points)	2.24	89	.028*	6.41 (1.08)	5.82 (1.40)	0.47
Simple processing score (4 points)	2.14	89	.035*	2.78 (0.52)	2.52 (0.63)	0.45
Assimilation score (6 points)	1.82	89	.072	3.62 (0.74)	3.30 (0.92)	—
Medium level score (4 points)						
Deeper processing/reflection score (4 points)	0.79	89	.429	2.75 (1.40)	2.52 (1.36)	—
High levels score (combined—4 points)	0.82	89	.415	2.22 (1.65)	1.91 (1.60)	—
Knowledge restructuring score (2 points)	0.48	89	.633	1.16 (0.91)	1.07 (0.88)	—
Meta-cognitive processing score (2 points)	1.22	89	.226	1.06 (0.88)	0.84 (0.84)	—

*t*: *t*-value; *df*: degrees of freedom; *p*: *p*-value; *M*: mean; *SD*: standard deviation.

Note: \* $p < .05$ , \* $p < .05$  one-tailed.

**Table 5.** Descriptive Statistics for pre-, post-factual knowledge scores and factual knowledge gain of participants overall, intervention, and control group.

Factual knowledge scores (maximum scores in brackets)	Overall M (SD)	Intervention M (SD)	Control M (SD)
Pre-knowledge (12 points)	5.47 (2.10)	5.34 (2.12)	5.60 (2.09)
Post-knowledge (12 points)	10.99 (0.81)	11.02 (0.81)	10.95 (0.82)
Factual knowledge gain (12 points)	5.52 (2.02)	5.68 (2.08)	5.36 (1.95)

M: mean; SD: standard deviation.

the analysis of post-factual knowledge scores using a two-sample *t*-test (two-tailed) exhibited no significant difference [ $t(89) = 0.38, p = .703$ ] between the intervention and control group.

Second, as additional exploratory analysis (beyond pre-registration), we analyzed whether both groups had gained factual knowledge through the reading and writing tasks, using within-subjects *t*-test (two-tailed). The analysis showed that both the intervention group [ $t(43) = -18.14, p = .001, d = 3.54$ ] and the control group [ $t(46) = -18.85, p = .001, d = 3.37$ ] exhibited significant gains in factual knowledge; these effects can be considered as very large.

## 5. Discussion

### 5.1. Knowledge construction

Our results show that the tested intervention—a predefined concept map built-up paragraph by paragraph as a user reads a scientific text—leads to more knowledge construction than simply reading the scientific text. This result supports our first hypothesis (H1) on knowledge construction. Further analyses showed that the intervention supports the basic knowledge construction level *simple processing* (significantly higher scores in the intervention group for this level and the category *low*). Our results show no significant differences in more complex knowledge construction levels *deeper processing/reflection, knowledge restructuring, and meta-cognitive processes*. These fine-granular results are stable both in an analysis per knowledge construction level and in an analysis that groups knowledge construction levels into the three categories *low, medium, and high*. These results go beyond the existing literature on predefined concept maps (Chang et al., 1997; Eppler, 2006; Novak, 1993; O'Donnell et al., 2002; Sun et al., 2004), which indicates that they support knowledge construction without investigating the specific levels. Our result that predefined concept maps support basic knowledge construction levels rather than more complex ones indicates that such maps are suitable complementary knowledge representations for scientific (=complex, new) texts when it is relevant to support recipients with little prior knowledge to gain a first understanding of the scientific content. This can be the case, for instance, when research is used to inform public debate, business innovation, or policy-making. Yet, predefined concept maps may not be sufficient to support contexts of use where more complex knowledge construction is required, e.g., when knowledge from the scientific text needs to be practically applied or otherwise re-contextualized.

### 5.2. Learning outcome

Contrary to our expectations, the intervention group did not gain significantly more factual knowledge about the content of the scientific text. Thus, our study does not support the hypothesis that a gradually built-up concept map leads to significantly more factual knowledge when offered alongside a scientific text (H2).

