# BLINDNESS, TECHNOLOGY AND HAPTICS

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## Abstract

The blind and the visually impaired are in a unique position to appreciate and make functional use of haptic devices. Designing devices for the blind is, however, more arduous than many researchers and inventors expect. It is thus important to fully understand the needs and requirements of that community before attempting to create devices for them. It is also important to learn from past research and development in the application of technology for the blind. This survey provides an overview of current knowledge on blindness and rehabilitation technology relevant for the design of aids for the blind, and more particularly for the use of haptics with the blind.

The survey begins with a demystification of blindness and a discussion of the differences between blind and sighted. Follows a broad overview of the many attempts at applying technological solutions to problems encountered by the blind. The survey ends with a discussion of lessons learned from previous failures and successes in rehabilitation technology as well as speculation on the future of haptics and other technologies for people living with blindness.

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## 1. INTRODUCTION

The blind community has long been believed to be the most apt to reap the benefits of haptic research. While the sighted often fail to recognize the importance of their non-visual senses, the blind must make full use of them. As such, they are in a unique position to appreciate and make functional use of haptic devices. Designing devices for the blind is, however, more arduous than many researchers and inventors expect. It is thus important to appreciate as much as possible the needs and requirements of this community before attempting to create devices for them. It is also important to learn from past research and development in the application of technological aids for the blind. This survey provides some basic facts about blindness and surveys rehabilitation technology as relevant to the design of aids for the blind, with a particular emphasis on haptics.

The research literature on blindness is extremely varied in terms of investigators profiles, goals and scientific rigor [100]. Typically, the literature describes attempts at solving immediate problems with applied solution, gain knowledge about perception of the blind, or use the blind to test hypotheses about vision. Aiding the blind is also often used in the haptics literature as the motivation for research projects. This survey covers all types of literature, ranging from rehabilitation manuals to research monographs. Informal comments from the blind community, often available on the web, are also used to gain additional insight.

This survey is divided into three part. The first two sections provide an overview of the literature on blindness from the psychological and rehabilitation point of view. The goal is to provide a better understanding of blindness and of how the blind differ from the sighted. The next five sections provide a wide-ranging survey of the literature on assistive technology for the blind, with emphasis on haptics. Finally, the last section discusses the conclusions that can be drawn from the analysis of the literature.

## 2. Blindness and Visual Impairment

The blind and visually impaired form a heterogeneous group. Blindness and visual impairment vary in etiology, visual acuity and extent of the visual field [100]. The degree of visual impairment varies from no light perception at all to a slight blurring of vision, with every gradation in between [59]. The blind are said to have *light perception* when they can tell if they are in a dark or bright room. They are capable of *projection* if they can also locate the source of the light. Similarly the field of view may vary in extent or include blind spots.

The term *legally blind* corresponds to a set of criteria for blindness based on either low acuity or restriction of the visual field [59]. In the United States, legal blindness is defined as having a visual acuity of 20/200[1] or less, or having a visual field of 20 degrees or less. The term *low vision* is used to "describe individuals who have a serious visual impairment, but nevertheless still have some useful vision" [59]. 'Blind' is sometimes used in a restrictive sense to refer to people with at most light perception. 'Visually impaired' then refers to all the legally blind [100].

The age of onset of blindness is significant as it may affect a person's perception, representation of space and attitude towards blindness. A person who has been blind from birth is said to be *congenitally blind*, or *early blind* [59]. The term is sometimes used to include those who have lost sight in the first years of their life [16]. The *adventitious blind*, or *late blind*, have lost sight later in life [59].

Blindness is due to a variety of causes [41, 59]. According to [74], the leading causes are glaucoma, macular degeneration, cataract, optic nerve atrophy, diabetic retinopathy and retinitis pigmentosa. The American Diabetes Association adds that "diabetes is responsible for 8% of legal blindness, making it the leading cause of new cases of blindness in adults 20-74 years of age" [1]. This is significant since diabetic retinopathy is often accompanied by peripheral neuropathy which also impairs the sense of touch.

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[1] A visual acuity of 20/200 is defined as the ability to read at 20 feet what someone with normal vision could read at 200 feet.

Textbooks on blindness and rehabilitation often mention the inadequacy of statistics on blindness due to a lack of national efforts in collecting the data and the variations in definitions of blindness across agencies, states, or countries [16, 33]. See [74] and [9] for recent collections of statistics on blindness.

