Translating Scientific Content into Accessible Formats with Visually Impaired Learners: Recommendations and a Decision Aid Based on Haptic Rules of Perception

by

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Abstract

Students with visual impairments (VI) miss out on science because of inaccessible visual graphics (such as pictures and diagrams) of the phenomena that are the focus of curricula. My project examines how efforts to translate these into non-visual representations, such as raised line graphics, tend to be less effective than expected because they are perceived using "rules" of haptic perception by VI learners but developed using "rules"' of visual perception by sighted designers. In response, I introduce my recommendations, in the form of a decision aid, informed by a series of interlinked concatenated studies consisting of user testing, workshops, and co-design sessions composed of multi-disciplinary teams that included VI educators, learners, inclusive designers, musicians, and domain experts from engineering and the cognitive neuroscience.

Keywords: visually impaired, early blind, STEM education, accessibility guidelines, cross-sensory design, inclusive design, perception, visual impairment, special education, digital assistive technology.

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Chapter 1: Introduction

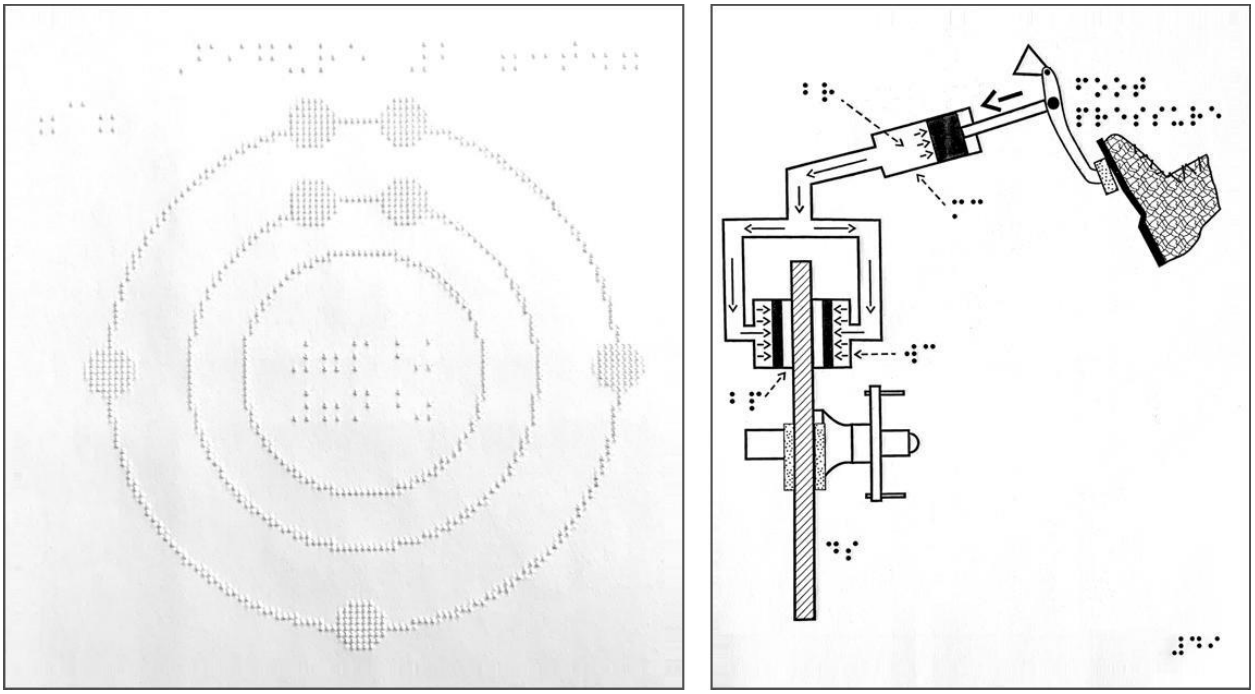
1.1 Background of Problem

1.1.1 A Deeper Problem Underlying the Design of Policies and Resources for Inclusive STEM education

Human rights-based accessibility legislation in many societies requires educational institutions to provide equal access to education content (Ontario Human Rights Commission, Government of Ontario, 2018; Quality education for all, 2018). This includes access to science, technology, engineering, and mathematics (STEM) content, for students with visual impairments. Existing guidelines, such as the Web Content Accessibility Guidelines (WCAG), provide a roadmap for the comprehensive design of content delivered face-to-face as well as online. Web Content Accessibility Guidelines (WCAG) require that digital information and user interface components are *perceivable*, i.e., "presentable to users in ways they can perceive." While WCAG does not distinguish between less and more effective non-visual representations, they do indicate that text alternatives will function to "*at least* provide a descriptive identification of non-text content" (e.g., Guidelines 1.1.1 Non-text Content, Understanding WCAG 2.1, 2019). They also recommend that "instructions provided for understanding and operating content do not rely solely on sensory characteristics...such as shape, size, visual, orientation, or sound" (e.g., Guidelines 1.3.3 Non-text Content, Understanding WCAG 2.1, 2019). Except for sound, the aforementioned characteristics, when presented digitally, would not be available to sensory modalities other than vision. For non-digital resources, braille explanations are used in place of text and images. Raised line graphic pictures and other resources that aim to preserve the spatial properties of visually depicted objects, are much more rare. For example, a non-profit organization, the Equitable Library Access Center (CELA) provides library materials in a format accessible to 2.7 million people, 90% of Canada's visually impaired (VI), through a national library network. In response to legislated requirements, most Canadian educational institutions, including the Alternative Education Resources for Ontario (AERO) at W. Ross Macdonald School and the Accessible Resource Center British Columbia (ARC-BC), have large amounts of braille explanations and produce professionally-produced textbooks with raised line graphics (Ontario Human Rights Commission, Government of Ontario, 2018; Snow Inclusive Learning & Education, n.d.; see Figure 1). Optical magnifiers, such as stand, electronic, and screen zoom magnifiers are types of assistive technologies that can enlarge and amplify visual graphics for low vision and partially sighted learners but are not sufficient for learners who are completely blind. In addition to these strategies, institutions provide support from experts and volunteers. However, even with legislated pressure to provide access for the totally blind, low vision and non VI learners, people with visual impairments continue to be underrepresented in STEM careers and subjects (Basham & Marino, 2013). Many attribute this under-representation to disadvantages fostered due to current educational policies (Frost et al., 2015) and to how educational institutions lack the design and technical personnel to implement solutions (Priscila , 2017).

Figure 1

Tactile Diagrams and Graphical Supplements



Note. Tactile diagrams and graphic supplements are created using Picture in a Flash (PIAF (Pictures in a Flash) |Piaf Tactile by Harpo., n.d.), which expands the image by the ink in the capsule or inflated paper reacting to heat The. Printing graphic image lines through a braille printer is considered a quick and easy way.

In this paper I suggest that the under-representation of visually impaired (VI) learners in STEM fields is rooted in sighted designers' heavy reliance on visual rather than haptic rules of perception. If unredressed, this could impede rather than foster access to science education even in the face of technological innovation, policy reform, and increased non-visual resources.

A mindset of a sighted designer may involve biased assumptions about how the sighted and the visually impaired see and interpret external representations such as visual and tactile pictures. Kennedy (1993, 1997) suggests that raised line graphics that utilize lines to represent edges can be effective and this technique is commonly used in the production of raised line graphics. Other researchers show evidence that VI learners understand the point of view of the depicted object (Heller, 2002), but this includes the condition of touching the experimental object in advance, so the same result may not be achieved in other experiments. A T-junction-like form defined as "a road junction in which one road joins another at right angles but does not cross it" (T-Junction., n.d.) is expressed through raised line graphics and reliefs. However, this expression may not be understood by visually impaired people.

In line with this argument, the research I present here suggests that an early blind user may misunderstand a perspective picture of an umbrella in which parts of the umbrella that are farther from an observer are depicted as smaller in size (more foreshortened) than parts closer to the observer. An early blind user may also find it less than intuitive that lines representing rings of Saturn continue behind the depicted planet. Lines breaking and meeting other lines at T-junctions may indicate occlusion to someone who is sighted, but not to someone who is early blind. This study is composed of a concatenated series of interlinked studies with expert science educators of VI, researchers and developers, and visually impaired science learners, and co-design with combinations of all of these. The following were the main findings:

- People with visual impairments tend to experience comprehension difficulties with raised line graphics that use perspective (which includes vanishing point and foreshortening) and occlusion (in which some depicted objects are obscured by others) and in the absence of light perception, they are unable to perceive luminance and colour.

  - 3D models tend to be more effective relative to raised line graphics for conveying spatial or topological information because depicted regions are treated in tactile or haptic recognition as copies of the topology of the represented objects.

- During haptic perception of surfaces in the physical world , changes in texture appear to correspond to changes in material. For example, a symbolic use of texture to suggest differences in color or luminance would not be readily understood by a person with total blindness. This in turn could slow down the recognition of what is being depicted or lead to comprehension difficulties.

- Comprehension decreases when the number of elements or “chunks of information”--increases due to users’ limited working memory capacity (Luck & Vogel, 1997; Vogel et al., 2001; Miller, 1956; Cowan, 2001). Abuse of texture to represent changes in luminance can add to the perceptual load of a visually impaired learner, further hindering comprehension.

- Comprehension decreases when the size of the object on the picture surface decreases and some elements become indistinguishable by touch (while still being distinguishable by vision). Thus, when depicting cell division it might be helpful to increase the size of the images for the sequences that contain more details.

- Voice information labels, created with devices such as Pen Friends (RNIB PenFriend III voice labeling system, n.d.), are sometimes preferred over braille labels because they can convey information about 2D or 3D representations without tactilely obscuring the content. However, the spatial distribution of the labels is not immediately clear. Therefore, guidance or explanation of approximate locations of labeled features may be necessary. However, the basic information must be clearly conveyed in braille. A speech recognition label may be preferred for longer text descriptions.

1.1.2 Lack of Comprehensive Design Guidelines Considering Cognitive Abilities of Visually Impaired Learners

There is a lack of empirically validated guidelines for the inclusive design of pictures and diagrams for students with visual impairments. This seems to render some of the existing resources ineffective and less likely to be used by educators and students, ultimately reducing the demand for similar resources. The diagrams and graphic line supplements provided by the resource team of the W. Ross Macdonald School for the blind (WRMS), for example, have reportedly little practical use in class. Instead, science teachers have been creating their own science materials. One advantage of this approach is that the teachers can use student feedback and performance to adjust the design of resources to student needs, often in real time. This approach, however, also has several disadvantages. In addition to the associated costs such as extra time and effort, the sighted educators may struggle with identifying what is exactly needed for their VI students. An example of a sighted educator's approach to design was given by Dr. Mahadeo Sukhai, a co-author of *Creating a Culture of Accessibility in the Sciences,* at a talk given to students enrolled in a graduate-level inclusive design course at OCAD University (August, 2019). He shared an account of a sighted teacher who attempted to make selected content accessible to her grade 11 totally blind biology student. The student could not participate in a frog dissection. The teacher 3D-printed parts of a frog and had the student assemble the pieces. Dr. Sukhai commented that the teacher would get an A for effort, but E for execution because “She got it wrong: the act of doing a dissection is very different from an act of assembling a plastic puzzle of that model.” One of the interesting findings in my project, for example, is that materials used as part of 3D models can be misunderstood as resembling the material of the represented objects. The metaphor of material may be intuitively understood by a sighted learner, but not by a VI student. Based on these preliminary findings, educators and designers are cautioned about their use of materials. A symbolic use of different materials and texture may require a text description or explanation.

Ideally the inclusive design of STEM resources should enable all users, including VI learners, to achieve the same learning outcomes. While this project does not anticipate all possible learning outcomes and all opportunities for error, it provides a novel, empirically driven and much needed (as cited in Topaloğlu & Topaloğlu, 2009) of resources. The guide (i.e., decision aid) is based on the findings reported in this paper as well as past research on non-visual and cross-sensory perception as studied in Design, Psychology, and related fields.

The decision aid aims to facilitate valid, reliable, and efficient decision making for instructors and developers who produce STEM educational materials for VI students. Ultimately, the goal is to reduce the learning gap for VI students by not only increasing access to images and data but also designing STEM resources with non-visual rules of perception in mind.

1.2 Research Questions and Objectives

What are the rules of non-visual / haptic perception? In what ways are these rules distinct from the rules of visual perception? How can the answers to the above questions inform more effective and feasible designs for the visually impaired?

The purpose of this study is to better understand the perceptual-cognitive processes of the visually impaired and to develop effective guidelines for the presentation of scientific data for completely blind and low vision learners, which can ultimately improve their accessibility and autonomy.

1.3 Target Users and Participants

While the stimuli used in user tests included Ontario's 8th, 9th and 10th grade textbooks, the insights gathered in all reported studies are expected to be useful for STEM learners more broadly, including, but not limited to, middle and high school students with any visual impairments.

1.4 Approach and Method

This study is largely exploratory and inductive in nature. It starts with semi-structured interviews, workshops, and user tests, and culminates in the proposal of a decision tree based on past theoretical and ongoing empirical work on the inclusive design of STEM resources for people with visual impairments. Quantitative data analyses are embedded in qualitative studies in line with a mixed “concurrent nested designs” approach (Mixed methods research, n.d.). This design is useful for gaining a broader perspective on the topic” (Hanson et al., 2005, p. 229). Further, our inductive approach provides a more intimate understanding of the challenges of STEM learners with lived experiences of visual impairment, which could be overlooked by controlled experimental studies. Note that the work presented here is the first crucial step of the ongoing research in our lab, which over time will incorporate both exploratory and experimental approaches.

1.5 Significance of the Research

In philosophy, “Eudaimonia means achieving the best conditions possible for a human being, in every sense–not only happiness, but also virtue, morality, and a meaningful life” (Philosophy, 2018). From the Eudaimonia point of view, which is considered “objective, comprehensive and morally valid” (Annas, 2004; Waterman, 2007b; as cited in Waterman, 2008, p. 219), inclusive developers can use their knowledge to continually observe and benefit from the interests of groups. Efforts should be made to find a better solution (p. 245). In addition, social participation activities that try to include socially marginalized people in basic human matters make designers' lives valuable. This study specifically started with support for equal learning rights of learners with visual impairments.

McCarthy (as cited in Sahin & Yorek, 2009) claims that although many students with visual impairments have similar learning abilities as their peers, their support environment is poor and their ability to improve is limited. Students with visual impairments can have equal educational opportunities through learning materials written according to the rules of visual perception, so they can understand the concept of abstract science phenomena and build a worldview. In addition, effective image and data transformation guidelines enable governments to fulfill their obligations to provide fair educational opportunities for students with visual impairments. The availability of these guidelines has a positive impact on learning independence and autonomy for students with visual impairments, and learning is expected to alleviate psychological, economic, and social problems. In the long run, this will encourage governments to develop educational policies that take into account the needs of the visually impaired.

As argued by Ursula Franklin, these discussions can nourish the soil of change (*Remembering the Brilliance of Ursula Franklin: The Real World of Technology*, 2016), helping a comprehensive idea develop an environment for people in socially marginalized locations.

1.6 Scope and Limitations of Project

The "concurrent nested designs" used in this study is a qualitative study in which quantitative studies are nested. In the absence of sufficient theories for VI learners, it is used for inductive research to discover and generalize learning patterns of VI people through observation. However, the limitation of qualitative research is that it takes a lot of time for various prototypes to be produced and tested until the researcher discovers a repetitive pattern to some extent. Quantitative conversion of qualitative data and showing objective results is not an easy task, and it has the disadvantage that researchers' bias is easy to intervene. Another limitation is that the process of recruiting students with visual impairments and obtaining parental consent is not an easy task, so students are encouraged to do so, and there must be direct or indirect benefits to receive. In this study, user studies were conducted with adult participants instead of VI students due to various factors, such as the busy situation of the WRMS and the large-scale strikes of teachers due to the government budget cuts. In order to generalize more objective research, a larger sample size is needed, and it is necessary to test the effectiveness of the proposed "decision aid" with actual teachers or developers.

1.7 Expected Outcomes

The purpose of this research study in terms of expected outcomes is twofold:

First, it is to identify and distinguish between haptic and visual “rules” of perception through the analysis of various scientific learning models produced by the sighted teachers and developers for VI learners.

Second, it is to propose a decision-making tool (i.e., decision aid) to help teachers, learners, and developers of educational resources to select effective and feasible designs from a set of options for non-visual communication and understanding of scientific content. The decision aid is assessed through joint design and interviews with students and staff in collaboration with W. Ross Macdonald School for the Blind (WRMS), CNIB, and Perceptual Artifacts Lab (PAL) teams. One of its functions is to bridge the gap between research on non-visual picture recognition and comprehensive design of pictures, diagrams and other representations.

The ultimate goal is to close the gap between research on non-visual picture perception and the inclusive design of pictures, diagrams, and other content.

1.8 Brief Overview of Chapters

Science curricula seem to be dominated by visual graphics, with realistic pictures (from now on referred to as just *pictures*) being the most prevalent (Chapter 2.3.1). Students with visual impairments access translations of these graphics via raised line graphics in braille versions of science textbooks, according to expert science educators of a flagship middle school for the visually impaired who I interviewed. These educators described various types of comprehension difficulties experienced by their students when using these raised line graphics. In response to these observed difficulties, they developed do-it-yourself (DIY) alternatives that included 3D models of difficult-to-comprehend raised line graphics (Chapter 2.4). A strength of these insights thus far is that they are derived from an extensive expertise of educators who worked with large numbers of VI science learners over a number of years.

Having developed a provisional understanding that reflects perspectives of sighted educators who work directly with VI science learners, I next turn my attention to strategies for translating science graphics developed by VI educators for VI science learners they teach (Chapter 3).

A blind informal science educator invited to a workshop organized by PAL employs custom-designed bass relief carvings of scientific imagery. These are of particular interest because of their potential to reflect strategies deemed to be effective by members of the target audience that might have been overlooked by sighted educators, researchers, and developers.