We see two possible explanations for this result. On the one hand, it could be that our intervention does not support acquiring factual knowledge beyond what readers acquire from the scientific text itself. This is improbable due to the previous literature on predefined concept maps (Chang et al., 1997; Eppler, 2006; Novak, 1993; O'Donnell et al., 2002; Sun et al., 2004) and our positive results on H1 (we did observe a learning process, namely knowledge construction). However, the literature frequently does not distinguish very well between different learning processes and outcomes. It could be that concept maps support constructing conceptual knowledge (this was tested with the summary writing task) but not the uptake and remembering of more isolated knowledge statements, which was tested in the pre- and post-factual knowledge tests. On the other hand, our methodology could have caused non-significant results. In that, we see three possible methodological reasons: First, the scientific text we used as reading material could have been so easy to understand that participants did not need a concept map to comprehend it. Since significantly more knowledge construction was observed in the intervention group, this is unlikely because study participants benefited (see results and discussion on H1) from the intervention. Second, we used the same knowledge test before and after the intervention. On the one hand, recognition effects could have occurred when participants repeated the test (Chan & McDermott, 2007). However, recognition was made more difficult for the participants by randomizing the order of the test questions and the answer options. On the other hand, participants might have selectively learned the information asked in the pre-knowledge test. However, it becomes evident from the summaries that they did not only focus on learning the facts from the pre-knowledge test but also integrated other facts into the summary than those asked in the knowledge test. Nonetheless, future research is needed to assess the intervention with knowledge tests with more items or a parallel version of the test. Third, the instrument we used to measure factual knowledge could have been not sensitive enough, i.e., the pre- and post-factual test was too easy. This interpretation is plausible because (i) we did not use a validated factual knowledge test (the test had to be specific to the information conveyed in the particular scientific text), and (ii) we have indications for the existence of a ceiling effect

**Design Implication: Cognitively Accessible Concept Maps***Design Characteristics:*

- Essential Concepts - essential concepts and their connections are formulated per paragraph of a text as a concept map
- Gradual Build-Up - the concept map gradually builds up paragraph per paragraph
- Color Cues - concepts for each paragraph are shown in a different color shade

*Contexts of Use:* As a complement to text in a digital environment, e.g., content platforms such as (open) science platforms or news platforms.

**Figure 4.** Design implication: characteristics and context of use of the interactive and gradually built concept map (CoMap tool).

(Uttl, 2005; Wang et al., 2008) in the results. Our factual knowledge test consisted of 12 single-choice questions with 12 points as the maximum number of points that could be achieved; thus, this number represents the ceiling. If a participant gained more knowledge than was tested for, the points in the post-factual knowledge test could not represent this. Consequently, participants who scored lower on factual knowledge in the pre-test could achieve a higher knowledge gain. The analysis showed that 26 post-test scores reached our instrument's upper limit (ceiling—12 points), and participants scored a total of 10.99 ( $SD=0.81$ ) points on average. We interpret this as indicating the ceiling effect (Austin & Brunner, 2003). In summary, we believe that the lack of support for H2 is due to this second methodological issue; however, only specific further experiments can answer this open question.

### 5.3. Implications for design

The fundamental question that motivates our research is how interface and information design can help that knowledge encoded in a scientific text can be taken up by lay audiences. This work has two implications for interface and information design, the first of which concerns specifically the design of cognitively accessible concept maps (Section 5.3.1) while the second concerns the process of evaluating computational interventions designed with this purpose (Section 5.3.2).

#### 5.3.1. Designing cognitively accessible concept maps

Our findings show that gradually built-up predefined concept maps are an appropriate visual complement for text when it is desirable to support basic levels of knowledge construction. Given the more specific use case targeted in our research, concept maps are a suitable complement to scientific texts when they target a lay audience. This is typical on online news platforms where public debate on scientific topics takes place and also applies to (open) science platforms that connect researchers across disciplines. Such interdisciplinary academic discourse is thus served by supporting the communication of results to audiences with differing domain knowledge. Further, it is a characteristic of current open science platforms that they are web-based and

