Pondering the reading of visual representations

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English Abstract—We follow a theoretical approach to define the concept of reading visualizations. In the past, researchers often assessed readability based on the cognitive processes at work during an individual's engagement with a visual representation. The commonly used term "reading" in these studies, however, often lacks consistency: sometimes it refers solely to the extraction of textual information, while in other instances it is limited to the interpretation of visual signals such as patterns, color gradients, or object sizes. We argue that there exists a gap in the literature for a comprehensive, unifying definition of reading that would potentially broaden the horizons of design spaces and analytical frameworks in our field. To address this issue, we discuss models of reading text and how they can potentially relate to visualization reading.

1 Introduction

Consuming information is an important goal for viewers of visualizations [4]. In order to consume information from a visualization, the viewer has to actively *read* it [5, 8, 11, 13, 19, 27]. How effective this information consumption is, is often assessed through the concept of *readability* of a visualization.

We started the process of developing a validated scale to formally assess perceived readability of visual representations. As a first step, we conducted a systematic review of the questionnaire items previously used by researchers to assess perceived readability of visual designs. The examination of these items showed a wide variety of terms related to concepts such as *clutter*, *assessability*, *complexity*, *effectiveness*, *visibility*, *speed*, *recognizability*, *confidence*, or *overview*. Participants of prior studies also commented on readability using further related terms such as *visual organization*, *comprehension*, *meaningfulness*, *distraction*, *legibility*, or *obviousness*.

Unfortunately, the concept of "reading a visualization" has not been formally defined in the literature, making it difficult to determine which terms may actually measure readability rather than another related concept. The one model perhaps most related to our work is van Wijk's [30] model of visualization (Fig. 1). The author summarized the key elements of a visualization and its usage. Reading a visualization is a core activity linking the I, P and K components in this model.

To the best of our knowledge no cognitive model of reading visualizations exists but such models are crucial for research [16, 23]. By summarizing cognitive processing theories, they help broaden our understanding of the solution space and can serve as effective scaffolding for design. Here we discuss our ongoing efforts to better understand the concept of reading visualizations.

2 Related Work

Cognitive psychologists categorize reading as one of the most complex tasks that humans undertake [9]. As such, it has been a long term topic of interest for researchers. In this section, we describe common definitions and cognitive models of reading.

2.1 Definitions of reading text

Reading has been defined as the process of extracting information from printed words [14, 17]. Rayner et al. [28] provide a more detailed definition: *"reading is the ability to extract visual information from the page and comprehend the meaning of the text."* Neuroscientists, such as Fischer-Baum et al. [10] further refined the description: *"reading allows our brains to transform patterns of retinal stimulation into abstract representations of words (i. e., meanings and pronunciations)"* [10].

These definitions use terms specific to written language (e. g., *text* or *words*), which make them difficult to apply directly to visualizations. While it is easy to infer how data visualizations can produce *"patterns of retinal stimulation"* for the viewer, the idea of *"pronouncing"* visual data is not as straightforward.

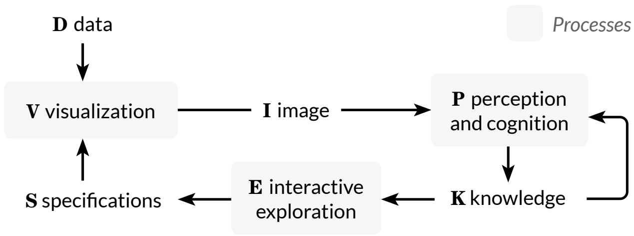

Fig. 1. A simple model of visualization from van Wijk [30].

2.2 Models of reading text

Cognitive psychologists identified two components in reading [15, 21]: **word decoding** and **linguistic comprehension**. Before discussing how to transfer the concept of reading to visualizations, we examine models of text reading to better grasp the cognitive processes at work for each component.

2.2.1 Word decoding

Fig. 2 gives an overview of the Dual-Route Cascaded (DRC) model, which focuses on word decoding in read-aloud tasks [7]. While visualizations are rarely read out loud, the model can help us identify the cognitive processes at work to recover bits of meaning from visually encoded data (A to E).