The American Foundation for the Blind estimates that there are 10 million blind or visually impaired people in the United States [9]. In a survey realized in 1994-1995, 1.3 million Americans (0.5%) reported being legally blind. Of this number, only 10% were totally blind and another 10% had only light perception. The remaining 80% had some useful vision. Few statistics appear to be available about the age of onset of blindness. It is reported that "only eight percent of visually impaired people are born with any impairment" [56]. In Canada, it is estimated that 666,500 are blind or have low vision [3]. Of these, 144,100 are in Quebec. Worldwide, an estimated 180 millions are visually impaired, of which 40-45 millions are blind [74]. It is estimated that 80% of blindness and serious vision loss could be avoided or treated in developing countries.

The prevalence of blindness is much higher for the elderly. It is estimated that 1.1% of the elderly (65 and over) are legally blind compared to 0.055% of the young (20 and under) [59]. It is also reported that "more than 50 percent of individuals with visual impairments also have one or more other impairments" [16].

Considering the continuing progress of medicine and science, it is surprising to note that blindness is expected to increase in the coming years. It is predicted that the number of blind people will double by 2030 [74]. Leung and Hollins [75] explain that the number of blind children is expected to increase because "the proportion of babies born to mothers at the extremes of the child-bearing years is increasing" and because "medical advances have made it possible for many premature infants, who in the past would have died, to survive". The aging of the population in developed countries and the growth of the population in developing countries are also causes of concern.

## 3. Neurology and Psychology

The blind and the sighted live in different perceptual worlds [60]. Some aspects of the environment can be perceived only through vision. Properties of the environment that are better accessed through touch or hearing, however, are more salient and better attended to by the blind. It is natural to ask, then, in what way visual deprivation affects the perceptual and cognitive abilities of the early and late blind.

We begin with an overview of the effects of blindness on the brain. This is followed by an examination of the effect of blindness on the senses of touch and audition. Finally, the issue of mental images and spatial perception is addressed.

### 3.1. **Brain Plasticity.**

Deprivation of visual input to the brain during a critical period of development is known to cause permanent damage to the visual cortex [61]. A number of experiments performed with cats and monkeys have shown that animals deprived of vision early seem to have no response to stimuli once vision is restored [61]. They behave as if they were blind. There is a critical period however after which visual deprivation seems to have no permanent effect. These conclusions are confirmed in humans by clinical observations following the removal of cataracts.

Brain imaging techniques have been used recently to study the plasticity of the brain. Brain plasticity refers to functional reorganization occurring in the brain as an adaptation to demands or trauma. Studies with Braille readers have shown, for example, that the representation of the reading finger in the somatosensory regions of the cortex is disproportionately large [44, 52]. Similarly, studies have shown that the visual regions of the brain can be activated by tactile or auditive stimulation in the early blind, and to a lesser extent in the late blind [49, 47, 52]. The two types of reorganizations are termed uni-modal and cross-modal plasticity.

The cause and significance of these results are the subject of debate in the literature. It is not clear, for example, that an increase in cortical representation of a finger translates into an increase in tactile acuity. The observed brain activity may not be functionally relevant to the task being studied. Some studies have shown, however, that deactivation of the primary visual cortex (V1) in the early blind causes a drop in Braille reading performance [47]. Similarly, Amedi et al. showed that deactivation of V1 interferes with verbal processing in the blind, but not in the sighted [20]. A recent study by Goldreich and Kanics also explains observed improved tactile acuity in the blind by cross-modal plasticity [52].

3.2. **Sensory Compensation.** The theory of sensory compensation, according to which the blind's remaining senses are heightened to compensate for the loss of sight, has long been debated. While many textbooks on blindness take a conservative stance against the theory (e.g. [62, 100]), there is mounting evidence from recent studies for limited sensory compensation in the blind [26].

Stevens and Weaver, for example, state that "one consequence of blindness appears to be enhancement across the broad categories of auditory perceptual and cognitive functions, particularly in cases of early-onset blindess" [96]. Zwiers et al., on the other hand, showed that some sound localization skills may be impaired in the early blind due to the unavailability of visual feedback for calibration [107].