Three VI science learners also attended the workshop and, together, we explored the increased effectiveness of the bass relief carving, but a small number of difficulties (Chapter 3.1).

At this point, I shift from pure induction to co-design in Chapter 3.2, bringing together visually impaired and sighted participants in a co-design workshop to develop a representation of anatomical structures (i.e., brain's visual system), reinforcing what had been suggested in prior phases of the investigation: VI participants produced full 3D models of the anatomical structures in question, whereas sighted participants produced raised line graphic translations, suggesting the possibility that 3D models might be preferred by VI learners relative to raised line graphics.

To delve more deeply into this possibility, in Chapter 4 I review the results of the user studies that suggest how raised line graphic translations of visual imagery were deemed to be equally difficult to comprehend, even though they were of different levels of complexity. A 3D version of the items represented via the raised line graphic was deemed to be easy to comprehend. Strikingly, even with more knowledge of the item represented via the raised line graphic (provided by exploring the 3D version) the raised line graphic was not deemed to be easier to comprehend.

Chapter 4.5 reviews the results of our explanation for what was revealed over the course of these studies: sighted developers follow rules of visual perception to design 3D raised line graphics whereas learners with visual impairments follow rules of haptic perception; 3D models are more effective relative to raised line graphics because they align with the rules of haptic perception.

Chapter 5 selects the findings of Chapter 4 related to the non-visual model translation proposal, and categorizes things to be considered when VI people perceive images and data based on other scholars' theories and user tests. Perspectives that act as pain points at all levels of complexity, especially for VI people, can be converted to a plan view or elevation view in advance. Next, the applicable criteria (picture, diagram, graph and table) for each type of scientific visual data can be applied. The concrete concept and the abstract concept apply different working memory limits to distinguish the complexity that VI learners can feel. It measures the importance of a tactile spatial relationship and whether it is a concrete concept that is considered abstract only for the visually impaired due to special circumstances. It is suggested that other types of information be presented separately. It helps developers and teachers who produce STEM materials for VI learners to create solutions that are supported by clear theories and evidence using appropriate model types for each resource (text description, raised line drawings, reliefs, 3D models, and the use of technologies, etc.).

Chapter 6 conclusion provides a condensed explanation of the key findings and contributions of the entire study and the models presented as solutions in decision aid. Recommendations for instructors and developers are followed by a discussion of the directions for future research.

Chapter 2: Literature Review and Environmental Scan

2.1 Perceptual-Cognitive Barriers

2.1.1 Perceptual-Cognitive Processes of the Visually Impaired and Sighted

A design of accessible representations of scientific content should ideally build on our knowledge of properties shared by the different perceptual and sensory modes (touch, haptics, vision, audition, etc.). In this section, I highlight these “cross sensory correspondences” as well as the unique aspects of haptic, visual, and auditory perception.

In translating scientific content, it may be useful to distinguish, early on, between the so-called concrete and abstract (i.e., amodal) concepts (Barsalou, 2009; Coppin, 2014; Coppin et al., 2016). For example, a curve of a coastline, depicted in a nautical chart, is an example of a concrete object (Coppin, 2014; Coppin et al., 2016), as it is directly perceivable through sensory modalities such as vision. A curve has attributes such as direction, and it can be depicted using lines.

According to Kennedy (1993), both the slighted and the blind understand that raised lines can stand for edges of surfaces. Like the sighted, users with visual impairments can detect changes in angles or directions of raised lines. Thus both vision and touch process spatial information. So does the sense of hearing or audition. By relying on information such as the differences in amplitude and binaural cues (e.g., the difference in the time of arrival of sound at the left and right ear), listeners can localize sound in a three-dimensional space. This includes the horizontal plane (azimuth), the vertical plane (elevation) and distance (depth) (Wallach, 1940). This information is obviously available to any listener with normal hearing, whether sighted or blind. Biggs, Coughlan and Coppin (2019) used these principles in co-designing and testing binaural maps for the blind. These maps enable visually impaired users to use the binaural maps as the sighted would use corresponding visual maps. The capacity for the perception of sound in depth was leveraged in the sonification of a famous infographic, Napoleon's march (Windeyer & Coppin, 2018)

Changes in direction are the underlying aspect of linear perspective, which is used in navigation and actions such as pointing (Wnuczko & Kennedy, 2014). An iconic use of gestures to convey spatial and topological relations among soccer players and the ball was utilized by a VI soccer spectator and his sign language translator (Sarmiento & Copppin, 2018) Recognition of perspective pictures is a different matter. According to Heller, McCarthy, & Clark (2005), late blind individuals can understand perspective pictures after little experience. However, our ongoing research suggests that the recognition of perspective pictures poses a consistent difficulty, especially to blind subjects with no prior visual experience or a memory of such. Here we anticipate a divergence between vision and haptics. What is perceptible to the sighted may not be perceptible to the blind.

Properties that are imperceptible may be treated abstract. A rainbow is visible, but it is not tangible. Abstractedness can be defined as "a measure of the degree to which a concept picks out entities that one can touch, see, hear or smell (Spreen & Schulz, 1966; Borghi & Cimatti, 2009).

Attributes, qualities, or value judgments such as the concept of "sharpness" (a sharp turn; a "sharp" tongue) are also examples of abstract concepts, because they are amodal. In this instance, the processing of abstract concepts may be less influenced by sensory input and more influenced by top-down factors such as past knowledge and experience. This may lead to large variations across individuals in the understanding of such concepts. To avoid misunderstandings, text descriptions may be more suitable than pictures in conveying abstract concepts (Coppin et al., 2016).

Next, consider the cognitive load. Cognitive load refers to the amount of working memory used to hold information. The more data is maintained in working memory, the slower and more error prone we become in manipulating information. In this paper, I will refer to representations that contain more data to be maintained and manipulated as more "complex." Working memory capacity refers to the amount of information one can hold in immediate awareness for later use. Interestingly, the amount of time one can hold haptic information in one's working memory may not differ much from the duration of visual memories (Lu et al., 1992; Baddeley, 1996; as cited in Harris et al., 2001, p. 8268).

Working memory correspondances for haptic and visual perception of stimuli carry important implications for design. Hypothetically, if it was found that users could hold less information at the given time if the information was acquired through haptics (or vision) then the complexity of haptically explored representations would need to be reduced. The goal would be to optimize the speed and accuracy of information proces.

2.2 Addressing Barriers to Accessing Scientific Content

One challenge to developing techniques for making STEM curricula fully accessible could arise from the lack of clarity regarding what exactly is being lost in translation from images to text. To address this challenge, consider the existing classifications of content and the proportion of images relative to text. Dimopoulos et al. (2003) systematically categorized various types of visual science data on the basis of “type” and “function” (Table 1). The authors also noted that there are 11.1 images per 1000 words in a science textbook or over 500 images according to Ladner et al. (2005).

Table 1

Classification of Visual Images From Dimopoulos et al. (2003)

Variables	Features	Examples
Type	Realistic	Photographs & Diagram
Type	Conventional	Codified visual images: graphs, maps, flow charts, molecular structures, diagrams
Type	Hybrids	Co-exist: Realistic & Conventional
Function	Narrative	Used for an explanation of science or technology or natural process
Function	Classificational	Classification of the relationship or middle class of people, place or object (e.g. hierarchical order)
Function	Analytical	Inter-object relationship and detail description
Function	Metaphorical	Semantic symbols (e.g. cultural symbols)

I argue that it is the loss of critical spatial, topological, or geometric properties of images that render aspects of STEM curricula inaccessible to learners with visual impairments (in line with Coppin, 2014; Coppin et al., 2016). Larkin's and Simon's (1987) distinction between spatial properties of diagrams and sentences can enable us to more technically characterize this challenge. They define a *diagrammatic representation* as a "data structure in which information is indexed by two-dimensional location" (p. 68). In diagrammatic representations, each element is in a spatial, topological or geometric relation with every other item of that structure (Table 2, left). They contrast these to sentential representations, characterized as "data structures in which elements appear in a single sequence" (p. 68). In sentential representations, each item is adjacent to the items before and after it in the sequential list (Table 2, right). The text in the body of a science textbook would align with the sentential definition whereas the visual graphics of Table 1 aligns with the diagrammatic definition. Many are hybrids of the two (Table 2, middle).

Table 2

More Iconic, More Symbolic, and Hybrid Representations in Terms of Three Perceptual Models

Type	More iconic	More symbolic	Hybrid
Seeing	Pictorial graphics	Text	Pictures or diagrams with textual labels, tables
Hearing	Non-linguistic sonification	Text-to-speech	Tables
Touching	Raised line graphics, 3D models, reliefs	Braille	Tables, pictures or diagrams with braille or audio labels

2.3 Visual Graphics of a 9th Grade Science Textbook

2.3.1 Science Curricula Rely on Graphics; Images Dominate

My initial analysis of *Science Perspectives*, a textbook for the Ontario Grade 9 academic science curriculum and found that it contains 595 images (Table 3). Over 100 of these are diagrams, graphs and/or tables. Among these, images account for 78.2%.

Table 3

Classification of Images and Data Science Perspectives 9 Student Book

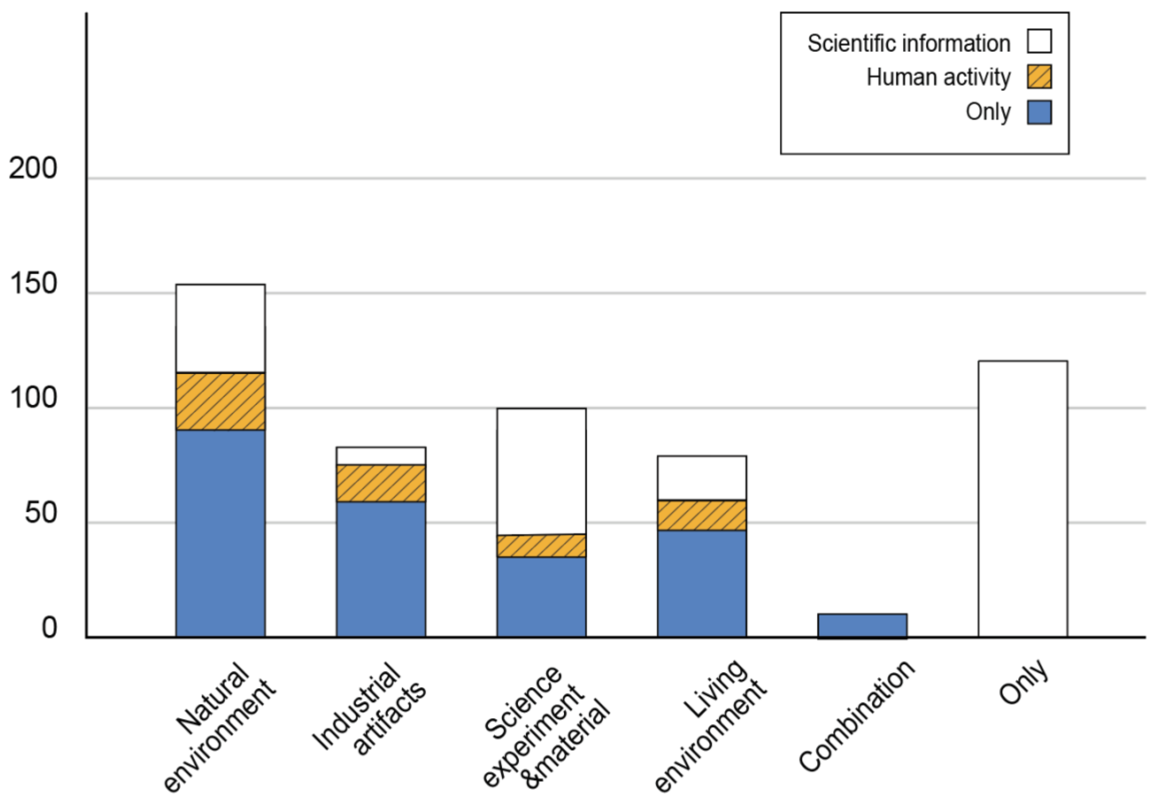
ID#	Content type	Usage count	%
1	Image	462	78
2	Table	74	12
3	Venn diagram	2	0
4	Pie graph	5	1
5	Bar graph	0	0
6	Line graph	5	1
7	Tree diagram	3	1
8	Chemical structure	4	1
9	Electric circuit diagram	26	4
10	1&7 combination	1	0
11	1&9 combination	3	1
N/A	Ambiguous classification	10	4
Total	**All visual materials**	595	100

2.3.2 Reclassification According to Content Relevance and Composition

To examine the significance and content relevance of visual materials, I reclassified the entire set of images and data such as diagrams, graphs and tables into a different taxonomy. First of all, the content relevance was identified using categories of natural environment, industrial artifacts, science experiment & material and living environment. Scientific information consists of a combination of text, arrows, and illustration diagrams, some of which overlap with the images when they are applied to the visual materials. In addition, non-image data is classified as "scientific information" itself, and thumbnail data that do not play a significant role in content are separately classified (Figure 2). Ten of these data were duplicated in two or more items, but no human activity and scientific information was added.

Figure 2

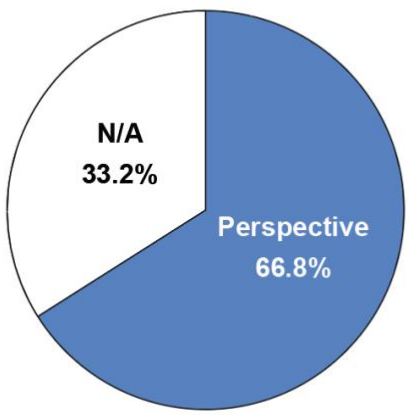
Reclassification According to Content Relevance and Composition



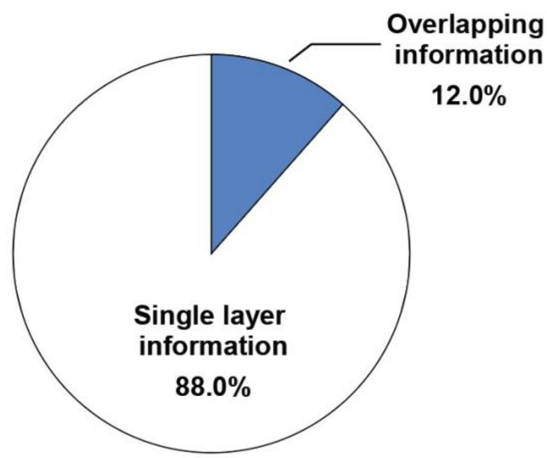
2.3.3 Overlapping Perspectives and Other Information that Prevents Content Delivery

Figure 3

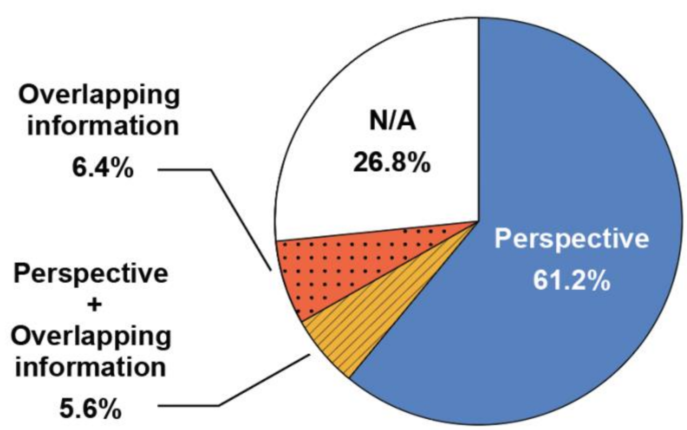
Tertiary Classification Based on Perspective and Information Overlap



***a**. Contents with perspective view*



***b**. Apply overlapping text, arrows, and illustration diagrams*



***c**. Percentage of simultaneous application of perspective view and additional information*

I sought to better understand the problems expressed by experts about student difficulties with raised line graphics. I found visual perspective cues in 66.8% of visual graphics, overlapping text, arrows, and illustration diagrams in 12% (Figure 3b), and both perspective and overlapping information in 5.6% (Figure 3c).

- From this analysis, I identified a need to better understand the effectiveness of raised line graphic translations of perspective pictures in 9th grade science textbooks (Figure 3) through the next phases of the study.

2.4 Experts' Survey and Semi-structured Interview: Haptic Translations of Graphics via Raised Line Graphics

2.4.1 Objective

The main objective of expert interviews and surveys was to understand how teachers design or use existing STEM resources and how effectively students with visual impairments access these.

2.4.2 Participants

I approached two teachers of general science, chemistry and biology subjects in grades 9 and 10 at W. Ross Macdonald School for the blind (WRMS). Classrooms at this school can accommodate up to 10 students, but currently 5-7 students routinely attend classes. At the time of the interview, 5 completely blind and 6 low vision students attended biology class, and 15 low vision students attended chemistry class. The degree of disability among students varies slightly from person to person, and most of the totally blind students were born blind, often due to retinopathy of prematurity (ROP; Lattin, 2019). Not all students are familiar with braille, but students who are congenitally and totally blind are very good at braille. However, students generally prefer to use Jaws or Voice Over when acquiring information using technologies such as cell phones, iPads or computers.

2.4.3 Materials

After a preliminary interview, I emailed a survey document containing 29 questions. The questionnaire consisted of 7 sections: "professional background, about VI students, science related questions, web accessibility, information delivery, learning materials and evaluation method" (Appendix A: Survey Questions for Science Teachers at W. Ross Macdonald School for the Blind).

2.4.4 Methods

I conducted a survey of 29 questions and a semi-structured interview of about 1 hour and 30 minutes with two science teachers at WRMS.

2.4.5 Results

Teachers described their need to develop their own translations of textbook material instead of utilizing the raised line graphic supplements produced by the school's resource team (AERO). For example, although raised line graphics textbooks (that reflect the appropriate STEM topics for the grade level; Figure 1) are custom designed for the school, teachers described how these are still too difficult for students to understand, even with (or perhaps even because of) the book's different textures and legends that aim to "translate" the visual graphics required for STEM concepts to blind and low vision learners. Thus, to meet current needs, and in direct response to difficulties experienced by students who use raised-line graphics textbooks, teachers invest considerable time in creating their own learning materials (that reflect a wider pallet of representational types and affordances; e.g., Figure 4).