offer texts in a web-based format (Disch et al., 2022). This makes it technically easy to add an intervention, such as the CoMap tool, as described in this article. Beyond this, our intervention is in itself technologically simple (i.e., it does not need substantial computational power and algorithms) and can accompany any text visually in a digital environment. The intervention is similarly resource-efficient regarding the readers' cognition—it is a reflective and passive learning intervention for supporting knowledge construction (e.g., as opposed to an intervention for active learning, like presenting a quiz or a problem to solve). Subsequently, we argue that an interactive, gradually built concept map as the CoMap tool is a good support for reading scientific texts in online environments. We argue that the following three are particular design characteristics that contribute to the positive results: (1) selection and formulation of essential concepts per paragraph, (2) gradual build of concept map during reading, and (3) concepts for each paragraph are shown in different colors (see Figure 4). In our work, we propose two specific design elements (i) gradually building up the concept map in parallel to the reading progress (per paragraph) and (ii) coloring based on the paragraph where concepts and connections first appear in the text.

#### 5.3.2. Measuring the learning process using knowledge construction theory as a part of the design process

The second design implication is of a methodological nature. In this study, we evaluated our intervention, the CoMap tool, using knowledge construction theory to understand the effect of the intervention on the learning process. Specifically, we used knowledge construction levels to understand in a fine-granular manner this process. In our case, the understanding that the fundamental knowledge construction levels seem to be mainly supported backs our desire to facilitate a lay audience to understand scientific texts. Supporting more complex knowledge construction, such as meta-cognition, may be desirable in other design scenarios. Designers could use our present study as an example of how to use knowledge construction theory to measure the learning process, especially using a measurement of the knowledge construction levels to gauge the applicability of the intervention they are studying to

**Design Implication:** Measuring the Learning Process Using Knowledge Construction Theory as a Part of the Design Process

*Procedure:*

- Type of Knowledge Construction - decision whether individual or collaborative knowledge construction is targeted
- Assessing Levels - operationalization of assessment of respective knowledge construction levels (specific to use case and intervention)
- Comparing Levels - in comparative experiments: measuring which/to what degree knowledge construction levels are present in the groups (e.g., comparison between intervention and control group)

*Contexts of Use:*

- HCI or educational technology - informing research and intervention design, when the aim is:
  - measuring the learning process in a fine-granular manner,
  - identifying/comparing interventions and design features intended to support knowledge construction,
  - gaining an understanding of which contexts of use and which target group the interventions and features are appropriate for

**Figure 5.** Design implication: measuring the learning process using knowledge construction theory as a part of the design process. The procedure described in this Figure corresponds to the process of using the knowledge construction theory We used in the present article. Note that Measuring the knowledge construction levels is task- and intervention-specific, so the operationalization We describe in this article can be used as an example blueprint but not directly transferred to any intervention.

different contexts of use and different target groups (see Figure 5).

We argue that knowledge construction theory provides an excellent theoretical baseline for application in HCI as (1) substantial literature both on individual and collaborative knowledge construction is available (Dole & Sinatra, 1998; Gunawardena et al., 1997) is available and describes fine-granular levels for both cases, (2) mature models that show the connection between individual and collaborative knowledge construction exist (Cress & Kimmerle, 2008; Kimmerle et al., 2015), and (3) previous literature has mapped knowledge construction theory to existing designs for computationally supporting knowledge construction (Disch et al., 2022). Thereby, with knowledge construction theory, HCI researchers have an extensive, theoretically and empirically well-elaborated framework of conceptual constructs at hand that supports the comparative examination of designs, complementing existing and widely used measures that target usability, user experience, or task performance.

#### 5.4. Limitations and opportunities for future research

Reflecting on our work, we see the following promising research directions. They are connected to the limitations of our work in the sense that we did not investigate all interesting questions in-depth. First, following the literature on concept map design rationales (e.g., Cañas et al., 2005; Novak, 1993; Padilla et al., 2017), there is room for research on *the influence of fine-granular design decisions*. Our assumption that the gradual build-up of concept map eases cognitive load (see Section 5.3.1) could benefit from specific experiments. Further, research on the visual and interactive design of concept maps could investigate whether certain

elements can support more complex knowledge construction (e.g., more interactive features, such as hiding read/learned concepts or indicating the number of concepts displayed).

