Data Accessibility: Tactile, Haptic, and Sonified Data in Data Visualization

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PSYC 6135
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June 27, 2021

Introduction

Approximately 36 million people in the world are blind and an additional 217 million have moderate to severe vision impairment (Lee, Choe, Isenberg, Marriott, & Stasko, 2020). Furthermore, the World Health Organization estimates that, globally, 1.5 billion people live with hearing loss, 430 million of whom require rehabilitation services (WHO, 2021). Given that hearing and visual impairment affects so much of the global population, it is necessary to consider appropriate adaptations for various learning needs and data accessibility. However, despite the need for alternative learning mediums, data is often presented specifically for individuals with intact vision and audition. Estimations have purported that scientific textbooks and journals contain approximately 1.3 graphical representations per page (Gorlewicz et al., 2018), making accessible data visualization extremely important in the fields of education and higher academics. Indeed, only 6% of visually impaired individuals receive a bachelor's degree in the United States (Tennison et al., 2020).

In the ever-expanding landscape of data visualization, there is the opportunity to provide accessible data to individuals with unique learning needs. For the purposes of this paper, data accessibility will refer to the extent that data is presented to users in a format that they can easily understand and interact with. The goal of data accessibility is to ensure that communities who have been historically excluded from data access (e.g., blind and deaf communities) may now interact with, understand, and create data representations.

Where visual and hearing impairments may once have been understood as a learning disadvantage, recent research may suggest otherwise. For example, neural reorganization, which is common in individuals with sensory loss, acts as a compensatory process and increases the acuity of intact senses. Such reorganization is well observed in the domain of blindness for both humans and animals, whereby neurons in multisensory brain areas show increased responsiveness to auditory and somatosensory stimuli (Singh et al., 2018). Moreover, tactual or auditory stimuli activate the visual cortex in blind subjects, facilitating their ability to 'see' (Boven et al., 2000). Vision is purported to have approximately 500 times greater 'sensory bandwidth' than the sense of touch (Gorlewicz et al., 2020), but as a result of neural reorganization, individuals with visual or auditory impairments become better at differentiating subtle changes in auditory representations and tactile sensations, laying a foundation for the use of touch and sound as a means to represent data (Boven, Hamilton, Kauffman, Keenan, & Pascual–Leone, 2000).

It has only been in the past two decades that the visualization of data become readily accessible for visually- and hearing-impaired users, as the introduction of tactile graphics, haptic learning, and data sonification has begun to develop more rapidly. The current paper presents an overview of the field of data accessibility and offers suggestions for enhancing user friendly data for individuals with varying sensory needs.

Tactile and other Haptic Data

Haptic pertains to the sense of touch, including tactile perception used to feel textures and manipulate objects with high dexterity, as well as kinesthetics of proprioceptive perception used to feel forces on the body and sense the position of body parts (Fritz & Barrier, 1999). Nevertheless, literature often makes a distinction between tactile graphics – raised Braille and dots/lines, and haptic data – more dynamic forms of touch and kinesthetic proprioception.

Tactile Graphics - Tactile graphics are simply raised line drawings that can be felt (Lee et al., 2020). As the use of visual maps and graphs in printed work began to rise in the 1960s and 1970s, increased efforts were made to convert visual graphs into tangible forms for visually impaired users (Barth, 1987). For example, 1971 marked the first set of guidelines in the educational system for teaching tactile graphic displays, specifically map interpretation, to visually impaired students (Barth, 1987). In 1979, a Workshop on Tangible Graphic Displays was held at the University of Louisville where participants, including 17 blind individuals from various backgrounds, determined that intensive training of broad graphic materials be introduced at an early point in the education of visually handicapped students (Barth, 1987). *The Development of Fundamental Skills in Tactile Graph Interpretation: A Program for Braille Readers* report by the U.S Department of Education was release in 1987 (Barth, 1987), and tactile graphics have continued to be a mainstay in the teaching of data graphics to visually impaired individuals.