Figure 4

Molecular Structures Created by a Science Teacher at WRMS

Note. Braille and embossed line versions (top), magnetic versions (bottom left), and 3D models (bottom right).

DIY Translation Techniques by Teachers. One teacher became proficient at employing Picture in a Flash Tactile Graphic Maker (PIAF) technology (Figure 1) and 3D printers. However, not all teachers were able to develop these prototyping skills. Additionally, teachers employ tactile magnets and 3D molecular models to convey specific biochemistry concepts (e.g. transcription in molecules, Punnett squares, shapes of molecules, and organic chemistry formulas). Representing chemical structures, particularly for organic chemistry curriculum, is especially difficult, as it currently relies on highly visual graphics, they indicated.

I found that, although teachers are driven to provide complete and thorough explanations of content , they lack empirically-validated guidelines to inform the designs of their translations for students. For example, a chemistry teacher predicted that a 3D model of a molecule would be more effective for recognizing the overall shape of the molecular structure relative to a braille or magnetic model. However, completely blind students who could not see the colour (which would have enabled sighted students to distinguish parts of the model) could not accurately distinguish atoms/parts of atoms. The teacher expressed disappointment, but could not find a better way to improve the presentation (Figure 4).

Chapter 3: Workshops

Whereas the prior phases of my project sought to begin developing an understanding of the target problem by learning from experts with extensive experience working with VI learners, I next turned to learning from expert and non-expert VI individuals.

Two workshops, organized in the Perceptual Artifacts Lab at OCAD University, were attended by sighted and VI participants to explore the potential of various types of tactile representations. Workshop 1 was conducted to explore and evaluate wooden relief models of planets and galaxies and to discuss potential improvements based on the participants' feedback. Of particular interest, was the possibility of exploring the perceptual cues of base relief examples that were commissioned by a CNIB staff member who was themselves a member of the VI community they were serving and who had extensive experience with the use of the models for workshops focused on scientific topics. Also, of interest, was an opportunity to better understand how the VI participants understood broken lines and junctions (and intersections) among the lines.

The workshop on prototype building (Workshop 2) was conducted to determine how the sighted and the VI participants would approach the task of creating an accessible representation of the human visual system based on a diagram with descriptions from a biopsychology textbook. As suspected, a VI user attempted to build a 3D model of the visual system, whereas the sighted users first attempted to replicate the diagram via raised lines. Next iterations were more dynamic, with moving wooden rods to show changes in angles-subtended by objects in relation to the retinal image. Participants expected to combine the ideas provided by both VI and sighted users to create an interactive prototype in which the lens adjusts as the object changes the distance to the retina.

3.1 Workshop 1: Haptic Perception of Reliefs

3.1.1 Objectives

The workshop on haptic perception of reliefs by sighted and VI adults offered an opportunity to discuss strategies that may have been overlooked by educators, researchers, and developers involved in the education of the VI.

3.1.2 Participants

Participants included three VI men (including one totally early blind inclusive design graduate student and one late blind undergraduate psychology student) and one VI female. All participants with visual impairments were over 30 years old. The remaining 5 participants were sighted inclusive design researchers.

3.1.3 Materials

Wooden relief translations of pictures of Saturn (Figure 5, upper left), galaxies (Figure 5, upper right), and a black hole were created at the request of the team at CNIB. The braille title stickers for both models are attached to different locations on the model. (Figure 5).

Figure 5

Workshop #2 Wooden Reliefs (top) and A Picture of A Team Exploring The Reliefs (bottom)

Note. Reliefs included a tactile picture of Saturn (top left) and the Milky Way Galaxy (top right), also shown being explored by a visually impaired user (in the bottom image).

3.1.4 Methods

Participants with visual impairments tactilely exploring them to learn about various astronomical phenomena. In the middle of the session, they shared what they had discovered with researchers, and asked questions about what they did not yet understand. After further explanations by the researchers, the participants re-explored the relief models and discovered new aspects. Finally, all participants discussed the pros and cons of the relief model and possible improvements to future iterations of the model (next).

3.1.5 Results

Two out of three people with visual impairments, including one totally blind participant, did not immediately understand that the broken line perpendicular to the curved line of the planet was intended to represent Saturn's rings continuing behind the planet. However, one remarked after a few minutes that this is how an occluded ring would probably be represented to a sighted user: "It looks like this because the ring may not be seen depending on the angle when looking at the sky." The VI expert who commissioned the tactile picture described how it took them weeks to gain the same insight. Another error became apparent when the early and totally blind user perceived that the picture showed three rather than two rings. This was presumably due to the misinterpretation of the spaces between the two rings as another ring.

Another participant who was exploring the Galaxy Relief found out through tactile exploration that it was a kind of planet, but could not comprehend the meaning intended by the sharply sculpted and protruding parts (which stood for bright, shiny, high luminance features). After the CNIB participant explained that it was a brightly lit part, he again focused on the embossed part and replied, "Since the brightly shining parts appear spiral, I think the entire galaxy is the spiral shape." Researchers agreed that a non VI group could easily find the spiral in relief through vision, but it was difficult for VI people to find this through tactile sense.

Reliefs have the advantage of being produced with less time and cost than 3D models, but researchers concluded that this is more dimensional than a raised line graphic that is flat, but has limitations in delivering a complete spatial form like a 3D model. The incomplete stereoscopic effect did not completely convey the exact form the educator was trying to convey to the VI participants. In addition, the braille title on the border of the wood board side was the only information that could be conveyed in braille. Since it is difficult to add labels inside the reliefs, this model exposes the limitations of this format.

3.2 Workshop 2: Co-Designing Prototype Translations

At this phase, I had gained an initial understanding of the target problem from expert teachers of the VI, finding, among other things, that many of their raised line graphic translations of STEM textbook imagery are difficult for the VI students to understand. This often requires teachers to develop their own DIY materials that draw upon a wider “sensory palette” of design possibilities, such as 3D models (Chapter 2).

Thus, these insights from Chapter 2 introduced an emerging question (EQ):

- EQ 1. What is the effectiveness of 3D models relative to raised line graphics for the different types of visual graphic translations identified in Experts' Survey and Semi-structured Interview section? (Chapter2.4).

From there, to gain a better understanding of the types of STEM visual graphics that experts are translating from, I analyzed a standard STEM textbook for the target age group, finding, among other things, that,

- Over half of the visual graphics translations were of perspective pictures and
- Many other visual graphics contain overlapping features such as text, arrows, and imagery that might not effectively survive a translation process to raised line graphics (Chapter 2.3).

This finding raised two more emergent question at this phase in my project:

- EQ 2. Is there a relationship between perspective in pictures and comprehension difficulties when translated to raised line graphics for VI learners (Chapter 4).
- EQ 3. Is there a relationship between overlapping features in graphics and comprehension difficulties (Chapter 4)

The workshop I organized with expert VI educators and learners (Chapter 3) provided a much needed opportunity to learn directly from the VI experts with the most lived experiences with the problem by reviewing heavily used, custom commissioned representations/translations of visual imagery. This experience showed how:

- 3D relief models were commissioned rather than raised line graphic translations of the type that were described by educators as difficult to use previously (Chapter 3).
- However, the 3D relief models still included picture-like properties, such as visual occlusion. Thus, although these were an improvement over the raised line graphics examples I had previously examined, they still engendered some comprehension difficulties for the VI learners and educators.

At this phase, my project was still exploratory, but a co-design prototyping session provided an opportunity, within a semi-open-ended setting of my own design, to explore the emerging questions that had arisen thus far, in addition to any new insights that might not have yet been encountered.

3.2.1 Objective

The objective of the co-design prototyping workshop was to collaboratively explore multi-sensory and cross-sensory approaches to representing STEM content otherwise presented via visual graphics, but in a manner that reflected the preferences, and were informed by the lived experiences of, a diverse group, including VI impaired learners and experts. Participants chose to prototype a non-visual model of the brain's visual system. This was an opportunity to observe the types of designs preferred by visually impaired and sighted vision users, and to interactively discover why.

3.2.2 Participants

Participants included 7 adults, over 18 years old, including one blind female, C. (visitor from CNIB), late blind male, SC, (undergraduate psychology student), one early totally blind male, MS (inclusive design graduate student), and one late blind male, MA. Note that SM and MS participated in both workshops reported in this paper.

3.2.3 Materials

Materials included a biopsychology textbook (Biopsychology 9th Edition, Pinel, J. P., 2013) and various craft materials.

3.2.4 Methods

Participants were asked to show, via their prototypes, and in a manner that reflected their preferences, and that were informed by their lived experiences, one or more aspects of the human visual system. This included: (1) displaying how an object is projection projected as a retinal image through the structure of the human eye, (2) displaying how the lens of the human eye adjusts in response to an object being at various distances from the retina, and (3) the structure of the optic chiasm.

3.2.5 Results

Overview of the first iteration. The VI participant, an undergraduate psychology major, prototyped a 3D model to display the structure and layout of the human optic chiasm (Figure 6, top left). The group of sighted participants, on the other hand, developed a tactile prototype that was somewhere between a raised line graphic and a relief (leaning much more toward the conventions of a raised line graphic). It displayed a plan view of a human visual system, showing: a distal object, a proximal stimulus (retinal image of the distal object) visual fields, an optic nerve, an optic chiasm, and visual cortices (Figure 6, top right). The 3D model of the VI participant emerged at the same pace as the other prototypes, with difficulties arising slightly due to how the components of his model “hung in the air” (given the 3D nature of this design) and therefore required pieces of wood (stilts) to prop up the components. As the VI participant remarked: "I had difficulty in accurately expressing the complex structure".

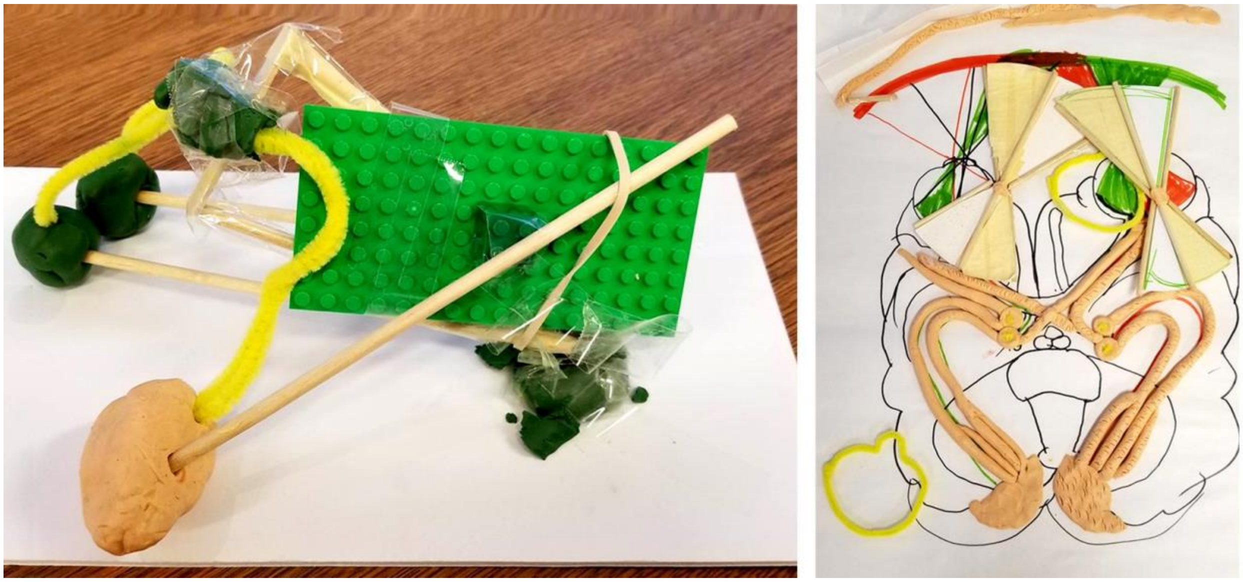
Preliminary Thoughts on Effectiveness. In addition, he did not seem to fully grasp the structural description of the eye as revealed by the model, especially in regards to how the changing distance of the object affects its retinal image. The sighted participants began the task by creating an enlarged copy of a textbook picture, with raised lines. While the task lasted for the entire duration of the workshop (approximately 2 hours), the tactile diagram was relatively easy to complete. A challenging aspect was how to dynamically show that reducing the distance of an object to the observer will increase the size of angles projected onto the retina. One researcher created a contraption consisting of intersecting and moving sticks that increased angles as the object moved closer to the eye (Figure 6 in the lower left).

The resulting prototype employed clay to display selected features of the visual system, including the optic nerves. Although the sighted users agreed that the outcome was impressive visually, VI participants indicated that it was not very effective (relative to a more 3D version, for example). In particular, the use of raised lines made it difficult for the VI participants to quickly identify where the nerves intersect. One VI participant misunderstood that the texture of the clay modeled in the brain would be similar to that of the actual brain. Finally, the VI participants commented that it would have been faster to understand the model if it had been explained as simple information about the entire model before the model was explored.

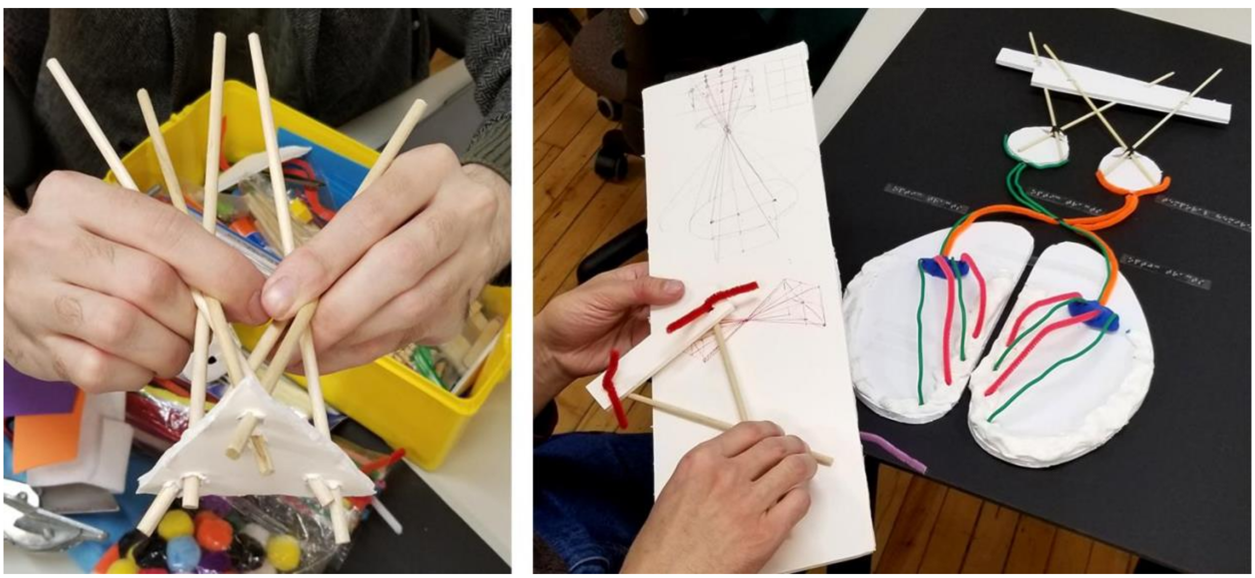
Second iteration. For the next session, we added the wooden stick contraption for showing the relationship between changing angles and retinal images (Figure 6 bottom right). This aspect of the prototype was effective in that the VI participant was able to figure out what was being represented (the concept of light refracting through a lense [with light rays being represented by the dowels] and how the angles between these would change based on the distance of the object from the lense of the eye). Building on the observation that diagrams with flexible parts were effective at conveying the information about changing angles, all participants agreed that it would be worthwhile to explore this further in designing 3D models. A raised line diagram with a wooden contraption only showed changes in horizontal angles (i.e., azimuths). But a 3D contraption could help users appreciate changes in both horizontal and vertical angles, and angles subtended by parts of objects extending in depth relative to the observer (Wnuczko, 2019). Because the second prototype also used materials other than clay to represent optic nerves, the VI participants were finally able to distinguish between the individual optic nerves, and to identify where they cross. In both models, the participant first explored the large outline, then tactilely explored the details inside.

Figure 6

Based on the Understanding of the Eye Structure Model, the First (top) Prototypes Created by the Participants and the Second (bottom) Prototype Based on the Feedbacks Discussed at the First Meeting



a. *An eye structure prototype (left) created based on a understanding of the VI participant and a prototype created by two researchers with non VI (right)*



b. *A second prototype created by a researcher without VI using an interactive 3D model (left) that shows how a lens is adjusted according to its distance from an object. Second eye structure prototype with simple versions of the interactive 3D model (right)*

Chapter 4: User Studies

4.1 Objective

These user studies aimed to discover how non-visual scientific models such as raised line graphics created by sighted developers are understood by VI learners. Based on the presented findings, it can be argued that raised line graphics often fail to provide a satisfactory / meaningful experience for VI STEM learners, because they rely more on visual rather than haptic rules of perception.

4.2 Participants

Three participants participated: one totally early blind man with no memory of visual experience and two VI men who had vision loss as adults.

4.3 Materials

Materials included a raised line drawing kit, 3D models of molecules, and a raised line drawing of cell division. A voice scanner using RNIB's PenFriend 2 Voice Labeling System (RNIB PenFriend III voice labeling system, n.d.) was also used for some models. (Appendix B: Experimental Questions)

Table 4

Intentional Design of Scientific Images and Data Prototypes (✓: Applicable)

Type	Metaphor of material	Complexity of expression	Spatial relationship	Perspective
Eye structure	✓	N/A	✓	✓
Umbrella	✓	✓	N/A	✓
Molecular structure	✓	N/A	✓	N/A
Cell images	N/A	✓	✓	N/A

4.4 Methods

Students under the age of 16 can participate in research with parental consent, whereas adults with visual impairments were not age-restricted. The privacy of participants was respected and they participated in the research within a safe environment. They were informed of their right to refuse to respond or withdraw their participation, and indicated this via a signed consent form. The user studies were recorded via videos, note taking and semi-structured interviews.