Similarly, a recent study has shown evidence of better tactile acuity in the blind [52]. Using highly controlled stimulus, the authors showed that "the average blind subject had the acuity of an average sighted subject of the same gender but 23 years younger." Warren, on the other hand, reports mixed evidence concerning pattern and form perception [100].

Despite the controversy, it is generally agreed that the blind are more proficient at attending to nonvisual stimulus and that they make better functional use of nonvisual senses [62]. It seems, for example, that "the blind have, through need, learned to attend better to auditory stimuli and therefore can make more use of the available auditory information than sighted people" [100]. A good example is the "obstacle sense", or "facial vision", that allows the blind to feel the presence or absence of obstacles. Researchers have shown that the obstacle sense is mediated by audition, from echodetection and echolocation [62, 100]. The obstacle sense can in fact be learned by blindfolded sighted subjects. The blind are also particularly skilled at attending to voices [62]. Similarly, it has been shown that curvature is judged better by the blind due to better exploratory techniques [100, 62].

3.3. **Space Perception & Mental Imagery.** The extent to which vision is necessary to mediate the perception of space and the formation of mental images is also the subject of much debate in the literature. A comprehensive treatment of this topic is beyond the scope of this survey. See [97, 68] for more information.

Vision is proposed by some to provide "a framework into which all spatial sensations can be integrated" [62]. Others define this framework as an integration of the various senses, in which case the weight given to the remaining senses is increased in the event of blindness [37]. It is likely however that "having vision during a particular developmental period may allow the establishment of a spatial perceptual system that is more effectively integrated than would be the case without vision" [100]. This may explain why the late blind sometimes outperform the early blind in experiments on spatial perception.

The concept of mental imagery is also of interest. A mental image is defined as a "mental experience which occurs in the absence of stimulation, but which resembles the experience that occurs when a stimulus is actually present" [60]. In the sighted, mental images tend to be strongly visual in nature. It is known, for example, that "sighted subjects tend to visualize objects they examine by touch" [60]. There is, however, "compelling evidence that haptic mental imagery exists in congenitally blind people" [60]. Haptic mental images, however, appear to be different in nature than visual images. It seems, for example, that the early blind "have a greater ability to perceive vividly both the front and back of a palpated object at the same time" [60].

## 4. Daily Living

The previous sections provided a brief introduction to world of the blind. In this section, we begin the survey of technical aids and assistive devices for the blind.

Many specialty items are available to help the blind perform the simple tasks of daily living more efficiently. These range from reading the time to identifying the content of food cans. The Online Shop of the Royal National Institute for the Blind gives an interesting overview of available devices including watches, alarm clocks, magnetic Braille labels and tactile tags for clothing colors [7]. While many such aids are affordable, others, such as UPC scanners, can be expensive.

Other commonly used aids, such as Braille, the long cane, and guide dogs will be discussed in detail in the following sections. The numerous aids for people living with low vision will not be discussed in this document; see [63] for more details on that topic.

## 5. Mobility and Orientation

Numerous aids exist to help meet the mobility and orientation needs of the blind. Mobility is defined as "the ability to travel safely, comfortably, gracefully, and independently" [60]. Orientation refers to the ability to situate oneself relative to a frame of reference.

The long cane was invented in the 1940s and is still the most widely used mobility aid with a recent estimate of 109 000 American users [63, 9]. It allows the detection of obstacles and drop-offs within a 3-foot range. This short range forces the user to be prepared to stop or to correct course quickly, and thus limits walking speed [63]. The cane cannot warn of overhanging objects such as tree branches. The cane is easily identified by other travelers, warning bystanders to get out of the way but also marginalizing the blind [30].

Despite its shortcomings, the long cane is a wonderful instrument providing surprisingly rich information. It is generally used by making arcs, tapping on each end [63, 30]. The sounds emitted by tapping can be used for echolocation. The contact dynamics also provides information about the texture and slope of the ground. This and "cues through the soles of the feet" are a rich sources of information [34].

The guide dog is also a popular mobility aid with approximately 7000 users [9]. Guide dogs are effective but must be trained by professionals and cared for by their owners. Their cost is approximately $12,000 to $20,000 and their professional life is of approximately five years [90].

Innumerable attempts have been made to leverage technology to supplement or replace these two "low-tech" aids. The resulting devices are commonly known as electronic travel aids (ETAs). The rest of this section provides an overview of the range of ETAs that have been experimented with, with particular emphasis on tactile stimulation. Readers are referred to [56, 73, 30, 63, 34, 21, 16] for more extensive surveys.