Currently, tactile graphics can be read by the visually impaired user on paper or through the use of certain tactile devices, such as refreshable Braille displays with peizoelectric actuated pins. Conventional visual graphs can be converted to tactile graphic form in several ways. These include being printed on Braille embossers or swell paper, an embossed metal template can be made to create plastic forms, or the graph can be traced onto specialized tactile drawing film (Kalia et al., 2014). Regardless of the technique, a 2D embossed version of the graph is the product. Studies have shown that tactile graphics provide touch readers with many of the benefits that visualizations provide sighted readers, and indeed, accessibility guidelines recommend the use of data graphics for visually impaired individuals (Lee et al., 2020).

As one can imagine, the use of surface texture in tactile graphics can only present a fixed and limited amount of information to tactile readers. Braille labels and keys are often used to annotate the content, but this annotation is not accessible for many blind users, as approximately 90% of blind people in the United States cannot read Braille (Suzuki, Stangl, Gross, & Yeh, 2017). Recently, research has indicated that one of the difficulties in understanding embossed tactile graphics is largely due to inaccurate shape perception (Kalia & Sinha, 2011). Not surprisingly then, Kalia and colleagues (2014) demonstrated that when sighted individuals had to draw (recreate) everyday objects from either 2D embossed line drawings or 3D renditions (3D printed), they were significantly more accurate with the 3D renditions because they could grasp them, enhancing shape perception. In a similar vein, Hahn et al. (2019) developed plastic 3D renderings to teach the physics of sound to visually impaired Highschool students, finding them extremely helpful (Hahn, Mueller, & Gorlewicz, 2019). With the affordability of 3D printers now, it is likely that there will be an increase in the use of 3D graphical models, particularly in the education system where they can be used year after year.

One of the new advancements in the field of tactile graphics is dynamic tactile markers. Specifically, Suzuki and colleagues (2017) created a software/hardware system that actuates magnetic elements on top of a static tactile graphic. Their system, FluxMarker, can move multiple small magnets on a grid to various possible locations, and can be programmed to move based on questions asked to it (see Fig. 1). This group found very positive reactions from a group of blind individuals when using the FluxMaker for location finding or navigating on maps, data analysis, physicalization, feature identification, and drawing support. This tactile graphical technology eliminates the need for Braille and is useable for individuals with both vision and hearing impairments. Moreover, because the users ask a specific question and the markers move accordingly, this reduces any possible confusion that can occur when graphics have too many elements. Although fairly affordable (~ $40 USD per sheet) and reprogrammable, it is a more costly and potentially time-consuming option. Nevertheless, it appears to be a promising technology that allows individuals questions to be answered in a non-linguistic and non-auditory format (i.e., not a screen-reader or voice-controlled personal assistants).

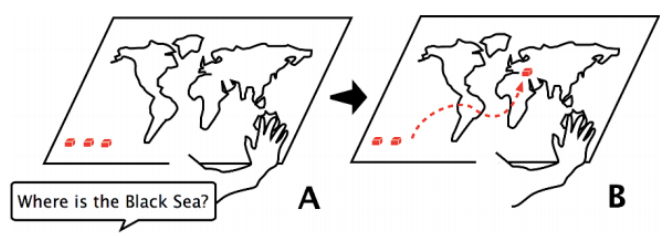

Figure 1. The FluxMaker dynamic tactile graphics allow an individual to ask a series of questions and magnetic tactile markers on the 'page' move. For example, A) an individual asks where a specific location is on a map and B) the magnetic markers move to that location for them to feel (Suzuki et al., 2017).