4.5 Discussion of Main Findings and Considerations for Inclusive Design

4.5.1 Metaphor of Material: Results Part A / B / C

Under the rules of haptic perception, luminance and colour do not exist and perceived transitions in textures during tactile exploration tend to signify transitions in materials. Under the rules of visual perception, colour and luminance exist and can be represented pictorially through dots and textures (Kosara et al., 2003). However, when these visual rules, and the picture-making practices that accompany them, are converted into raised bumps and lines in haptic displays, the rules of haptic and visual perception interact in a manner that leads to misunderstandings about the nature of a given material. This problem has been observed repeatedly in our research. For them, “bump” is “bump” and “curve” is “curve”. They are faithful to their senses rather than to understand the use of materials as a way of metaphorical expression. This is thought to be because tactile perception of the visually impaired is similar to tactile perception of the visual group, but as Norman & Bartholomew (2011, as cited in Baumgartner et al., 2015) argue the perception of the shape of an object is influenced by the investigator's past visual experience.

Results Part A: Metaphor and Materials of a Representation. In a second workshop to translate the structured image of the eye, I noticed how the VI participant perceives the materials used in the prototype (see Figure 6). Clay was an easy material for participants to use when building low or medium fidelity prototypes, but VI participants considered clay used in the brain model of the second prototype to be similar to the texture of a real brain. This is an example of how a material that a representation (or model) is constructed from can be used metaphorically to refer to other phenomena (the texture of the brain), a direction for future work. In general, I found that these VI participants tended not to accept tactilely experienced materials of representations as metaphors that referred to other materials that were being represented.

On the other hand, I found that metaphorical use of textures failed in raised line graphics. For example, a participant perceived the used texture (which was intended to stand for or a darker region) not as the author intended but as standing for an object (such as a fan blade.

Results Part B. Misconceptions about Colours Used in Materials. Misunderstanding of the materials used as the metaphor of expression was also found in our other tests. After hearing about the different colours and sizes applied to 3D model atoms in a molecular structure test (Figure 10), one of the participants understood that this was the colour of the actual atom. "I definitely considered this because I had never heard the metaphor of the material before," he replied. Colour coding appears to be a necessity for low vision, and the misunderstanding of low vision learners' materials was not tested in this experiment.

Results Part C. Different Textures Are Considered Different Materials. The raised line graphic material of WRMS was intended to convey sections separated by different colors and brightness by applying different textures to the fabric part of the umbrella made of the same texture (Figure 7 right). However, for students with visual impairments, differences in texture were considered material differences, and the legends used by the producers did not help to distinguish them. Because the designer used the texture symbolically, in a way that is implicit to a sighted user but not a blind user, the pattern was a hindrance to the learner's recognition of the object and its parts. Nevertheless, as VI learners use textures as an easy way to differentiate between different parts of an object, developers should consider using textures to clearly communicate their intentions.

In all of the above cases, if the Instructor (Result part A, B & C) provides preliminary information on the application of metaphors of textures, colours, and materials before the student's search for material, the misunderstanding of the students' material understanding can be prevented or reduced.

Figure 7

Umbrella Tactile Picture with Perspective (right) and Two Cross-sections Were Drawn by a Totally Blind Male Without Visual Experience (left) and a Totally Blind Male With Visual Experience (middle)

4.5.2 Complexity of Expression: Results Part A / B

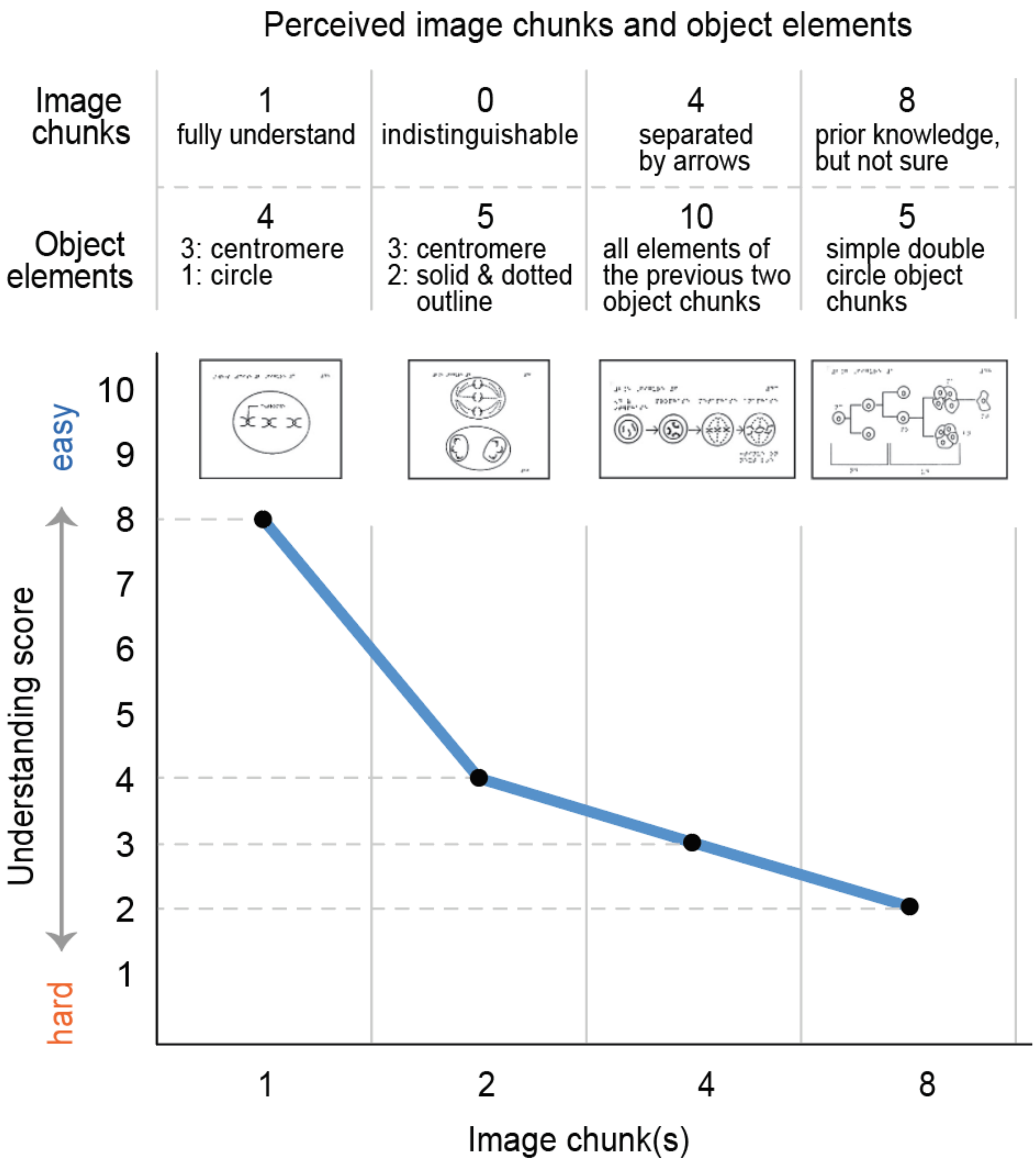
Short-term memory has a limited capacity (e.g., 7 ± 2 classic experiments by Miller, 1956; 4 ± 1 according to Cowan, 2001). On a digit span task, for example, someone with the capacity of 7 ± 2 would not be able to recall more than 5 to 9 digits in a string of numbers. Cowan's estimate is more conservative, because he took into account a potential confound -- the chunking of information. For example, when presented with a string of numbers such as 1648273, one familiar with the Toronto area code of 416, would likely group numbers 1, 6, and 4 together -- this becoming one "chunk" of information. In terms of visual images, Luck and

Vogel (1997) suggest that the capacity is limited to four colors and directions at a time. It is a prediction in this study that as the amount of information (i.e., complexity of a representation) increases, the perceived difficulty of information acquisition will also increase.

In this study, I measured how information acquisition by the visually impaired varies as a function of the number of presented elements such as cell objects with a score of 1~10 with 1 indicating "*very hard to understand"* and 10 is "*completely understandable"* indicating. As predicted, increasing the amount of information presented in the image was accompanied by an overall increase in the perceived difficulty in the recognition of depicted objects (cells) and the elements that comprise them (larger circles standing for outlines of cells; lines inside the circles standing for centromeres and arrows) (Figure 8).

Figure 8

Image Understanding Decreases with the Complexity of the Image



Note. Prior knowledge of the symbolic representations of cells during cell division and separation of elements with arrows are ways of grouping or "chunking" information.

Results Part A. Degradation of Translation Accuracy as Number of Image Elements (Chunks) Increase. In the analysis of the first, leftmost diagram in Figure 8 (see the image of a single cell), a totally early blind subject correctly identified the represented object and the elements inside it. He reported that the difficulty level was “8” on a scale from 1(most difficult) to 10 (least difficult). After exploring the second diagram (circles without arrows), he correctly recognized the details of the two large circles, but did not know that this was a representation of two distinct cells. He reported being confused about the relationship between two circles on a page. He reported the difficulty level of “4” on the same 10-point Liker.

The next diagram showing four circles with arrows was seen as slightly more difficult than the previous one (receiving a score of “3”). Here, the subject focused more on identifying elements within the large circles rather than identifying the circles as distinct objects (cells). He identified the shape of elements inside the first two leftmost cells, but failed to do so for the next two cells with a larger number of lines inside them. After exploring the rightmost diagram, the participant recognized that one cell split into two. However, the cluster of two clusters of four adjoining was not recognized initially. Overall, the difficulty level was reported around “3” and “2” on the 10-point Likert scale with “1” indicating highest difficulty.

Results Part B. Braille, Lines, and Arrows Affect Image Complexity. In one object test, a totally blind subject fully understood all image types and components, but the score did not reach 10 because of the lack of braille description. The braille title only describes the figure number but not image title. However, in a third test, involving exploration of the diagram depicting four cells, the subject did not recognize what it depicted initially, but immediately understood what it depicted once the braille description was added.

Braille, lines, and arrows that are added to describe the image can help learners recognize or organize information, but when overused, they can also increase complexity and delay exploration of stimuli. Participants also noted that voice support would be helpful for explaining detail. Too much braille would clutter the explored content. The arrows shown in the rightmost diagrams in Figure 8, may have further facilitated the recognition of depicted relations. Interestingly, arrows were preferred over lines of a tree diagram used in the rightmost figure. The subject remarked, "I prefer the arrow in the third picture because a simple line is difficult to predict the direction of progress."

4.5.3 Use of Perspective: Visual Experience Aided Perspective Comprehension in Raised Line Graphics / Results Part A / B / C

As noted in Table 3, I classified 76% of the graphics in the STEM textbook as realistic pictures (relative to tables, various types of data graphs, and diagrams). I distinguished realistic pictures from these other types of graphics by their use of occlusion, foreshortening, and colour.

Overall, I found that in almost all cases, the raised line graphics textbook with braille labels produced by the WRMS replicated features of realistic pictures in some tactile form. For example, as shown in Figure 7 (right), the raised line umbrella includes the use of foreshortening to convey depth, texture to convey (what could have been) colour in the original source image under the umbrella, and shadows on the top surface. I found that raised line graphics that employed perspective and/or foreshortening were more difficult to comprehend relative to top or front views of the depicted objects for all of our totally blind and low vision participants, regardless of the complexity of the raised line graphic. There appeared to be a correlation between experience with visuals and comprehension capability, where more experience corresponded to an increased capability to comprehend pictorial cues in raised line graphics. This suggests that perceiving depicted objects in perspective and/or through foreshortening benefits from visual experience that is more familiar to sighted learners relative to blind and low vision learners. Thus, I predict that a representation that relies on (or utilizes) perspective is predicted to be more difficult to comprehend for VI learners relative to representations that do not rely on (or utilize) perspective.

Visual Experience Aided Perspective Comprehension in Raised Line Graphics; Lack of Visual Experience Impedes Perspective Comprehension. My three-part analysis of raised line graphics perspective pictures in comparison to 3D objects with VI participants that follows suggests that visual experience aided perspective comprehension in the raised line graphics that I tested whereas a lack of visual experience impeded perspective comprehension.

A. I first found that our raised line graphics of differing complexities were deemed to be equally difficult to comprehend by our VI participants.

B. Further examination revealed that both of the raised line graphics that I tested were rife with pictorial cues, such as perspective, foreshortening, occlusion, and bumps (that appeared to be attempts to convey colour and luminance), all features that align with the rules of visual perception, introducing the possibility that these pictorial features, and perspective foreshortening, in particular, was contributing to comprehension difficulties experienced with our raised line graphics that I was testing.

C. Semi-structured interviews with our VI participant, M.S., introduced a compelling explanation, that raised line graphics were being perceived using “rules” of haptic perception, but the translations, based on visual pictorial graphics, and most likely produced by sighted specialists, were developed following “rules” of visual perception. Under rules of haptic perception, only features within the range of touch are perceptible, haptically perceived change in texture signifies a change in the material, and haptically perceived change in shape signifies a change in surface structure. “Rules” of visual perception, manifested in raised line graphics, such as converging perspective raised lines, skewed raised-line shape depictions of distal objects, crisscrossing raised lines to depict visual occlusion, and textured raised-line bumps within shapes, do not exist haptically. Therefore, if raised line graphics present tactile marks that are available haptically, but configured according to visual rules, those raised line graphics will be difficult to comprehend. A point by point review of specific features of the representations that I tested helps demonstrate this explanation.

- A textured curve at the top of the raised line graphic umbrella was deemed to be difficult to comprehend by our VI participants. Closer examination revealed how the textured curve appeared to be intended to represent a change in luminance (a shadow) at the top of the umbrella, a cue that aligns with the rules of visual perception. However, shadows and changes in luminance do not exist within the rules of haptic perception. The result was therefore difficult for VI participants to comprehend.

- Raised line closed shapes that resembled petals of a flower, with alternating shapes filled with texture bumps, appeared to be intended to represent the underside of the umbrella, with the texture bumps within alternating petal shapes possibly inspired by changes in bands of colour in an original source pictorial graphic upon which the raised line graphic was based. However, colour does not exist under the rules of haptic perception. Because, under the rules of haptic perception, a transition in texture most likely corresponds to a change in material, M.S. appears to have perceived the interconnected leaves with alternating textures, as the spaces between blades of a fan, not the underside of an umbrella.

- M.S. was provided with a 3D umbrella, which he ranked as easy to comprehend (a score of 9). However, when M.S. was re-introduced to the raised line graphic of the umbrella, he scored it at the same level of comprehension difficulty as before (a score of 1, very difficult to comprehend), suggesting that haptic exploration of the 3D umbrella did not transfer to aid comprehension of the raised line graphic umbrella.

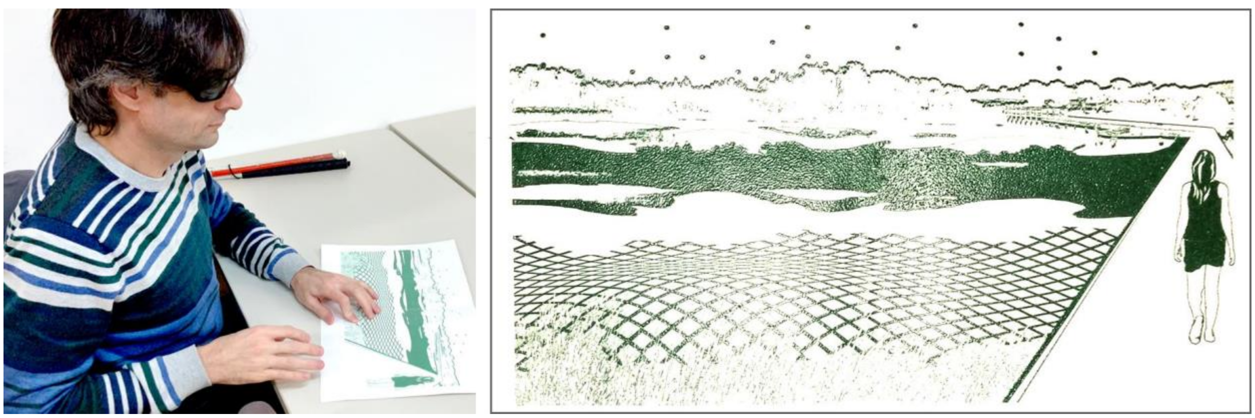
- The session concluded with a more in-depth interactive discussion and guided haptic exploration, where M.S. explored both the 3D umbrella and raised line graphic umbrella, in an attempt to understand relationships between features of the raised line graphic umbrella and the 3D umbrella. This activity concluded with M.S. attempting to draw a copy of the raised line graphic umbrella (Figure 7 left). Only the curved top of the umbrella and the hooked handle of the umbrella were reproduced in his drawing. I observed that the only features of the raised line graphic umbrella that were reproduced were the features that aligned with the rule of haptic perception: The 3D umbrella includes a curved top umbrella surface that aligns with the rules of haptic perception, as does the graspable handle.

Results Part A: Raised Line Graphics of Differing Complexities Were Deemed to Be Equally Difficult to Comprehend. Figure 9 shows a raised line graphic panoramic picture of a river scene, whereas Figure 7 (right) shows a foreshortened raised line perspective picture of an umbrella, viewed at an angle from below, via single-point perspective. Both were assigned scores of 1 by totally blind and low vision participants (1 indicates a representation is deemed to be “the most difficult to comprehend” relative to the other representations tested with them). Note how the participants deemed both representations to be equally difficult.

However, the representations are not equally complex. The complexity ranking is informed by Mario’s (2005) classification table that ranks image complexities via algorithmically generated outlines. One independent object is “a little complex” if no outlines overlap with other object outlines. The river scene is composed of seven or more objects with some overlaps, so it is similar in complexity to the “very complex” images of Mario (2005).