ETAs can be divided in two classes, depending on their main use. A first class provides a warning of obstacles and facilitates the selection of a clear path. A second class helps the blind orient themselves with respect to their environment and travel to a given destination. It is important to remember that many of the devices presented here are intended to supplement rather than replace the white cane or guide dog [30].

5.1. **Obstacle Avoidance.** These aids provide advance warning of obstacles and allow the blind to find a safe, clear path. It is possible to distinguish between those devices providing rich and those giving simplified information. This distinction is sometimes blurred in practical devices.

The first approach is to present rich information for the user to process and analyze. The expectation is that with extensive training users can learn to interpret the information for obstacle avoidance purposes. There is disagreement, however, "over whether the additional information that [these devices] provide is worth the very considerable extra cost and the effort in training" [30].

A popular system is the SonicGuide [63, 30]. Also known as the Binaural Sensory Aid, this device uses ultrasound to scan the space in front of the user and creates a stereo audio signal that varies in pitch to indicate the distance of obstacles. The system fits conveniently in the frame of a pair of glasses. Although the rich information provided by the SonicGuide can be extremely useful, learning how to decode this signal requires significant effort. Downie [42], an experienced user of ETAs, comments:

> “At the end of training, I could do some very useful things with the aid. However [. . . ] I was still developing skills for a couple of years.”

There is also fear that the audio signal could mask important environmental sounds. Although significantly more complex to implement, devices relying on the tactile channel may thus present advantages. While audition is already tapped for echolocation, the sense of touch is largely unused while traveling. It is thus possible to stimulate the skin without interfering with the normal activities and environmental cues used by the blind. Moreover, it may be easier to represent spatial information on the skin rather than through audition.

The best known such aids can be classified as vision substitution systems since they provide sufficiently rich information to be used as more than ETAs. These devices will be discussed in section 8.2. A similar audio device, the vOICe, will also be described in that section.

The alternative approach consists of presenting only limited information to the user. This approach has the benefits of requiring less training, reducing the cognitive load of device operation and often lowering the price tag.

The Sonic Pathfinder is similar to the SonicGuide but pre-processes the sensor data and presents “only that information which is of immediate practical interest to the moving pedestrian” [58]. The information is presented as simplified audio signals which are less likely to interfere with environmental sounds. Despite its simplicity, training was still shown to be critical for correct use.

Another device, the Laser Cane, comprises three lasers that scan the space in front of the user [63]. Each laser activates a tone and one of the beams also activates a vibrating pin. A more recent device, the UltraCane, uses ultrasound to similar ends [13]. The UltraCane has the appearance of a normal long cane but doubles as an ETA. The location and distance of obstacles is transmitted to the user through four distinct vibrating buttons on the handle.

The MiniGuide is held like a flashlight by its user [6]. As the ultrasound beam of the device hits an obstacle, the MiniGuide vibrates at a frequency that indicates the distance. An audio version of the device is also available.

Ulrich and Borenstein created an ETA inspired by mobile robotics that guides its user around obstacles in a very intuitive manner [90, 99]. The GuideCane is a small wheeled robot held by the blind like a cane. As it is pushed in front of the user, the robot scans the area with ultrasound and determines a path that avoids any obstacle. The robot then turn the wheels in the appropriate direction. The user feels the rotation of the GuideCane and intuitively follows the path chosen by the device. Despite some good results with the device, the authors acknowledge that “ultrasonic sensor-based obstacle-avoidance system is not sufficiently reliable at detecting all obstacles under all conditions” [90].

Finally, many researchers have used arrays of tactile stimulators to guide users. Ross and Blasch tested a system with three shoulder tappers that guide a blind person, for example to cross a street [87]. Similarly, Ertan et al. used an array of 4x4 vibrating stimulators for guidance [45].

5.2. **Orientation.** Although obstacle detection and avoidance is important, low-tech travel aids such as the long cane and the guide dog satisfy those needs for many blind people. This may be why "many blind travelers place travel orientation ahead of obstacle detection in importance" [34]. Here orientation refers to the way in which one finds his position relative to a reference frame and finds a route to a destination. This task is complicated by the unavailability of visual landmarks.