In our technological era, there are now programs to help create and read graphs on refreshable Braille displays, such as the Braille Note Touch Plus (Humanware). A benefit of these digital methods is the ease at which they can be updated with the newest graphics and data. Nevertheless, the Perkins School for the Blind in Boston stresses the use of "old school" methods for *teaching* graphics, including tactile graphics, 3D models, and physical graphing boards, before introducing any digital software to students. A similar response was given by the principal of the Ontario regional school for the blind, W. Ross Macdonald School (Brantford; personal communication with Dan Maggiacomo, June 16, 2021). In fact, the Braille Authority of North America outlines the specifications for all types of tactile graphs used for teaching (brailleauthority.org). As such, tactile 2D graphics and 3D models will likely continue to be used in special education centers, despite rapidly advancing technology in tactile graphics other domains of accessible data visualization.

Haptic Data - One of the earliest accounts of haptic data visualization, including the use of the term, was Project GROPE, established in 1967. One of the project arms developed a haptic display for *feeling* molecular forces (Brooks, Ming, Batter, & Kilpatrick, 1990; C. J. Roberts & Panëels, 2007) (Fig. 2). Chemists reported that they had a new understanding of the details of receptor sites, their force fields, and why a particular drug might dock well or not. Following the introduction of Windows and Macintosh desktop computers in the early-mid 1980's, haptic displays such as the PHANToM device (1992; see Fig. 3) and GHOST software (1996) were created, allowing for an immersive tactile/kinesthetic experience of data (C. J. Roberts & Panëels, 2007). In these haptic displays, to facilitate the differentiation of data elements and their various characteristics, friction and texture were readily used. For example, different surface textures might have be used instead of different colours seen on a visual graph (Fritz & Barrier, 1999). Graphs might additionally employ the use of "grid lines" by generating a very small force when the line is passed, facilitating the interpretation of distance across the graph. As one might imagine, being able to determine the exact data points (i.e., numeric values) is difficult using non-language formats. Indeed, haptic display methods of data visualization enable the interactor to get a sense of data trends, where Braille is then required to represent exact numbers (e.g., on the axes) (Fritz & Barrier, 1999). For example, using the PHANToM force-feedback controller, visually impaired individuals were tasked with exploring line graphs to find interesting features such as the maximum and minimum values and any points of intersection. While participants could generally discern the shape of line graphs, the perception was often distorted and inaccurate (J. C. Roberts, Franklin, & Cullinane, 2010). Since this point, haptic technology has continued to develop at a fairly steep rate, whereas the applications for this technology, particulalry data visualization, have been much slower (C. J. Roberts & Panëels, 2007). For example, the Novint-Falcon, a haptic device similar to a computer mouse, was originally developed as a gaming device, but was later shown to assist visually impaired individuals' understanding of graphs and charts created in Microsoft Excel (J. C. Roberts et al., 2010).

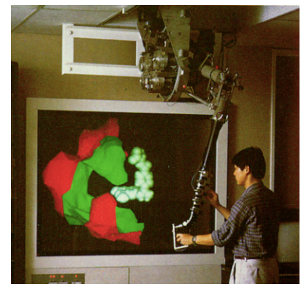

Figure 2. Project GROPE and the Argonne Remote Manipulator (ARM), enabling individuals to feel receptor sites and the bonds between molecules (Brooks et al., 1990).

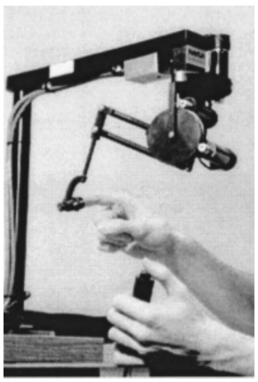

Figure 3. The PHANToM haptic interface device (Fritz et al., 1999).