Second, existing literature is inconclusive about how *the design and content of concept maps should be personalized and tailored* to the user (e.g., to prior knowledge). We assume, for instance, that novices could benefit from accessing in-depth explanations of concepts by clicking on nodes. Experts could benefit from a collapsed concept map that only expands as needed or from brief definitions without explanations. For design, this means (i) exploring interactive concept map representations that allow users to control the visual representation of the concept map and (ii) recommending different designs when the computer system is aware of user characteristics, such as background or knowledge (called user model, cp. e.g., Fischer, 2001). In this regard, future research efforts on predefined concept maps as an intervention for knowledge construction could connect to existing research on the use of artificial intelligence in education and adaptive systems for learning (cp. e.g., Alevn et al., 2016 for a general overview of adaptation strategies to support learning, and D'Mello and Graesser (2013) for a specific intelligent tutoring intervention that supports reading).

Third, *someone must produce a predefined concept map*. This is a practical limitation of the tested intervention, though not an insurmountable one: for example, academic journals already ask authors to provide a summary and bulleted lists of the main findings of scientific articles—they could also ask authors to provide content for supplementary concept maps. Also, other stakeholders, such as academic publishers or open science platforms, could provide concept maps as a service that adds value to scientific content. In parallel with the considerations of whose responsibility it is

to create the predefined concept maps, there are considerations of whether the creation could be (partially) automated. Extant literature (Falke, 2019; Valerio et al., 2012; Zouaq & Nkambou, 2008, 2009) (see also Section 2.3.2 above) gives reason for optimism. However, further research on automated concept maps is needed to optimize the trade-offs between algorithmic qualities, such as efficiency and accuracy on the one hand and support for knowledge construction (levels) on the other hand.

## 6. Conclusion

In conclusion, this work makes two contributions to HCI: (1) This work argues that it is desirable that audiences with different levels of (domain) knowledge can understand scientific texts for a variety of reasons, including interdisciplinary academic discourse, public debate, and policy-making, or business innovation. Design can facilitate the knowledge construction that is necessary to create such understanding. The experiment described in this article evidences that the intervention of showing a gradually built-up predefined concept map supports the fundamental level of individual knowledge construction, i.e., *simple processing*. This implies that this intervention is suitable for making scientific texts—being an essential type of research output—cognitively accessible to a lay audience. While effective, the intervention neither requires a teacher to be present nor readers to engage in a specific learning activity. Additionally, while a high-quality concept map for a scientific text is needed, no complex technology, such as for an intelligent tutoring-based intervention, is required. Therefore, the intervention can be integrated in a technically simple manner into a multitude of digital platforms. (2) We showcase how knowledge construction theory can be used as a theoretical foundation for measuring the learning process in a fine-granular manner by assessing which knowledge construction levels an intervention can support. This measurement of the knowledge construction process could be used when designing for knowledge construction as a complement to existing and widely-used metrics, such as usability, user experience, or performance-based measures, to evaluate design. This contribution is interesting for a wider part of HCI and educational technology research whenever the design goal is to support knowledge construction.

## Ethical approval

This research was conducted following the principles of the Declaration of Helsinki and in compliance with the local legal requirements. This research was conducted in Austria; in Austria, non-clinical studies do not necessarily have to be approved by an ethics committee. At the time the study was conducted, there was no ethics committee at the authors' university. Please note that we have checked the box "ethics approval" during submission to the *International Journal of Human-Computer Interaction*, as otherwise, a submission would not have been technically possible in the online form; this procedure was clarified beforehand with the journal

editor Prof. Constantine Stephanidis. All participants received an information sheet informing them of their rights and the anonymity of the data. All participants gave written informed consent to participate in the study. All participants gave informed consent for anonymized publication. This study was preregistered on the [aspredicted.org](https://aspredicted.org) (Wharton Credibility Lab-University of Pennsylvania, 2015) website under *AsPredicted #98212*.

## Notes

1. All students of the course could reach all points when fulfilling mandatory assignments and the exam. Participation in this study offered students the opportunity to gain additional points. We clearly stated that students who did not participate in the study had no disadvantages in passing the exam.
2. Participants were recruited through a university course in which only students can participate, but not all of them indicated their field of study. Hence the percentages do not add up to 100%.

## Disclosure statement

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