In recent years, a number of solutions have been proposed to provide navigation signs for the blind. Although fairly simple technically, these solutions generally require retrofitting buildings and street signs to incorporate active or passive beacons. The Talking Signs® system relies on infrared transmitters that broadcast verbal messages to handheld receptors [10]. A blind user entering the lobby of a building scans the environment with his device and hears 'information desk' or other messages depending on where the device points. Although installed in some cities, these devices have not yet been widely adopted.

Another alternative is to rely on positioning systems, geographic information systems (GIS) and mobile computers. For example, VisuAide (now HumanWare Canada) recently released a commercial product that combines a GPS receiver and a portable digital assistant (PDA) to provide the blind with information about their location, points of interest, and routes [12]. The Sendero Group also proposes the BrailleNote GPS that combines a Braille note taker with GPS positioning [2]. These aids greatly benefit from their reliance on generic mass market technologies, most notably from a reduction in cost compared to technologies developed exclusively for the blind.

The acquisition of spatial information from tactile maps and virtual reality systems will be discussed in section 6.2.2.

## 6. Access to Information

The sighted make heavy use of visual media to disseminate information. In this section, we discuss the technologies developed to provide equal access to these written, printed, and digital documents. We begin with a discussion of textual information. Follows a discussion of the more complex problem of graphics, maps, and 3D virtual environments.

6.1. **Text.** This section discusses the two main media used to gain access to written or textual information: Braille and voice. We then discuss the special case of access to printed material through technology.

6.1.1. *Braille.* Braille was invented in 1829 by Louis Braille [100]. Each Braille character consists of an array of two columns and three rows of raised or absent dots for a total of 64 possibilities. Computer Braille adds a fourth row. While print is read by the sighted at an average rate of 300 word per minute (wpm), experienced Braille readers can generally achieve only 100 wpm [60]. The lower reading speed is probably due to the sequential nature of Braille reading, among other factors [60]. The reader is referred to [79] for details on Braille reading.

Braille literacy is low [74, 56, 60]. While most clients of rehabilitation centers learn at least the basics of Braille so that they can read labels, few choose to study it more intensively [63]. This may be explained by the effort necessary to learn Braille and, in the case of digital media, the availability of cheaper alternatives [83].

Braille can be printed on paper and various other materials [98]. The resulting documents, however, are much bigger than their equivalent print version. Digital media now allows Braille to be displayed on refreshable Braille displays. A display typically consists of a linear array of 40 or 80 electromechanical Braille cells refreshed by an embedded or by a desktop computer. While effective, refreshable Braille displays are expensive due to the number of parts. Although attempts have been made to find alternative technologies (e.g. [28, 83, 85, 76]), none has yet proved sufficiently reliable to replace commercially available displays.

6.1.2. *Voice.* Textual information can also be accessed by asking or hiring someone to read out loud. Although pleasing, this method makes the blind dependent on others. Another method consists of using recorded speech. Numerous books are available on tape, audio cd or cd-rom. More recently, digital talking books and the DAISY standard have allowed better indexing and navigation of media. Portable talking book readers are available commercially [4].

Synthetic speech can also be generated from computer software or hardware. Much cheaper than refreshable Braille displays and requiring no knowledge of Braille, voice synthesis is popular for access to digital media and more generally to computer interfaces. Although normal speech can be fairly slow, it can be compressed to reach rates up to 275 wpm without affecting comprehension or retention significantly [100].

6.1.3. *Print.* Much of the written information available to the sighted is in the form of printed text, and cannot all be expected to be translated to an appropriate medium for the blind. The accessibility of print is thus a problem.

The Kurzweil Reading Machine was the first to combine an optical scanner, optical character recognition software, and a speech synthesizer to provide access to printed material [63]. The various components of that system are now widely available commercially and allow the blind some access to printed material. Such a system, however, is not portable and may not be capable of recognizing degraded text or handwriting.

Using the approach of sensory substitution (see section 8.2), the Optacon maps images obtained from a small camera into a tactile sensation experienced through a miniature tactile display [29]. The display consists of an array of 24x6 pins mounted on a mechanism similar to that of conventional Braille displays. Each pin of the display is associated with an optical sensor of the camera. When the intensity of the light reaches a certain threshold on a sensor, the corresponding pin taps against the skin at a specific frequency. As the camera slides over a printed character, a corresponding tactile sensation moves across the fingertip. With considerable training, an average reading speed of 35 wpm can be achieved ([63], citing [38]). The device can also be used, to a lesser extent, to explore printed graphics (see next section) or as an ETA (see section 5). The Optacon has also been used to explore graphical user environments by pointing the camera at the computer screen [95].