Currently, there are some new haptic data tools utilize other forms of haptic sensation, such skin dragging and skin stretching (Bardot et al., 2020). In skin dragging, a device contacts the skin to provide information over space. Individuals have been shown to be able to detect the device's position to within 1.2cm and to estimate

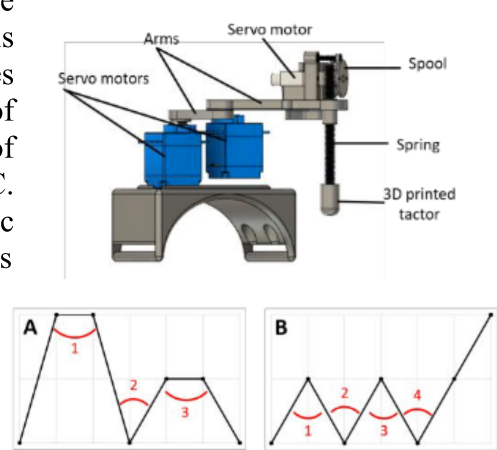

Figure 4. (top) Example of a skin dragging device (tractor) that would rest on the upper arm and drag/palpitate the arm to display a graph. (bottom) Representations of a three-point (A) and four-point (B) graph from the tractor. (Bardot et al., 2020).

the length of its movement to within 1.44cm (Dobbelstein, Stemasov, Besserer, Stenske, & Rukzio, 2018). For example, Bardot and colleagues (2020) created an electromechanical tactor (Fig. 4 top) that 'drew' graphical data on the forearms of individuals. Specifically, the tactor used continual, light-touch contact along one axis, with harder contact/pushes for each data point followed by 500ms pauses (Fig. 4 bottom). Currently, the device is large and cumbersome, but the authors suggest possible developments of bracelets or watches with skin-dragging technology that could display data such as heart rate, intensity level of movement, etc.

A possibly more applicable avenue in haptic data is the addition of vibrotactile elements to touchscreen display graphics. Vibrotactile information (i.e., the use of a vibration) is not new; in 1966, input from optical sensors were used to actuate an array of vibrating pins so that an individual could feel and interpret written text (Linvill and Bliss, 1966), and in 1970 the Tactile Television converted camera images of basic shapes into an array of vibrating points (Collins, 1970). Currently, vibration is used as supplementary information for the user in many electronic devices, such as cell phones, tablets, and video games. For use in graphics, vibratory feedback is commonly used in two ways on touchscreen-based platforms: (1) to create a physical representation of what is being interacted with, and (2) to provide an affirmative response to a user's kinesthetic motion when interacting with the surface of the screen (Tennison et al., 2020). Typically, vibrations <3 Hz are perceived as a slow and undulating motion, 10 - 70 Hz perceived as flutter, and 10 - 300 Hz as a smooth/constant vibration. Additionally, by varying the amplitude over time, the perception of rhythm is created, and this creates patterns that are often highly discriminable (Tennison et al., 2020). These simple vibrotactile graphics can be supported on small screen such as cellphones, despite their low resolution. Tennison et al. (2020) determined that vibrotactile feedback at 2.5 Hz is best for mapping to slow, dashed sensations, 10 Hz for mapping to quick, dotted sensations, and 50 Hz for mapping to constant, solid sensations, whereas values in between are difficult to discriminate and >100 Hz can be interpreted as solid and not representative of a line. Additionally, lines must be >4mm apart in order to distinguish them (Gorlewicz et al., 2020). Gorlewicz and colleagues (2020) determined that vibrotactile information was especially beneficially for visually impaired individuals to interpret the spatial arrangement and distance between items or line segments.