Figure 9

Early VI Participant Testing A Highly Complex A Raised Line Graphic Panoramic Picture of A River Scene



Results Part B: Perspective Increases Comprehension Difficulty in Raised Line Graphics.

M.S. assigned a comprehension score of 9 (easier to comprehend on the 10 point scale) to the 3D umbrella after haptically exploring it. Even more revealingly, when M.S. returned to haptically re-explore the raised line graphic perspective picture of the umbrella, he re-assigned it with a score of 1 (still very difficult to comprehend, Figure 11). This suggests that the knowledge gained via the 3D umbrella did not inform his understanding of the raised line graphic representation of the umbrella.

Results Part C: Raised Line Graphics Were Perceived Using "Rules" of Haptic Perception, Not Visual Perception. The semi-structured interview with M.S that followed his haptic exploration of the 3D umbrella suggests why he described his comprehension of the 3D umbrella as high and his comprehension of the raised line graphic umbrella as low. It also suggests why the only part of the raised line graphic that he could comprehend (and recall) was the curved top of the umbrella and the hooked handle.

Rules of the haptically perceived world versus the visually perceived world. Whereas M.S. never had access to the visually perceived world, he has had access to the haptically perceived world. Haptic perception would not include foreshortening, for example, where distal objects become skewed in perception. Indeed, under the "rules" of haptic perception, distal objects cannot be perceived, only proximal objects that are within the range of physical touch. A haptically perceived bump on the surface of an object means there is likely a bump on the surface of an object. A haptically perceived curve means that a surface is probably curved. A change in texture means there is probably a change in material.

Thus, a plausible explanation for what M.S. experienced with the 3D umbrella model is that it could be understood within a schema that corresponded to MS's everyday experience with haptic perception. The 3D model followed the "rules" of haptic perception (haptically perceived bumps and curves correspond to bumps and curves of an object that the participant is touching). Haptically perceived differences in texture would be perceived differences in material, perhaps. Let me next recruit this explanation to better understand what M.S. reported:

The confusing textured curve at the top of the umbrella. The texture under the curved raised line at the top of the umbrella (that I perceive as stippling or shading through visual perception of the raised line graphic as shown in the figure) was most likely included to replicate (or serve as a translation of) a change in luminance(a shadow), at the top of a pictorially represented umbrella upon which this raised line graphic was based. Under the rules of haptic perception, a change in luminance, or shadow (possibly only as a change in temperature, if sunlight was obscured, for example), would be difficult to perceive, as would a change in colour. Under the rules of haptic perception, where a haptically perceived texture transition most likely corresponds to a transition in material, M.S. would perceive the textured curve at the top of the umbrella, not as a shadowed region, but as a different material.

Perceiving the underside of the umbrella as a fan. The alternating textures under the umbrella (that I perceive as stippling or shading through the visual perception of the raised line graphic shown in the figure) was most likely produced to replicate (or serve as a translation of) a change in colour.

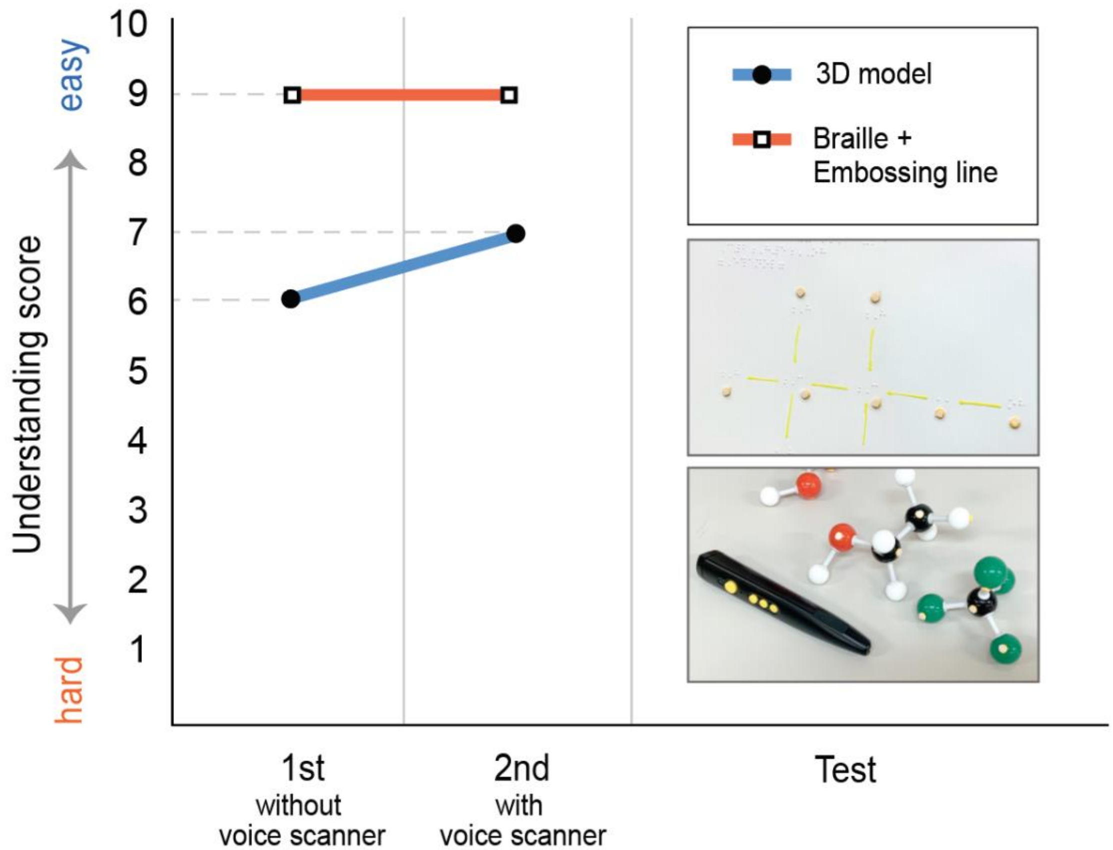
The sketch by M.S. included only the curve at the top of the umbrella and the hooked handle, not other features presented by the raised line graphic of the umbrella. As indicated, M.S. assigned a score that reflected his difficulty comprehending the raised line graphic of the 3D model. During the interview, he indicated that she was able to comprehend only two parts of the umbrella graphic: The curved top of the umbrella and the hooked handle.

4.5.4 Use of Voice Information Technology: Results Part A / B

In an expert interview, a science teacher noted that "there is still a difficulty in conveying the information of the 3D molecular structure to students with visual impairments," so I created the braille molecular structure used in chemistry class in WRMS to identify the problem. Molecular models were selected according to the number of atoms (6 types; HF, H2O, CO2, CH4, CCL4, C2H5OH). Next, diagrams and 3D models of "Braille + embossing" combinations were created, respectively. Later, voice scanner systems were added to both models to assess the usefulness of using the technology.

Figure 10

Changes in Understanding of 2D and 3D Molecular Models Using Speech Recognition Scanner



Results Part A: High Accessibility of Molecular Structures Presented Using Raised Line Graphics with Braille Labels. The molecular structure presented via embossed raised line graphics with braille labels (Figure 10, right) was easily recognized by VI users who could read braille. A 10 point Likert scale with "1" denoting most difficulty understanding and "10" denoting least difficulty in understanding. An early totally blind subject responded with a score of 9 on a 1 (difficult to understand) to 10 (easy to understand) in response to Likert Scale regarding his understanding of the simplest hydrofluoric acid (HF) and the complex C2H5OH (Ethanol). The braille text on molecules was short, making it easy to convey information. I retested by adding Penfriend labels to (replace or augment) the braille labels, but subject's comprehension was the same score (9), and he replied, "How to recognize short information as a scanner is cumbersome and time-consuming." Contrary to expectations, the visually impaired had a high understanding of raised diagrams, including simple information, where the use of technology was not significant. However, this is a result limited to VI people who are good at braille.

Results Part B: Difference in Information Depth Not Measurable by Score. Participants' understanding of the 3D molecular model was initially scored 6, but slightly increased to score 7 when the voice scanner system was applied. What was observed in this experiment was that the initial score was 6, but it was difficult to make an absolute comparison with the score 9 of the 2D drawing. It is an understanding of a given prototype, which may not accurately reflect the understanding of the molecular structure itself. The participant identified the spatial positional relationship between atoms that was not understood in the previous embossing diagram through the angle of the 3D model's plastic lines. This is hard to see in the diagram drawn by embossing, and even though the player's score was 6, he actually understood more facts than the previous experiment. It can be seen that 3D models are more effective in terms of delivering spatial relationships to learners that cannot be expressed in 2D.

Chapter 5: A Decision Aid for Translating Scientific Images and Data

5.1 Introduction

The documented underuse of existing “accessible” scientific images and resources by teachers of VI students, as well as the reported challenges VI users face in the recognition of some non-visual representations, highlight the need for empirically-driven guidelines for inclusive design of STEM learning materials. Such guidelines should aid in a reliable and effective conversion of visual images and data to formats that are ideally as easy to use by VI users as the original ones are used by the sighted. Inspired by past empirical and theoretical work (e.g., notably Coppin’s perceptual-cognitive model of affordances; Coppin, 2014) and insights gathered in the presented research, I propose a set of such preliminary guidelines. These are presented in the form of a decision aid for selecting designs from a set of options. The options include (1) text descriptions, (2) raised-line drawings, (3) relief models, (4) 3D models, and combinations of the above. The decision aid specifies that text descriptions will be superior to tactile pictures when conveying information about abstract (i.e., amodal) concepts (Coppin et al., 2016). Object properties that are imperceptible to touch due to scale (e.g., the shape of an island) will be best represented using pictures or 3D models in addition to text descriptions. Finally, because shapes and sizes take a literal meaning within the framework of haptic rules of perception, tactile pictures showing front or top views of objects or 3D models are preferred alternatives to perspective pictures. I predict that the use of the decision aid will be more effective (i.e., will lead to better learning outcomes) than the standard methods.

5.1.1 Objective

The objective is to provide reliable and efficient decision support to teachers and developers who create STEM training materials for VI students to produce scientifically accessible informational materials that take into account the perceptions of VI learners.

5.1.2 Research Question

How can I leverage key insights regarding the perception and memory of VI learners to develop an optimal decision aid for designing accessible STEM resources?

5.2 Process for Developing the Decision Aid

1. The first step in the process of developing the decision aid consisted of reviewing existing taxonomies for categorizing different types of representations (see Table 3; Figures 2 and 3). Of special interest at this stage was to identify which aspects of the categorized representations (e.g., pictures with perspective and overlapping information) were especially difficult to recognize by the VI users. One of the key

insights at this stage was that perspective views should be removed or replaced with elevation or plan views.

2. Next, the complexity of images and data was assessed, based, in part, by drawing upon the working memory literature (Cowan, 2001; Luck & Vogel, 1997; Miller, 1956) and the results gathered from user tests. Complexity was defined in terms of the number of distinct elements (e.g., lines, shapes, and textured regions) present: As the number of elements increases, so does the complexity of a given scientific representation. This, in turn, was expected to increase the difficulties understanding or recognizing what is being represented - this being measured on a Likert scale with "1" indicating low difficulty and "10" indicating high difficulty. Of interest was not only the perceived difficulty of given representations, but also what VI considered as "distinct elements" compared to the sighted. In one user test, a VI subject misunderstood texture (which was intended to stand for or a darker region) as standing for fan blades. This meant that the user perceived more elements (four fan blades) than would a sighted (a single umbrella piece)

3. Next step was the formulation of guidelines based on the insights gathered in user tests (reported in Chapter 4). One of the key findings emphasized at this stage was that VI users exploring scientific materials tend to be faithful to their senses rather than to understand the use of materials as a way of metaphorical expression. Translations of scientific content into accessible formats fails when the designers do not recognize or

take into account a mismatch between how the sighted and VI users understand texture as well as elements such as perspective and overlap.

4. Next, the analyses in steps 1-3 set the foundation for establishing key steps for converting materials into accessible formats. These roughly included (1) Perspective removal, (2) Identification of the type of representations (picture; diagram or graph; table) to be translated, (3) Distinction between perceptible and imperceptible features of represented objects, (4) Reduction of complexity of a picture, diagram/graph, or table (5) Questions regarding the importance of texture and spatial features of represented objects.

5. Based on the observed challenges of VI users failing to distinguish between overlapping content, the next formulated guideline was to separate overlapping content into distinct layers. This stage was also marked by a rough proposal of options from which to select the one that best fits recommendations. The listed options included (1) text descriptions, (2) raised line graphics, (3) reliefs (i.e., 2.5D models), and (4) 3D models.

6. At the final stage the effectiveness and ease of use of the emerging decision aid was verified and revised in the context of specific images and data.

5.3 Considerations When Converting Images and Data (Findings & Analysis)

5.3.1 Replacing Perspective View with Plan or Elevation Views

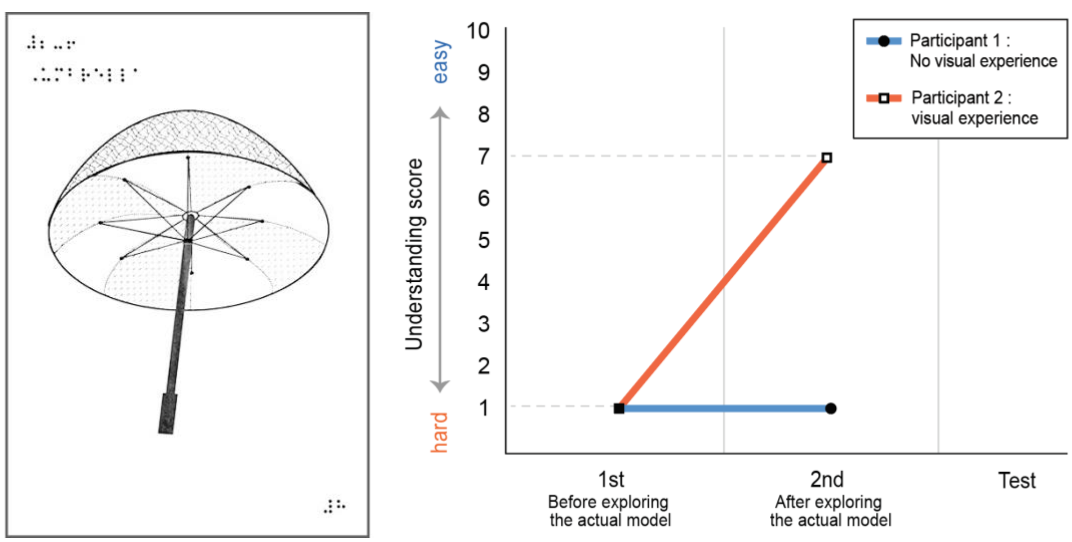
66.8% of images in the science textbook used in this study were classified to contain a perspective view (Figure 3a, 3c). That is, the shapes of depicted objects were distorted in line with the rules of linear perspective such that parts farther from the observer were depicted as shorter (i.e., more foreshortened) than similarly sized parts closer to the observer. It is interesting to note that the common practice of coping visual images mis-aligns with the recommendations of the Braille Authority of North America’s Guidelines and Standards for Tactile Graphics (2010) which suggest simplifying three-dimensional perspectives to two dimensions. Could it be that this recommendation needs a stronger empirical support?

As mentioned before, there is surprisingly little research on the recognition of perspective pictures by VI learners. Past research (e.g., Heller, 1989a, as cited in Heller et al., 2002) and user tests reported in this paper (e.g., the aforementioned umbrella test) suggest that side views and top views of objects are easier to understand by the VI users than perspective views. These roughly correspond to plan and elevation views, respectively. Schematic plan and elevation views are devoid of perspective. The research presented here provides support to what we have intuitively known: perspective pictures are difficult to understand through haptic exploration alone.

User tests in this study provide another interesting insight: late blind users may recognize the content of perspective pictures after having explored a 3D model of the depicted object (Figure 11). This effect, however, was not observed for our early blind subject. The implications of the effects of haptic exploration of 3D models on the recognition of perspective views (e.g., Wnuczko, 2019) will be subject to our further research. For the purpose of creating quick and easy STEM resources for VI users, we acquiesce to the recommendation to remove perspective from translated images and opt for simple plan and elevation pictures.

Figure 11

Comparison of the Results of Participants who Differed from Past Visual Experiences when They Retested the Raised Line Graphic after Touching the Actual Model



5.3.2 Identifying Type of Representation to be Translated

Coppin's (2014) perceptual-cognitive model of affordances was used to help inform which types of representations (e.g., pictures, diagrams, text) should be specified in the proposed decision aid at all stages of design decisions. The content of representations was described in terms of concrete and abstract concepts (with anticipated consequences for perception and action). For example: a realistic picture is said to convey information about pictorial relations between pictorial objects (Table 5). It shows concrete objects one can see and/or touch. A diagram shows pictorial relations between symbolically represented objects. Here, the spatial relations between symbols such as text labels are meaningful. Text descriptions convey symbolically represented relations among symbolically represented objects (words). Coppin (2014) points out that text is suitable for conveying abstract concepts that are not perceivable via a specific sensory modality (Barsalou, 2009). Pictures are more suitable than text for conveying information about concrete objects. Pictures and diagrams are both suitable for communicating information about spatial relations. This translates to better recognition of depicted content.

At the stage of identifying type of representation, a developer is not asked to reflect in detail on the nature of each representation. However, the underlying principles form the basis for the subsequent recommended steps. For example, if the image to be translated is a realistic picture that shows a visible, but intangible object (such as a rainbow or a moon), the recommendation might be that a more symbolic representation such as text description is used instead of or accompanying a raised line picture (or some other representation conveying spatial properties and/or concrete objects; e.g., a 3D-printed model of a moon). The next section deals with the dichotomy between perceivable and imperceptible content.