The first steps involve pre-attentive processing to extract graphemes (e. g., letters, or other graphical units for non alphabetical languages such as Chinese). Then, a specific type of component called *lexicon* allows readers to recognize shapes, sounds and meanings of words. The lexicon is a part of human long-term memory; it is theorized to store words in the form of a dictionary with multiple entry indexes [18]: words can be accessed from sounds F, letters D, or meanings E.

We can observe that there are two-way connections between each step of the process from grapheme detection C to

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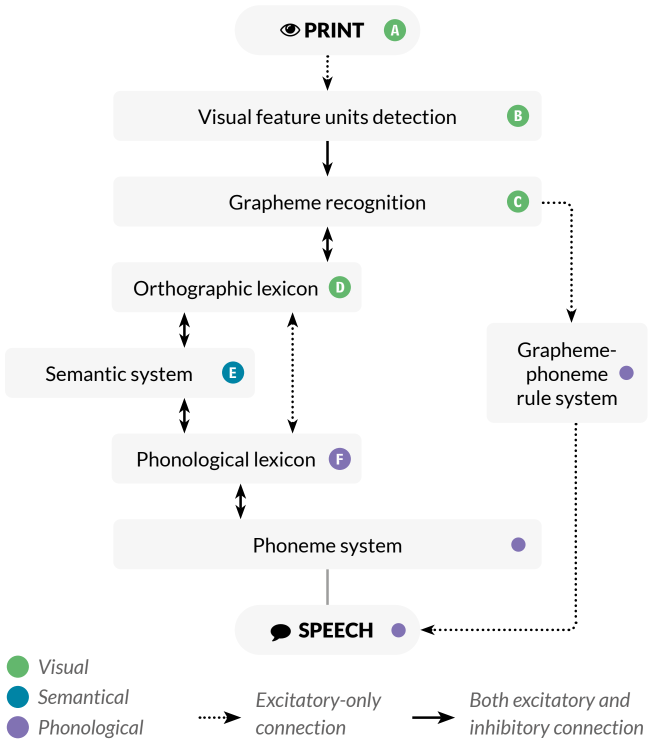

Fig. 2. The dual-route cascaded model of visual word recognition and reading aloud from Coltheart et al. [7].

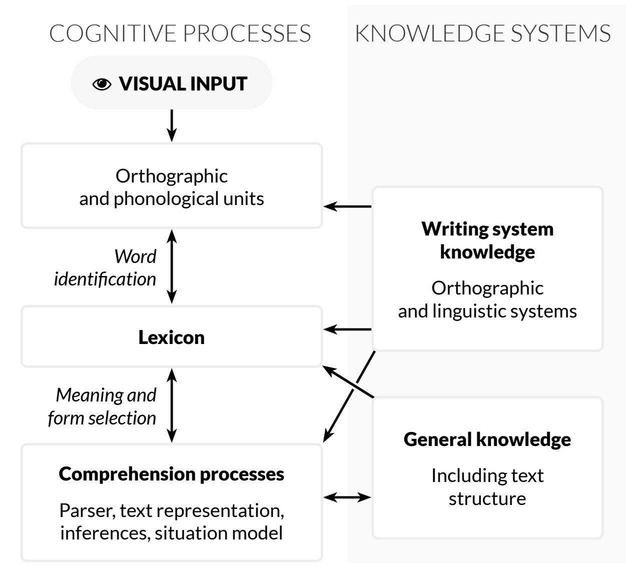

Fig. 3. The Reading Systems Framework [24].

semantics E. For example, the orthographic lexicon D influences the recognition of graphemes C and vice-versa. This model also shows how meaning is reached through parallel processing of shapes (D→E) and sounds (D→F→E).

We have no such model for visualization and we do not yet know which components of the DRC model may transfer. For example, it would be interesting to find out if sounds for words play a role at all for reading visualizations.

2.2.2 *Text comprehension*

The second component of reading is linguistic comprehension, which proceeds from word decoding and heavily relies on the interaction of top-down (knowledge-driven) and bottom-up (word-based) reading processes. Perfetti and Satura [24] proposed the Reading Systems Framework (RSF) as a global framework for text comprehension. Fig. 3 illustrates how this model emphasizes the role of the lexicon as a hub between word recognition and comprehension processes, and brings to light recurring inputs from knowledge systems (e. g., linguistic and orthographic systems, general and contextual knowledge).