In a similar line of research Bateman et al. (2018) have started investigating the potential use of electrostatic touchscreens for the interpretations of data graphics (and other images), for visually impaired individuals. Electrostatics apply voltages to a conductive surface in order to create friction on a user's finger. This technology was originally employed to create a tactile display by applying different voltages to an array of pins in order to produce texture (Strong and Troxel, 1970). The current electrostatic touchscreen employs two types of haptic effects: (1) temporal haptic effects, generated by rapidly iterating through a fixed array of intensities such that the perceived effect varies over time, and (2) spatial haptic effects, generated by mapping specific values to each pixel on the screen such that the perceived effect varies by location. Both of these effects can be used to create textures that, once applied to a certain area of the screen, create the perception of a haptic object. As a proof of principle, blind individuals were tested on their ability to locate a single electrostatic dot on the screen, and proved to be fairly accurate (78-97% accuracy) (Bateman et al., 2018). Interestingly, individual's accuracy appeared to increase towards the perimeter of the screen, likely indicating that the edges of the screen are used as reference points. This suggests that accuracy might decrease with larger screen sizes where there is more 'internal space' void of spatial references. Collectively, the use of vibrotactile and electrostatic technology proves very adaptable to technology that is presently very readily used, indicating its significant promise in the field of accessible data visualization.

Data sonification

Sound data is common in everyday life with a reliance on alarms, buzzers, and now smart speakers to provide a rich auditory landscape through which to understand the world. Inventions such as the stethoscope (1816) and the Geiger counter (1928) provided a means by which to convert imperceptible phenomena into auditory data. Thus, the use of sound as information is not novel. However, it was not until 1954 that researchers began to test sound perception, when Pollack and Ficks first introduced auditory displays to empirically test whether participants could distinguish sounds through different variables such as frequency, loudness, and duration of auditory data (Schito & Fabrikant, 2018). In 1974, Chambers, Mathews, and Moore created an auditorily enhanced scatter plot using frequency, spectral content, and amplitude, to use in multivariate data classifications (Frysinger, 2005). By the 1980s, various experiments were being conducted on how data sonification could be used for exploratory analysis with multivariate and logarithmic datasets (eg., Bly, 1982) and evaluating compound sound variables (such as pitch and volume) to test mappings of various dataset dimensions (e.g., Williams, 1990) (Frysinger, 2005). These experiments yielded results suggesting that not only could participants easily understand the sonified data, the combination of audio and visual elements increased user accuracy of the understanding of a dataset (Schito & Fabrikant, 2018).

However, the process of data sonification for research purposes is a relatively new endeavour. It was not until 1992, when Gregory Kramer established the International Conference on Auditory Display that data sonification was established as a new field of research (Schito & Fabrikant, 2018). Data sonification, which is "the use of nonspeech audio to display data" (Herman, 2008) is an important advancement in scientific research that allows visually impaired and blind users to interact with and understand data that has historically been presented visually. In addition, Hermann (2008) writes that sonification must be replicable (the same dataset is transformed in the same way and produces the same results) and that the objective elements in the data are systematically represented in the resulting sound.

As more researchers have become interested in the use of sound for understanding data, the field has continued to grow. Flowers (2005) writes that the field of data sonification has been integral in expanding our perception of data and the inclusion of auditory elements has the potential to increase our understanding of complex data, which also give insight into the perceptual differences between auditory and visual data and how both may interact to enhance data representations.

There are several different important elements in data sonification that can represent changes in data that parallel visual displays. For example, mapping data to recognizable sound patterns such as pitch, loudness, and duration can produce distinct sounds that are used to distinguish different variables (Last and Usyskin, 2015). However, the process of data sonification is not as simple as choosing random elements to translate visual data into sound. Interestingly, although the sound is integral to the interpretation of the data, Walker (2002; 2007) found that the labelling of the data is important to the interpretation. For example, students tended to assign different slope rates to variables called "temperature" and "pressure", displayed with the exact same sounds. Another important consideration in the development of sonified data is to understand the perceptual and cognitive expectancies for the user (Walker & Mauney, 2010). Previous research has highlighted that certain sound dimensions are better for different kinds of data representations. For example, Walker and Kramer (2005) found that temperature is best represented by frequency but that the size of a datum would better be displayed as tempo (Walker & Mauney, 2010).