Table 5

An Abbreviated Version of the Model Developed Adopted from Coppin (2014) with permission

Type	**Picture**	**Diagram**	**Text-sentence**
Example			
Relation	Pictorial	Pictorial	Symbolic
Object	Pictorial	Symbolic	Symbolic

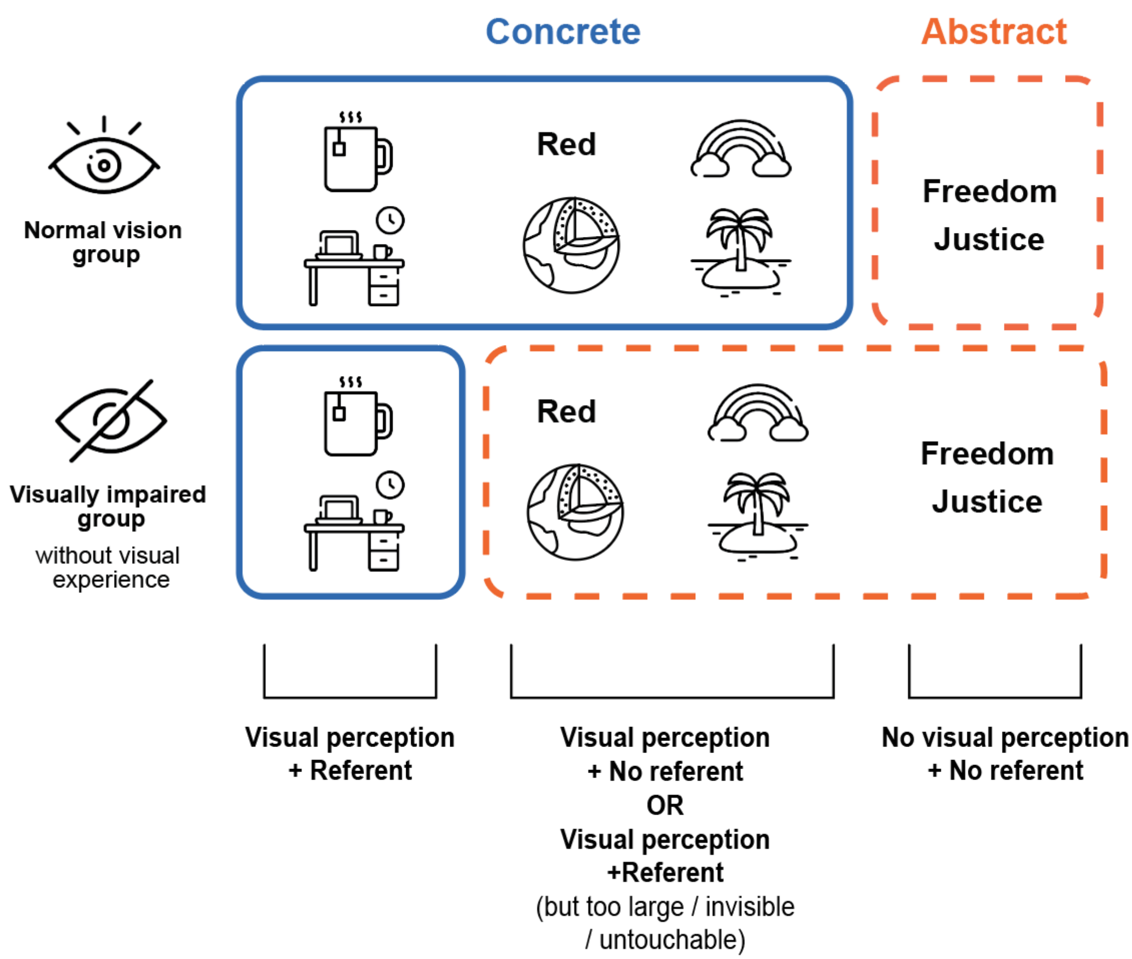
5.3.3 Perception Possibility

What is concrete for the sighted may be abstract for people with VI and vice versa. Evidence for this was found in a recent fMRI study by Striem et al. (2018). The authors found that for people with VI but not for the sighted, words describing purely visual phenomena such as “rainbow” or colour red triggered activation in the left dorsal anterior temporal lobe, ATL – a region associated with the processing of abstract concepts. This was also true of words describing objects imperceptible to touch due to a large scale (e.g., an island). The same brain region responded to amodal abstract concepts such as “freedom” in subjects with and without visual impairments.

Using Striem-Amit et al. (2018) definitions of imperceptibility, the 9th grade science textbook content, including pictures, diagrams, and tables, was analyzed in terms of the presence of concepts that are abstract to non VI group in comparison to a visually impaired group. The classification is illustrated in Figure 12. In the figure, common objects such as a desk or a cup would be considered concrete by VI and sighted users. A distant island or a rainbow would be visible to sighted users, but intangible (and therefore imperceptible) to VI users. Earth’s core would be neither visible nor tangible and therefore abstract to both sighted and blind users.

Figure 12

Comparison of Concepts that are Abstract and Concrete for Visually Impaired and Non VI Groups. Based on Striem-Amit et al. (2018)



5.3.4 Memory Capacity: Reducing Cognitive Load

Baddeley (1978, 1986, 1992) argues that human perceptual processes have “work memory” limitations that cannot over-storage and manipulate memory, which follows different methods for visual and language cognitive work (as cited in Bourke & Adams, 2003; as cited in Alvarez & Cavanagh, 2004). The search for effective models depends on the user's "complexity perception" (Mario et al., 2005), and in several studies (Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle et al., 1999), it has been reported that individuals' excellent "memory capacity" has a positive effect on their cognitive enhancement (as cited in Conway et al., 2001). Therefore, converting and providing visually inaccessible scientific materials to learners with visual impairments is a way to maximize their memory performance. I have found through the studies of several scholars that different cognitive limits can be applied to the concrete concept such as image, the graphs and diagrams visualized through the abstract but concrete object shapes, and the table which is a completely abstract concept.

Studies conducted by Luck & Vogel and Woodman (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) revealed that short-term memory capacity is limited by the number of elements regardless of function such as colour or orientation. The capacity system limit for visual perception is 4 or 5 elements (Alvarez & Cavanagh, 2004). Therefore, when converting a scientific data image into a haptic material such as a raised line, if 4 to 5 or more represented objects are included, this is likely to be perceived as a highly complex material by VI learners. This criterion applies not only to images containing representations of concrete objects that can be specified, but also to graphs and diagrams that can be classified as containing abstract concepts. This is because diagrams and graphs symbolize objects and fall into the category of abstraction, but their semantic relations are visualized through the form of shapes (Coppin, 2014). Among the various types of graphs and diagrams, such as Venn diagram, pie graph, bar graph, line graph, tree diagram, flow chart, chemical structure, and electric circuit diagram, especially Venn diagram and electric circuit diagram affect the relationship between information. So far, the influence of the number of items in haptic expression has no definite standard (Hatwell et al., 2003), but the Tactile Graphics Guidelines of The Braille Authority of North America (2010) also specified five line and texture limits. As a result, in terms of complexity, the working limit of visual and tactile data seems to be based on 4 or 5 elements..

Contrary to this, abstract concepts tend to be expressed as “semantic” or “verbal information” due to the lack of perceptual tendency to materialize (Striem-Amit et al., 2018). Peter Coppin (2014) also mentioned that abstract concepts involving symbolic objects are effectively expressed in language, but like visual information, they are affected by short-term memory. The perception of data complexity is that Miller's 7 ± 2 criteria (1956) were considered traditional, but Cowan claims more than four chunks of information as a loss point (Cowan, 2001). For example, in the case of data such as a table, if the number of cells exceeds 4, the learner's memory decreases.

5.3.5 Prioritizing Attributes and Representations for Final Design

In the next step, instructors need to consider the important purpose that visual material is trying to convey. This can be seen in terms of language communication, expression of texture, and transmission of spatial relationships.

First of all, among the concrete concepts with perceptible objects, photos of low complexity (including less than 4 or 5 elements of color, line, orientation and texture; Alvarez & Cavanagh, 2004; Braille Authority of North America, 2010) can be categorized as content that educators can convey by explanation. Likewise, the low-complexity of the traditional abstraction concept (less than 7 ± 2 classic experiments by Miller, 1956; 4 ± 1 according to Cowan, 2001), which has no visually recognizable and indicative objects, is sufficiently conveyed by explanation. However, even with highly complex content, there may be cases where information can be sufficiently delivered only by description depending on the content. Most of the images in the 9th grade science textbooks I analyzed are about natural environments, industrial artifacts, science experiments & materials, and living environments (Chapter 2.3.2). Among them, objects familiar to us, such as the natural environment and living environment, can be sufficiently explained in language and save effort for conversion to other sensory teaching tools. However, if scientific information is added to this, it may need to be translated using a cross-sensory method since it may interfere with the user's perception due to the overlap of information.

Concrete concepts that are considered too big or too small or invisible to the inside and cannot be touched, making them visually impaired, are important for grasping the learning intent that photography is trying to convey. If the purpose of this material is a simple texture transfer, relief with a cheaper and faster production process than 3D is suitable, and 3D may be an appropriate alternative for materials where spatial relationship transfer is important.

Spatial relationships between objects can be important for diagrams and graphs (that are abstract but contain some shapes), or highly complex photos (concrete concept). In our molecular structure model experiments (Chapter 4.5.4), participants with visual impairments did not understand the spatial relationship between atoms at all, despite a high level of understanding of the raised line molecular structure diagram. Surprisingly, when this was produced and provided in a 3D model, he understood most of the spatial structure, including distances and angles between atoms. "Spatial information" is not easily conveyed when searching for objects with touch (Hatwell et al., 2003), so it has been observed that translation using a 3D model is effective.

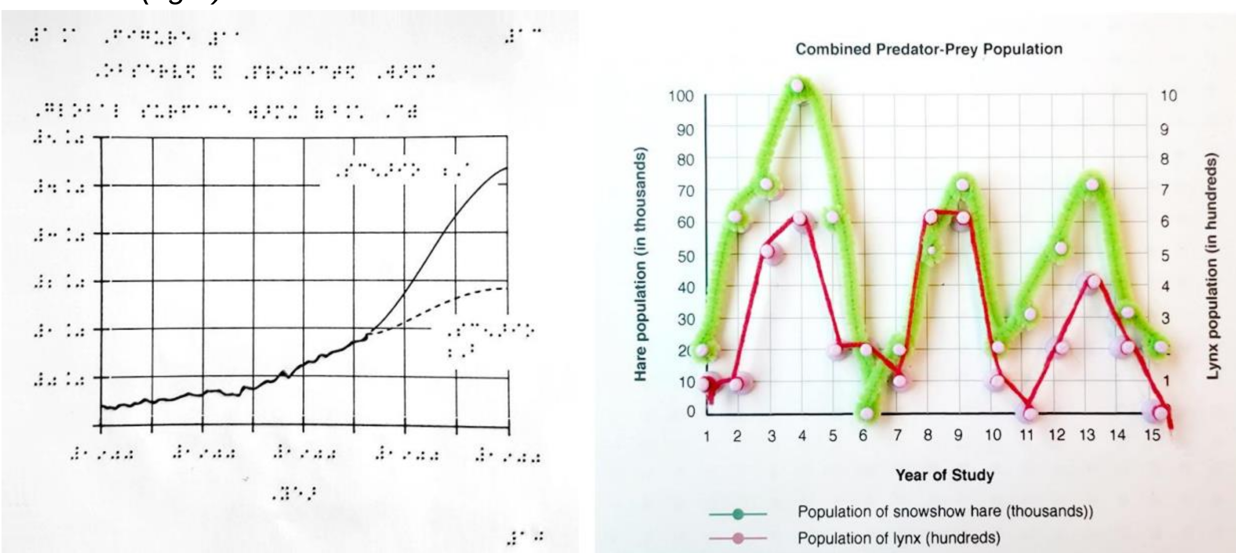
5.3.6 Use Overlapping Information of Different Kinds

Hybrid materials represented by "pictures or diagrams with textual labels, tables" (Coppin, 2014) interfere with the accessibility of VI learners due to overlapping information. It is expected that the five-step process described above will lead to a more effective non-visual translation solution for scientific images and data. However, if the overlap of scientific information is added to this, it can be regarded as a 'pain point' only for visually impaired people, like 'perspective view'. Therefore, in the last step, it is necessary to check whether additional information such as arrows and figure diagrams are included in the visual material.

In a cognitive experiment with the complexity of the cell raised line graphic in Chapter 4.5.2 (Results Part B), a visually impaired participant said, "I thought the line to add braille descriptions was part of the cell shape." As such, overlapping of different kinds of information results in distortion of the shape of the actual object. Therefore, the added information may not interfere with the perception of VI people when expressed in different layers with different materials (see Figure 13 graph sample).

Figure 13

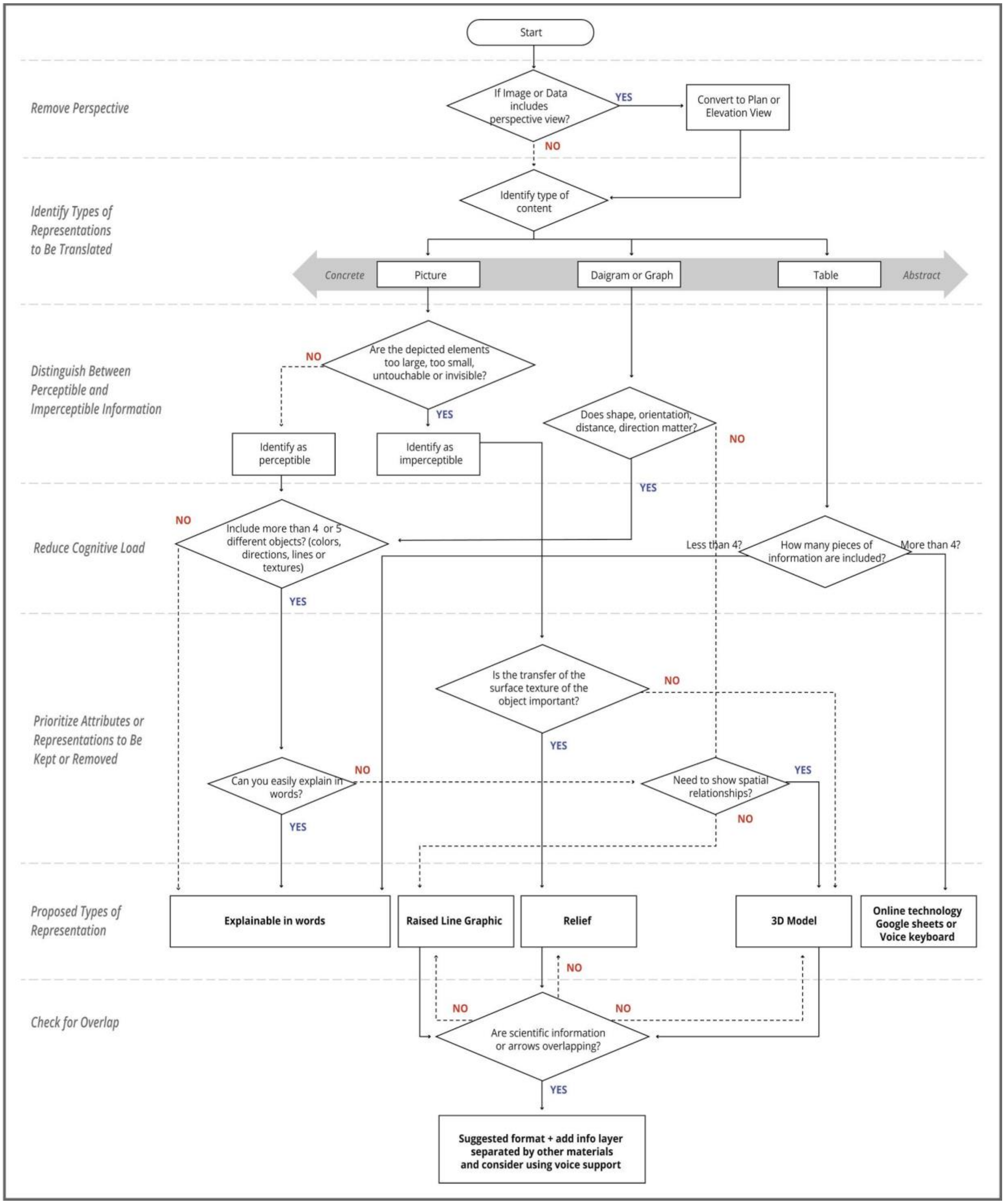
Raised Line Graph with Embossing (left) and Double Line Graph with Two Different Materials (right)



5.4 Result: Decision Criteria Chart and Directions for Teachers - How to Use the Decision Aid (Subconclusion)

Figure 14

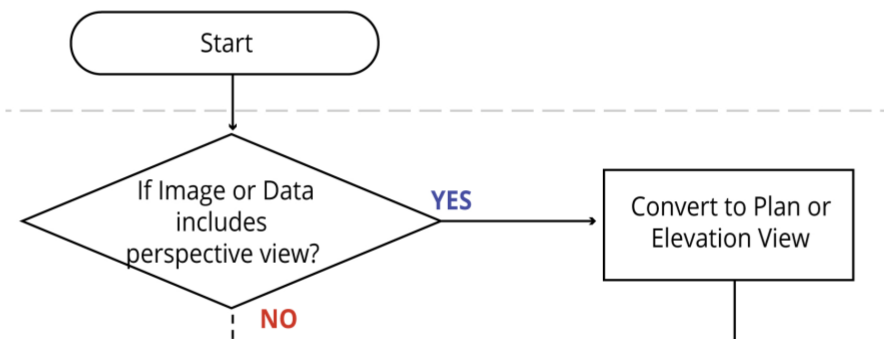
Decision Aid (Appendix C: Decision Aid File, the file is available to download in OCAD University's Open Research Repository)



- Step 1 (Figure 15): First, all image and data content, including perspective views, must be converted to a plan view or elevation view at an early stage of design. Developers are advised to choose a view most familiar to the users.