3 Discussion

Cognitive models of reading, based on an extended corpus of research in psychology, offer valuable insights to our research question. However, these models often specifically rely on text elements, and thus would not transfer easily to a visualization context. An added difficulty is the need to consider at least two other components for a cognitive model of visualization: *spatial processing* and *numerical processing*. Existing studies suggest that spatial processing can support numerical representations [20] and visual interpretation [22, 29], and that viewers' numeracy (i. e., their ability to understand and work with numbers) and ability to read graphs have shared cognitive skills dependencies [12]. Further work should seek to examine the cognitive effects of spatial and numerical processes to find out if, and how, they interact with a viewer's ability to understand a visualization.

Another obstacle in applying text reading models to a visualization context is that visual representations of data do not, in principle, translate to sounds the same way as words do—or even at all. Some visualizations present a large amount of text (e. g., word clouds, some networks, . . .) and activate the phonological processes of the Dual-Route Cascade (DRC) model, but some other visualizations may not even display a single word. To the best of our knowledge, the possible activation and role of phonological cognitive processes have not been investigated for silent, wordless data visualizations. Since there is some evidence of phonological processes at work in mental manipulation of numbers [25], we suggest that further research should focus on this particular question.

Conversely, some components of the discussed models (e. g., *visual input*, *lexicon* and *knowledge systems*) could be directly transferred to a model of reading visualizations. Fig. 4 shows our first attempt to collect the possible cognitive processes at work in retrieving information from a visualization.

First, we can associate the *image* (I) component of van Wijk's model of visualization ([30], Fig. 1) with the *visual input* of the Reading Systems Framework (RSF), or *print* in the DRC model. Then, based on the central role of the mental lexicon in both models and on existing research on visualization literacy [3, 6, 26], we can also postulate the existence of a "visual lexicon" with semantics dedicated to graphical elements (e. g., orthogonal lines representing data axis in a plot).

Furthermore, both models show two-way connections between their components. Such loops are observed at low levels (e. g., word decoding sub-processes from DRC), and higher levels (e. g., comprehension processes from RSF). These interactions allow readers to integrate sensory input into meaningful representations of the content, which in return informs ongoing decoding processes. We propose that the same may be true for reading visualizations. For example, the recognition of a word could have an influence on the identification of visual features (e. g., identifying a dot on a map

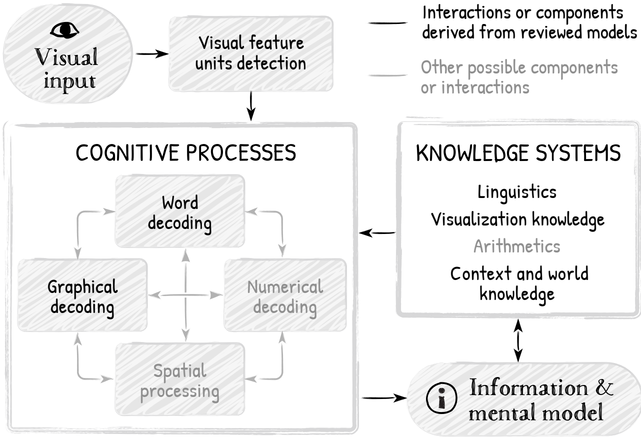

Fig. 4. Draft: Simple cognitive model of reading visualizations.

as the location of a city) and vice-versa (e. g., a quantitative y-axis labeled "capital " is understood to mean "financial assets" rather than the "administrative centre of a country").

Finally, the recurring interactions between cognitive processes and knowledge systems, a feature of the RSF model, are also highlighted in number processing [2] and visualization processing [6]. Consequently, we propose that a cognitive model of reading visualizations should show interactions between cognitive processes and the following knowledge systems: language, numbers, visualization, world and context.

Considering the aforementioned elements, we propose to define reading visualizations as *the cognitive process of converting visual encodings into information*. In this context, we use Ackoff's definition of information [1]: *data which is usable for a task*.

4 Conclusion

We propose a definition of reading in the field of visualization. We show a first attempt at collecting bottom-up and top-down cognitives processes at work in reading visualizations, and suggest that the concurrent semantic decoding of all types of visual content is deeply interlinked. Further research should aim to extend this theoretical grounding by reviewing more related work and studies of visualization perception, spatial reasoning and number processing.

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