Despite some complications with representing sound, recent experiments comparing visually impaired and sighted users have found that both kinds of users give similar estimations of the data. Walker and Mauney (2010) used magnitude estimation in experiments with visually impaired, blind, and sighted students. By asking participants to determine preferred mapping, scaling values, and polarity to "learn about how people "intuitively" and "naturally" interpret various types of audio information" (pp. 12), they were able to determine that group estimation was highly correlated when judging how much change and in which direction was required in mapping the sonified data, which was consistent for central and large slope mappings. However, there were certain differences in attributable slope mappings in which sighted users' slopes were more than double blind users. Additionally, Last and Usyskin (2015) found that users with increased experience with music were better able to perform interactive data mining tasks with time series data that were purely sonified. Studies such as these are important steps in understanding not only the ability of different users (sighted, visually impaired) to understand sonified data, but also to guide the design of data sonification that is better understood by the user rather than the preferences of the programmer.

While the field of data sonification represents an evolution in how people understand data, there are various drawbacks of this medium. First and foremost, it continues to exclude users who may be both visually and hearing impaired, where tactile data is better suited for such users. In addition, as outlined above, different elements of sound (e.g., pitch, loudness, timbre) may introduce user biases or variation in understanding across users and some users (e.g., more musically inclined) may have an obvious advantage in their understanding of complex, multivariate sonified data.

Future Directions

In and amongst the rapidly expanding technological advances in haptic and auditory graphing methods lies an important question; which graphical features or combination of features is optimal for which type of data display (e.g., relationship, group differences, proportions, time series, maps etc.)? It is fairly clear that tactile graphics and 3D models are extremely beneficial for teaching purposes, and specifications for different tactile graphics used in these settings have been outlined (brailleauthority.org). How various graphs are best represented in other settings is not as clear. For example, as stated previously, in sonified data, temperature is best represented by sound frequency, whereas data point size is more easily interpretable as sound tempo (Walker & Mauney, 2010). Furthermore, recent research has determined that tactile (i.e., embossed) scatter plot diagrams are easier and quicker for individuals to understand compared to tactile tables or electronic tables (Watanabe & Mizukami, 2019). These types of comparison studies of specific graph type are not as common. It might also be possible that certain graphical features are more beneficial for specific domains of data information (e.g., medical, stocks, environmental). Future research should strive to include many graphical formats with various domains of data when assessing new technology or data platforms. Moreover, it is well known that multimodal (e.g., visual + auditory, auditory + tactile) information is often processed faster and/or recalled better than unimodal information, and this is true for neurotypical individuals, as well as those with visual and hearing impairments (Boven et al., 2000; Jeong & Gluck, 2002; Williams, Light, Braff, & Ramachandran, 2010). Designing studies with these additional considerations in mind will help to discover the most effective methods for conveying data graphics to visually and hearing-impaired users. Recently, Gorlewicz and colleagues (2020) put forth a series of guidelines for multimodal graphics on touchscreen displays (Fig. 5) and demonstrated that the use of multimodal (sonification + speech sounds + vibrotactile) touchscreen displays was not only feasible but enabled information extraction comparable to hardcopy embossed graphics for a variety of graphical concepts. Moreover, the use of multiple modalities can increase the capacity to accurately represent multivariate data, as there are more 'sensory elements' available to represent variables etc. Although this field is still in its infancy there is an ever-increasing commitment for researchers to make data accessible for all users. For example, recent work by Ferguson (2018) tests parameter mapping for non-visual information such as auditory, vibrotactile, and electrotactile stimulation to better understand how user expectations map onto the values of sound and tactile data.

One final consideration is the use of the term *data visualization*. Although the term 'visualization' can be taken in an abstract manner to encompass the notion of forming a mental representation, the common use of the word takes on a more literal meaning (C. J. Roberts & Panëels, 2007). As this process only available to sighted individuals, we instead propose the term *data representation* for enhanced inclusivity.