Figure 15

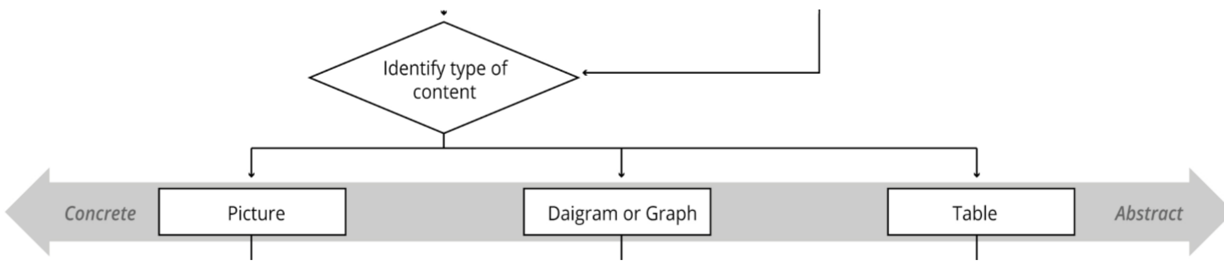
First Steps of the Decision Aid: The First Suggestion Is to Identify If Image or Data Contain Perspective. If so, the Advice Is to Convert to Plan or Elevation View.



- Step 2 (Figure 16): Next, developers are asked to identify the type of content or representation to be translated. Types of representations include a picture, diagram/graph, and table. Pictures are realistic images that typically show concrete objects. Tables are more abstract in that they typically contain symbols - text or numbers. Diagrams and graphs contain both symbolic and spatial properties.

Figure 16

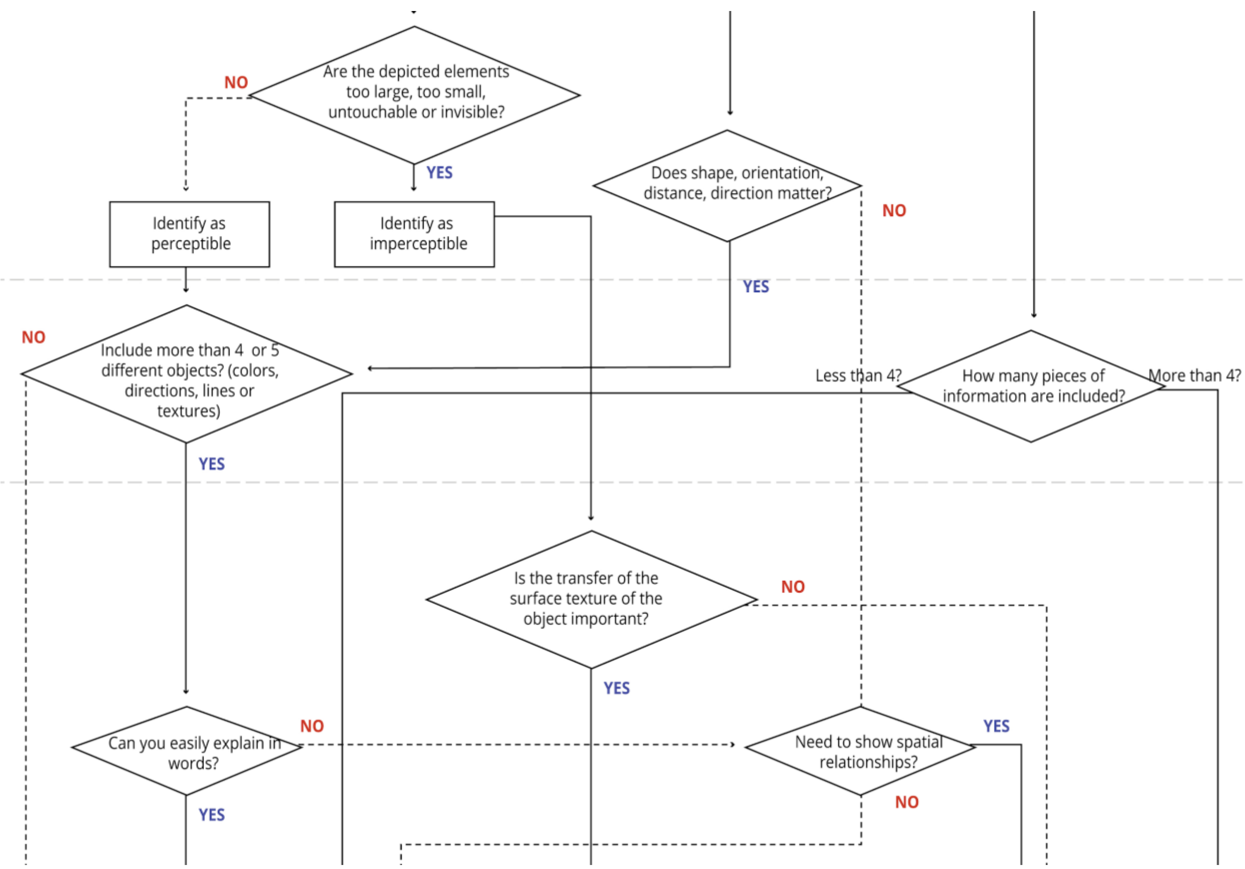
The Second Step in Decision Aid: Identification of Type of Content or Representation. Types of Representation Include Picture, Diagram or Graph, and Table



- Step 3 - Step 5 (Figure 17): Next, developers are asked questions in relation to each of these types of representation. The asked questions encourage the developer to (1) distinguish between what is perceivable vs. not perceivable, (2) determine if the content contains information about shape, orientation, distance, and spatial relations (these are important attributes that are better represented pictorially than with text), and (3) determine the complexity the user can handle for immediate use (to account for the limited memory capacity). If the representation to be translated into an accessible form is a picture, then one is asked to identify if the depicted objects are perceivable or not perceivable. A perceivable object is a concrete structure one can touch, for example. An imperceivable object is one that one could not touch or experience in some other way. A rainbow would be imperceivable to someone who is blind. If the representation is a diagram or a graph, one is asked: Does shape, orientation, distance, or direction matter? Nominal data such as people's names randomly listed in a table would lack such attributes. If the representation is a table, one is asked, "How many pieces of information are included?". Here pieces of information are data points or pieces of data that would be perceived as distinct by the user. User feedback may be useful here to identify what is perceived as distinct pieces of information.

Figure 17

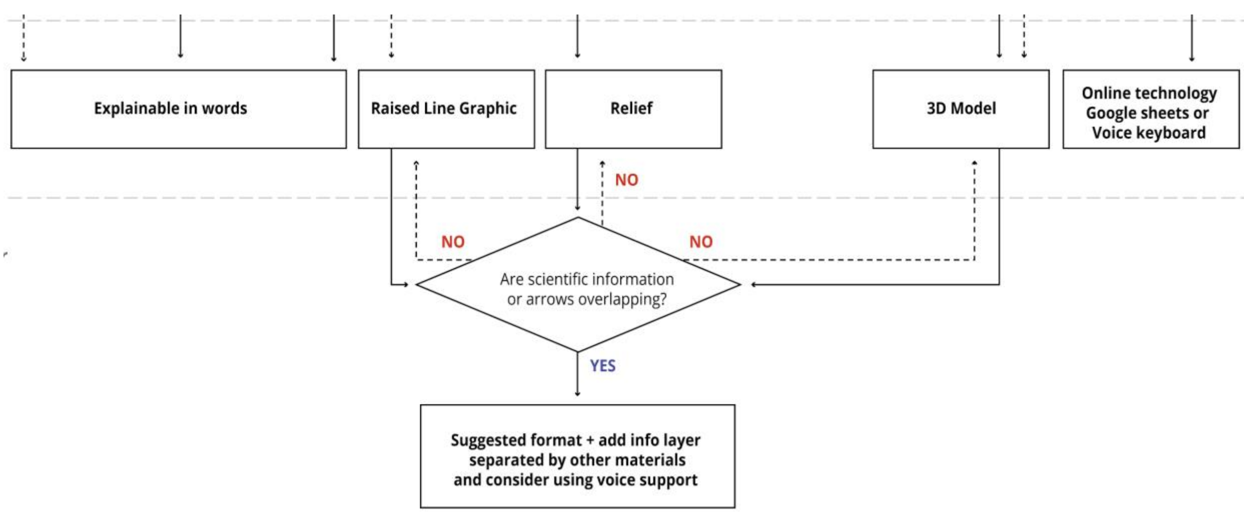
Intermediate Stages of the Decision Aid: Distinguishing between Types of Representation, Working Memory Limitations and Spatial Attributes



- Step 6 (Figure 18): At the final step, the developer is provided with a suggestion for a suitable non-visual translation of a given scientific content. At this stage, the developer is also advised to use separate layers for different types of representations so that arrows, braille, guidelines, diagrams, and other distinct content do not overlap.

Figure 18

Final Recommendations: Regarding Type of Representation to be Used and Check for Overlap



Note. The recommended solutions include text descriptions (i.e., explainable in words), raised line graphics, reliefs, 3D models, and online technology. If different types of representations overlap, then the advice is to separate these into distinct layers.

Chapter 6: Conclusion

6.1 Summary of Key Research Findings

Non-visual translations of graphics conveying STEM content produced by sighted designers and educators for VI learners do not appear to perform as intended. My observations and interactions during this project suggest that these “accessible” formats (certainly unintentionally) follow visual rather than haptic rules of perception.

First, perspective views make tactile image recognition difficult for most VI people, especially in the absence of a memory of a past visual experience. My research supports the hypothesis that perspective reduces comprehension, regardless of the complexity of images. Secondly, 3D models more effectively display spatial and topological information relative to raised line graphics (cf. Ghodke et al., 2019) and text descriptions, that lose all spatial and topological properties in the translation process from graphics (cf. Coppin et al., 2016)

In addition, variations in texture used to distinguish colour and luminance changes, are misperceived by VI users as denoting variations in the material used (Chapter 4). This could be due to haptic perception of a “bump” as a “bump” taking precedence over metaphorical expression: taking variations in textures as the symbolic representations of variations in colour or luminance.

In addition, the symbolic use of texture can increase the number of perceptually processed "chunks of information," thereby increasing the cognitive load and impairing VI learner's recognition of what is being represented. Another problem of complexity is increasing the number of images, or components such as overlapping arrows or guidelines. Such solutions can all make it more difficult and laborious to recognize scientific data. Developers should also be aware of the size of the image such that each detail is perceivable to VI users Lastly, the size constraints of braille labels limit how much information can be conveyed without obstructing represented content. Replacing it with voice recognition labels, can increase accessibility and comprehension of VI learners . On the other hand, users familiar with braille reported that the use of voice recognition labels was at times cumbersome. Braille was a preferred method for conveying titles as well as more detailed information. VI learners pointed out that the explanation of haptic models in advance was helpful in most user tests, and those who started tactile exploration immediately without any information spent much of the exploration time trying to figure out the shape and structure of the overall model.

6.2 Empirically Derived Recommendations for Cross-Sensory Translations of STEM Content for Visually Impaired STEM Learners

In a study by Sahin & Yorek (2009), an educator in one science subject points out that although students with impairments need more time to study, all students must complete the same curriculum. Spungin & Ferrell (2007) argue that the onus of providing a comparable learning experience for students with varying degrees of visual impairments falls on the teachers. They say that “teachers should be the focus of empowerment so that they could in turn empower their learners” (Carl 1995 , as cited in Maguvhe, 2015, p. 1).

Based on the literature review and the research presented in this paper, I provide the following recommendations for the educators and developers of scientific material for VI learners:

- Consider when text descriptions are most appropriate: (1) Use words to explain abstract concepts (Coppin, 2014; Coppin et al., 2016; e.g., amodal concepts such as “justice” or “beauty” and information about imperceivable (invisible and/or untouchable) objects such as the rainbow (invisible and untouchable) objects) (2) Use words to explain simple and/or familiar concepts.

- Raised line graphics: Raised line graphics contain up to 4 or 5 elements (colour, direction, line, texture) and are suitable for conveying simple spatial relations in left-right and up-down directions. Raised-line graphics are not suitable for conveying information about depth or perspective. For embossing, teachers can choose any available method. Consider low-fidelity models using Puff paint or plastic kit film and high-fidelity models inflating with a thermal printer using swelling paper.

- Relief (2.5 model): A relief, which occupies the intermediate position of 2D and 3D models, has a greater capacity than 2D model but less capacity than 3D model for conveying spatial information along the three spatial dimensions (left-right; up-down; near-far). Because it is faster and cheaper than the production of 3D models, a relief may be an effective alternative for showing spatial relations. Relief "enhances the sense of spatial hierarchy through line drawing, perspective projection, visual illusion" (Ji et al., 2020, p. 1), and it is easy to convey special texture through depth.

- 3D model: 3D models can show a 1:1 correspondence between the model and what it represents. It thus offers the most intuitive understanding of spatial or topological information in all dimensions VI users, and especially totally early blind users will find these models far more effective than any of the aforementioned alternatives. However, because it takes additional time to produce 3D models compared to raised line graphics or reliefs, it is recommended that their use is limited to conveying content that is difficult to express in words.

- Online technology (e.g., Google sheet or voice keyboard): Google sheets or voice keyboard are useful for the delivery of complex tables with more than 4 ± 1 pieces of information (Cowan, 2001). For example, a table can have variables of various data types in each cell. "In statistics, there are four data measurement scales: nominal, ordinal, interval and ratio". Nominal (labeling a variable without quantity), ordinal (which cannot be quantified like satisfaction, but conceptualizes a scale), interval (numerical scale without "true zero" indicating the exact difference between the value and Celsius temperature; eg, Celsius The temperature,, and ratio (which include "accurate values between units", which can be "statistical analysis", e.g., height, weight, and duration) have different representations (Types of data measurement scales: Nominal, ordinal, interval, and ratio, 2020). Also, tables often contain short sensations. If such a variety of data is included in a complex table, educators will have a limit to explain this to learners with visual impairments. Google Sheets is an alternative to systemic delivery of such complex table content. Especially for users who are computer savvy.

In addition, the use of speech recognition devices or sensors can be considered for intuitive recognition, providing more specific information beyond braille limits. For example, a voice-programmable keypad device such as Adafruit NeoTrellis M4 (Adafruit NeoTrellis M4 with enclosure and buttons kit pack, n.d.) can be considered as an intuitive tool for VI learners' table recognition (Figure 19).

Figure 19

Adafruit NeoTrellis M4 Table Prototype Designed to Be Recognized as Touch by Adding .mp3 Voice Files to the Keypad (left) and Visually impaired Participants Testing It (right)

- Remove perspective: VI users without visual experience consistently fail to recognize perspective in pictures, regardless of the complexity of the model, this research shows. Thus, it is recommended that perspective views are converted to plan or elevation views.

- Anticipate methods of exploration: Empirically-based knowledge of how VI people typically explore models under different conditions can help designers build better models (by anticipating the needed affordances for effective exploration). This research suggests that many VI people first tactilely browse the outer frame of the model and then explore through the details inside. The preliminary observations also showed that a late blind subject explored some models and other representations left to right, possibly being influenced by the experiences of writing and reading from left to right. One totally early blind subject, on the other hand, explored the same resources from top-to-bottom, possibly being influenced by the structure of the heading titles as they appear in online documents. Educators should be aware of such biases. One VI participant provided the following comments. "After getting advance information about a scientific model from an instructor, exploring it can save time and improve comprehension. If I have to figure out a model without any explanation, it creates a lot of cognitive load, and often it is recognized as a different model." The method of explaining the clockwise direction to inform the position is intuitive in that it specifies the direction based on the learner's position. However, if the learning content requires an absolute direction such as a map, educators should use the east-west direction.

- Add text description to explain symbolic use of texture: This research suggests that VI users tend to interpret textures in the presented models as the textures of the represented objects themselves. Therefore, if texture gradient is used in a symbolic way -- e.g., to denote variations in colour, luminance, or to distinguish between surfaces -- it is recommended that a text description or explanation and legend are added to avoid misunderstanding.

- Translate variations in colour only when necessary and explain the symbolic use: Any symbolic use of colours (e.g., in color-coding) or natural variations in color should be explained using a text description (Braille Authority of North America, 2010, p. 11-3).

Based on this research I also suggest that textures or other alternative ways of representing changes in colour are avoided unless necessary and accompanied by a text description.

- Simplify content to convey no more than 4-5 elements or groups of elements at a given time:
  - Reduce the amount of information: By simplifying content or deleting unnecessary elements of the model, the tactile perception of learners with visual impairments can be improved.

  - Place overlapping information into separate layers: overlapping of information, which is another factor of model complexity, can be solved through separation by type of representation (picture, diagram, text), since types of representation are likely to be perceptually grouped together into separate chunks. Braille, arrows, and lead guidelines can help minimize the need for separate layers.

- Increase size such that the details are perceived by touch and the depicted object is recognized with minimal haptic exploration : if the size of the image object is reduced due to the large number of images, the tactile understanding of the visually impaired is reduced. If you are using meaningless labels, it is effective to delete them and enlarge the image (see Braille Authority of North America, 2010, p. 12-3). Providing an appropriate image size can improve user access to information, and for learners in special situations (e.g., young learners; p. 11-4), teachers may need to resize the model to fit their hand size.

- Add braille labels, but do not overuse them:
    - Basically, all tactile models should be labeled with braille, and the same format should be used for all “braille, e-text, audio versions” (The Braille Authority of North America, 2010, p. 9-7). Depending on the properties of the label, the position will be different, and the title should be located at the top center of the tactile graphic (p. 5-8), and information such as properties or references should be located at the bottom. Additional braille information is helpful for VI learners, but above all, the representation of the image object itself must be prioritized. When conveying different information, numbers are less effective than alphabetic classification (p. 7-4). This seems to help improve the memory of VI learners rather than just numbering, as the first letter of a word in an information chunk is related to the content when used as an alphabetic key.

    - If teachers are unable to add detailed explanations in braille due to space constraints, you can consider using a voice recognition device such as PenFriend. However, I do not recommend using these devices for too simple information.

    - Learners who learn information using speech recognition technology on Google docs or web pages can be effective with heading. This is not a direct method of explanation, but it enables systematic classification of the elements to be described, which affects the cognitive abilities of VI people (Understanding Techniques for WCAG Success Criteria, 2008).