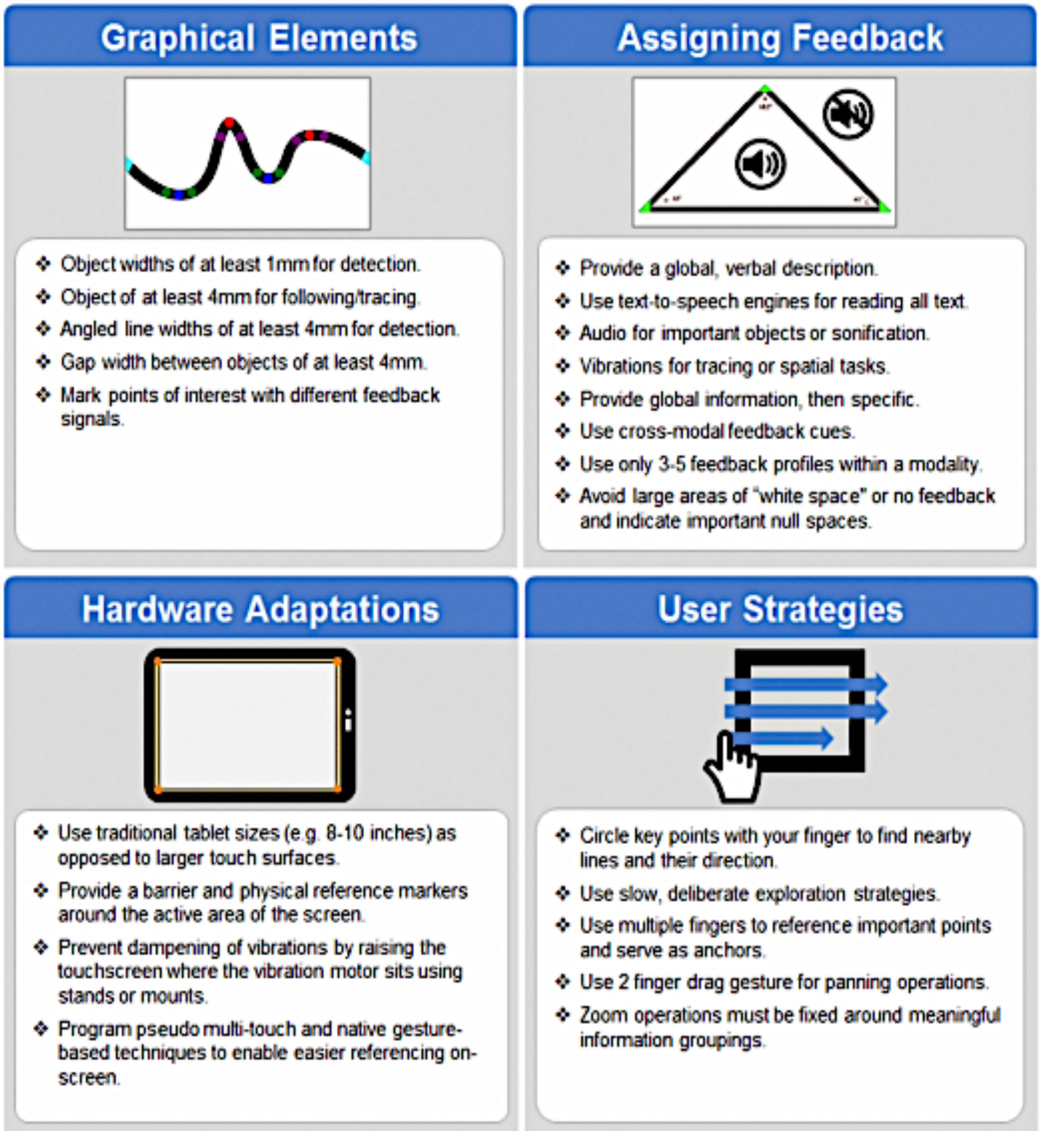

Figure 5. Gorlewicz et al. (2020) recommendations and considerations for creating multimodal graphics on touchscreen platforms.

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