- Method of delivering explanation
  - Concise and clear explanations can help guide haptic exploration of images and models. The descriptions can be designed to encourage exploration of larger outlines or regions to smaller elements. Many VI people prefer natural human voices rather than synthetic sounds. A choice between the two can further improve the experience and accommodate individual differences.

6.3 Conclusions and Contributions

Because “science experiences depend mostly on visual data” (Sahin & Yorek, 2009, p. 21), limited access to corresponding resources by VI learners violates their basic learning rights, reducing motivation and academic achievement in STEM subjects. Alarmingly, the interviews with teachers reveal that even the existing resources are underused, because they are deemed ineffective. The presented user-tests and workshops suggest that such impressions may in part stem from a misguided design. For example, many of the raised line images are copies of visual images. They often include perspective, overlapping elements, occlusion, and a (ab)-use of texture to denote changes in colour and luminance. These elements are not readily recognized by VI users, because they are derived from visual rather than haptic rules of perception, as outlined in this paper. I hypothesize that empirically-validated guidelines for the production of accessible STEM resources in line with the rules of haptic perception, will increase the demand for such resources. They will be significantly more effective (i.e., more accessible) and useful than many existing resources. The proposed decision aid is a step towards the development of an empirically-driven standardized approach. The decision aid will not only guide towards intelligently designed resources for VI users but also make the process more feasible. Also, it will save time and reduce cost. It is the hope that this research will contribute to a truly inclusive learning environment with increased learning opportunities and autonomy of VI STEM learners.

6.4 Future Research

Follow-up research will include both exploratory and hypothesis-driven studies that build on my initial insights about accessible design for VI learners. A part of that will involve experiments on common and distinguishing principles of visual, haptic, auditory, other-sensory and cross-sensory modes of perception. Thus, future research will contribute to continuously more precise guidelines for design according to the principles underlying non-visual perception.

The immediate next steps are planned to include (1) class audits at the School for the blind as a follow-up to teacher interviews, (2) workshops with more structured questions and instructions, (3) user tests with new prototypes developed using the proposed decision aid.

The purpose of class audits will be to record the extent to which teachers (and students) use existing resources or envision, design, and/or build new resources for more effective learning. In addition, new semi-structured interview questions will reveal more details about the extent to which educators and students engage in the do-it-yourself approach to learning. Of interest at a later stage of this study will be to verify the effectiveness of the proposed decision aids as it is used by teachers and developers of accessible STEM resources for VI learners. I may wish to compare the quantity and quality of resources built and used by teachers before and after receiving the decision aid.

The workshops, while unstructured, gave us a glimpse into the limitations of tactile pictures and reliefs. One interesting finding was that the blind can understand information for occluded surfaces, but this understanding is not intuitive. It takes time for VI individuals to understand that a line touching another perpendicularly stands for an edge that continues behind another surface. Would this information be more obvious if the tactile picture or relief had additional information for depth (e.g., a recess between overlapping surfaces?). This question could be addressed experimentally. Another finding was that the blind seem to show preference for designing 3D models and misunderstand the symbolic use of texture. This workshop could be replicated with a larger sample size and extended to include new stimuli with varying textures. In parallel to this research, it will be interesting to see how the sighted and VI users collaborate on subsequent prototypes. In what ways will the ideas converge? Thus far, it seems that all users agreed that 3D models would be most effective and interesting. A blind user, however, may use texture differently from a sighted user.

The next user tests could also use improved prototypes. For example, the tactile picture of the umbrella could have been misunderstood both or either due to its perspective view and an odd use of texture. The next prototypes might include a tactile picture of an outline of an umbrella without the texture in perspective and elevation views and an elevation view of an umbrella with a similarly symbolic use of texture. Which prototype will be more difficult to understand? I expect that perspective view will pose a greater difficulty than a symbolic use of texture, especially if these are accompanied by a text description or a text label.

I also identify gaps in the literature. Effective design of accessible STEM resources for VI learners will require a more in-depth study of the potential uses of online technologies. This research is in its infancy. By prototyping scientific models using sensors and special devices such as, for example, Arduino, Makey-Makey and voice keyboards, teachers can provide VI learners with an interactive environment for exploration. Educators should not be discouraged by the lack of prior knowledge of these skills. An exploration of new tools in the educational context will provide inclusive design researchers with the preliminary insights for a more structured research. Teacher's in-class and online interactions with students, as well as the use and design of accessible resources, serve as a "natural lab" for emerging new ideas, questions, and hypotheses.

As Dr. Mahadeo Sukhai pointed out, the educators should keep in mind the learning objectives of activities and problem-solving. Based on my research, I can say that a 3D printed frog with detachable components would be more effective than a raised line drawing in helping a student remember the spatial relations between organ systems. However, it would not offer an experience comparable to the dissection of a real cadaver. In fact, our research suggests that it could lead to a misunderstanding regarding the material properties of cadavers, including the texture of different tissues.

Part of STEM subjects, especially in science education, is experimentation. Participation in laboratory classes typically involves a heavy use of visual feedback and action based on that feedback. This is a difficult task for VI people to overcome easily. Related research should be undertaken to take into account the environment of laboratories and to provide an inclusive laboratory experience for VI learners using improved experimental tools and methods.

Finally in Chapter 3, I mention co-designing prototypes by teachers and visually impaired participants. We should not forget about self-initiated prototyping by STEM learners themselves. Sighted or blind, we may sometimes feel the need to draw a diagram, because the text description does not capture the essence of the conveyed message. Or we find other ways of visualizing or understanding material that was not described with enough clarity. Sometimes it is a matter of gaining a greater appreciation for knowledge and the feeling of empowerment. One of our lab-mates and MDes candidate, with visual impairments has developed on his own initiative a “tactile world” globe incorporating tactile and audio feedback. This initiative was the start of a major research project involving new and increasingly more effective iterations of the globe (Ghodke, Yusim, Somanath, Coppin, 2019, June). Such natural labs provide an exciting opportunity to learn more about the preferred modes of representation in the absence of vision and more feasible ways of approaching design.

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Appendices

Appendix A: Survey Questions for Science Teachers at W. Ross Macdonald School for the Blind

1) Professional Background

Q1. What is your professional background (e.g., list degrees, diplomas, certificates)?

Q2. How long have you been teaching?

___1-3 years

___4-6 years

___7-10 years

___11-15 years

___16 years or more

Other (specify) ____

Q3. How long have you been teaching visually-impaired students?

___1-3 years

___4-6 years

___7-10 years

___11-15 years

___16 years or more

Other (specify) ____

Q4. When and where do you work? Can you tell me what are the best and most challenging aspects of your job?

2) About Visually Impaired Students

Q5. How many students are in each grade and how many classes are there?

Q6. Please indicate the age range of the students with visual impairment you have taught.

___JK-SK

___Gr. 1-4

___Gr. 5-8

___Gr. 9-12

Other (specify) ____

Q7. Describe the type and degree of disability of the visually impaired students you have been teaching.

Q8. Please specify the approximate number of students with given visual impairments you are teaching/have been teaching most recently.

Total blindness: ___

Low vision: ___

Colour blindness: ___

For low vision students, how many can see shapes: ___

Other (specify)____

Q9. Of the low vision students, how many do you know had previous visual experience that they can remember?

Q10. Rank the needs of students with visual impairments to receive education from most pressing/urgent (#1) to least pressing/urgent (#7)? (Note: you can use the same numbers for needs that you feel are equally urgent)

___ Participation in regular classes

___ Understanding learning contents

___ Use assistive tools

___ Seamless communication

___ Improved autonomy

___ Psychological stability

___ Specially designed separate classes

Q11. Are there any other needs that you think are important? How would you rank those needs relative to the ones specified in the previous question (question #7)?
Other (specify the need(s) and rank it/them)

____

Q12. What do you think is the most difficult subject for students with visual impairments and why?

Q13. How many of your students (%) are familiar with braille? Please explain in detail how these students use braille. For example, to what extent do these students rely on braille compared with alternatives (for example, are audiobooks preferred over textbooks written in braille)?

3) Science Related Questions

Q14. What learning materials are currently used by visually impaired students in class? (textbook, Braille book, tactile image book, etc.) How effective are these materials relative to each other?

Q15. What are some of the most difficult parts of the science classes for visually impaired students to understand?

Q16. Do you use any special strategy/strategies for teaching students with visual impairments? Please describe.

Q17. What aspect of science classes requires most of your attention when you teach visually impaired students?

4) Science-related: Web Accessibility

Q18. How often do they use web content during class? How skilled are students in using online resources?

Q19. What software are they typically using for accessing online resources?

Q20. Are the online learning resources used in your classes well designed from accessibility standpoint? What could be improved?

Q21. Is the zoom-in feature on the iPad screen or other personal digital assistants, useful for some visually impaired students?

5) Science-related: Information Delivery

Q22. Which of the following is the most difficult for visually impaired students to understand? Rank the following items from least difficult (#1) to most difficult (#6). You can use the same numbers for items that you think are equally difficult.

___ Diagrams

___ Flow chart

___ Bar graph

___ Table

___ Image

___ 3D models

Q23. Are there any other types of images, models, or representations that you think are difficult for visually impaired students to understand?

How would you rank those other items relative to the ones specified in the previous question?

____

Q24. Is there a special way for students with visual impairments to recognize images or data? (e.g., clockwise description for location etc., raised line drawings, 3D models). Provide a specific example of teaching visually impaired student(s) how to recognize a specific image or data.

Q25. Rank the relative efficiency in the use of the following software from most efficient (#1) to least efficient (#4). You can use the same numbers to indicate that the given software items are equally efficient.

___ screen magnification alone

___ speech recognition alone

___ speech magnification + speech recognition, used together

___ software installed on existing OS (e.g., Voiceover)

6) Learning Materials

Q26. Do you make the learning materials yourself? If so, how long does it usually take you to make them?

Q27. Do you use special services (e.g., services provided by assistants; 3D printers; laser cutting) for creating new learning materials? If so, what are they? How long does it usually take for these learning materials to be created?

Q28. What should you consider if you use new materials for your students? (e.g., low production costs, concurrent usability, mobility, etc.)

7) Related to Science Class: Evaluation Method

Q29. What are the test methods for students with visual impairment? Please check all the methods you use.

___Voice support

___Braille printing

___Recording function

___Volunteer Help

___Screen magnification

___Audio Converter

___Screen magnification software

___Screen reading software

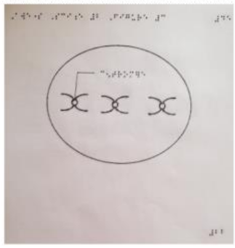
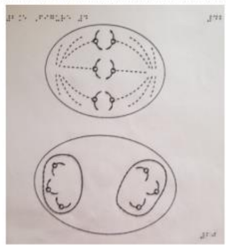
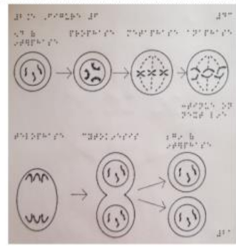
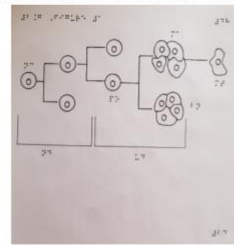
___Playable braille display

___An accessible personal digital assistant (PDA)

Other (specify) ____

Appendix B: Experimental Questions

Experiment 1

#1 Image Complexity	little complexity	less complexity < 7	very complexity >7	very complexity >7
This is to test the complexity of the image and to see if the proposed complexity of the nominal data, 7, also affects the number of image items.				
	1 image chunk	2 image chunks	2 image chunks / 2sets	8 image chunks
Braille book by W.Ross Macdonald				

Questions

First touch this image to see its contents. After that I'll ask you some questions.

Q1: How many distinct parts / elements / items can you identify here? Please explain what you learned from this picture.

Q2: Can you read braille? If so, are the braille labels used here sufficient to understand the content? If not, what explanation should be added?

Q3: Is the image the right size to convey the content? What if the image is bigger or smaller?

Q4: How many image elements have affected your understanding? Note that the number of items (chunks) in this image is one.

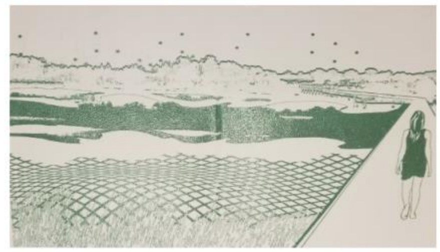
Q5: What is your score on this figure if you translate it to a score from 1 to 10? Note that 1 is very hard to understand and 10 is completely understandable.

Q6: [If they say more than 5 then ask them] "How could you make it clearer/more understandable? Do you have any suggestions regarding design?

Q7: Were there any parts of this image that you found more difficult? ...Why?

Q8: [Last after third test] The second and third tests contain arrows or lines that indicate the relationship between the images. Was it easy for you to recognize this? If not, how would you improve it?

Experiment 2

#2 Perspective difficulty	little complexity	very complexity >7
For people with vision, perspective is not a factor of image complexity. However, for all visually impaired perspective views are difficult. This is a test to confirm this fact.		
	1 image chunk but complex function	Linear Perspective with Different Sizes of Near and Far Objects
	Umbrella	Sea landscape
Braille book by W.Ross Macdonald		
Real model		

Questions

Touch this image to see its contents. After that I'll ask you some questions.

(Please speak as slowly and loudly as possible.)

Q1: How many distinct parts / elements / items can you identify here? Please explain what you learned from this picture.

Q2: How many image elements have affected your understanding? Was the representation of the image area in different textures effective for you to recognize the shape of the image?

Q3: This picture is a perspective view. Did you test this picture and notice it was a perspective? If you are aware of it or not, why?

Q4: What is your score on this figure if you translate it to a score from 1 to 10? Note that 1 is very hard to understand and 10 is completely understandable.

Next, let's test the 3D model.

Q5: What did you notice in this model? Describe the factors that influenced your cognition.

Q6: What is your understanding of the object when using the 3D model? Tell me a score between 1 and 10.

This time, let's test a more complex raised line image.

Q7: What did you notice in this model? Describe the factors that influenced your cognition.

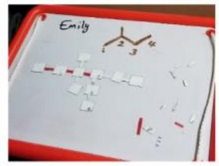
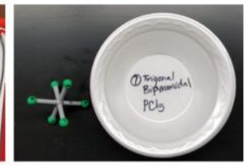
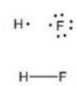
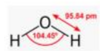
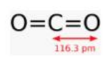
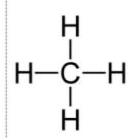
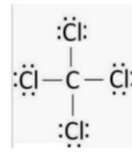
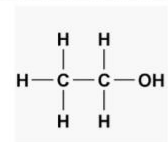
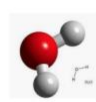
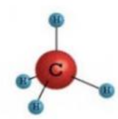
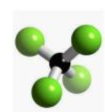
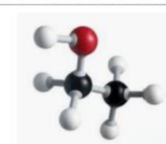
Q8: What is your understanding of the object when using the 3D model? Tell me a score between 1 and 10.

Q9: Were there any parts of this image that you found more difficult? ...Why?
Q10: How do you understand perspective? Explain what you know.

Q11: What is your understanding of Top View, Front View, Linear Perspective, and Relative Height and Size? Does creating an image in top view or front view make it easier for the visually impaired to understand?

Q2: How can we effectively deliver the projected image to the visually impaired? Please let me know your opinion.

Experiment 3

#3 Chemical structure	little complexity	little complexity	less complexity < 7	very complexity >7
This test aims to test the usefulness of materials for visually impaired students and to provide improved solutions by science teachers at W.Ross Macdolad.				
Natural lab materials	*Basic model CH4 / NH3 / BF3 / HF*			
Scientific materials created by W.Ross Macdonald Science Teacher	 			
	HF (Hydrogen fluoride)	**H2O (Water) vs. CO2 (Carbon dioxide)**	**CH4 (methane) vs.CCl4 (Carbon tetrachloride)**	**C2H5OH (Ethanol)**
General chemical structure notation		 	 	
Explanations	Simplest form molecule	**H2O**: 3 second simple structure / angled structure (not date) / single line connection-single connection / partially charged / electrically unbalanced **CO2**: 3 / double connection / fully symmetrical /-balanced / Fully neutral / semetric Screen reader support enabled.	The two have the same structure, even though they are different molecules. Students with vision can distinguish this by the color of the molecular model, which is difficult to distinguish for students with visual impairments.	Complex molecular structure with 7 or more elements
3D model		 	 	

Questions

I will show you the Raised images with the molecular structure sequentially.

Q1: Recognize these by hand first, then tell what you found in each picture.

Q2: Did the representation of molecules in braille help you recognize the picture?

Q3: How was it for you to recognize the line representing the molecular relationship?

Q4: What is your score on this figure if you translate it to a score from 1 to 10? Note that 1 is very hard to understand and 10 is completely understandable.

Q5: Were there any parts of this image that you found more difficult? ...Why?

Q6: This picture is actually made by a teacher for students with visual impairments. How effective are these materials for the students? Also, what are some ideas for improving this further?

Now let me show you 3D models.

Q7: Recognize these by hand first, then tell what you found in each model.

Q8: The difference in model size and colour distinguish the types of atoms. Did you recognize it?

Q9: How much can you understand the molecular structure by touching the model without explanation? Also, to what extent would the understanding increase if the instructor explained each molecule to you? Answer with a score from 1 to 10.

Q10: This time, I will show you the model that adds the speech recognition scanner.

Q11: Does adding Penfriend improve your understanding of molecular structure? Also, how did it affect autonomy?

Q12: What is your understanding? Answer with a score between 1 and 10.

Q13: What are some of the more effective ways of delivering molecular models that you think? Please tell me your opinion.

Thank you for testing for a long time. Finally, can you share your current state of vision with when you lost your sight? And, I want to know the most effective or preferred way for you to get information.

Appendix C: Decision Aid File

The file is available to download in OCAD University's Open Research Repository (Decision Aid.jpg)