### 6.2. **Graphics.**

While written information can be easily converted to Braille or voice, graphical information is not trivial to map to an audio or tactile medium. In this section we survey the efforts made to give the blind access to tactile drawings, maps, data and mathematical visualization, and more recently to 3D virtual environments.

6.2.1. *Tactile Drawings.* The blind usually do not draw because that medium is not adapted to touch. It is, in particular, difficult to feel the drawing as it is being drawn [57]. Tactile drawings are generally executed on swell paper using a special pen that causes lines to be raised. Many researchers have observed the way in which the blind draw in order to get some insight on their mental representation of 3D space. Although some rules appear to be universal, the drawings of the blind are in many ways different from those of the sighted [57].

Recently, Kurze created a drawing system for the blind specifically to study their technique [69]. The system relied on a touch tablet, voice recognition (simulated), voice synthesis and swell paper. The user could draw primitive shapes, such as lines, and record voice labels that could later be queried. Kurze noticed many differences in the way the blind draw. Many visual conventions, such as perspective, are not respected and objects are sometimes folded out or flattened. The drawing is also not restricted to visible parts of an object: all parts may be shown while maintaining the topology of the object. He later used these findings to implement a haptic rendering pipeline that converts a 3D model into a 2D drawing [70].

Producing drawings for the blind is not trivial. As noted previously, the use of visual conventions in a tactile drawing may not convey the intended information unless the reader receives extensive training [62]. Moreover, the sense of touch cannot resolve fine details as well as vision [62] and is not well adapted to 2D material [57]. Visual pictures must thus be simplified and carefully adapted if they are to be used by the blind. Even then, identifying tactile drawing is very difficult [57]. This may be particularly true for the congenitally blind [62, 57]. In the next section, a special case of tactile drawings – maps – is discussed in more details.

6.2.2. *Maps.* Maps are used extensively by the sighted to obtain spatial information about an area and to orient themselves. Maps can similarly be used by the blind in the classroom and to plan their displacements. Although verbal descriptions are more often used, tactile maps can also be created using techniques similar to those used for raised lines drawings [66].

Not unlike visual maps for the sighted, the use of tactile maps by the blind requires training in order to grasp the relation between the 2D map and the 3D space [57]. “This requires not only the mastery of symbol interpretation but also the understanding of basic concepts such as geographical compass points, distance and scale, relative position, and so forth” [66]. It must also be remembered that “the blind child is seldom trained to think in terms of spatial concepts, let alone representations of these concepts” [66].

Despite their benefits, tactile maps present difficulties. The information processing capabilities of touch are known to be much lower than those of vision [81]. As a result, less information can be packed into a tactile map compared to a visual map of equivalent size [81]. This is particularly problematic for labeling since Braille is generally bigger than print. The alternative, using keys for the text, is tedious and can interfere with the acquisition of spatial information [81].

The low processing capabilities of touch forces the map maker to carefully adjust the level of detail of the map. “Tactual maps must hold enough information to meet the needs of the users but not so much as to confuse him” [66]. In practice, multiple maps at different scales are sometimes used [66]. Efforts have been made in the past to standardize the environmental features found in tactile maps and their symbolic representation [66].

Efforts have also recently been made to augment tactile maps with audio feedback. A typical system uses a tactile overlay on a touch tablet. As the user explores the map, the system provides information about the region under scrutiny. See the Talking Tactile Tablet for an example [101]. These systems are useful but still tedious because of the need to manufacture tactile overlays and associate digital information to them. Jacobson implemented a similar system that removes the tactile overlay and replaces it with rich audio feedback [65]. As the user slides his finger over a touch pad, audio feedback is provided in the form of speech, verbal landmarks, earcons and environmental sounds.

The use of interactive haptics is limited due to the cost of high-fidelity devices and the unavailability of commercial tactile displays. The use of haptic devices, however, could alleviate the need for tactile overlays. The BATS project attempted the use of consumer-grade haptic devices combined with audio feedback for map exploration [81]. The devices (“mice, trackballs, joysticks, and gamepads capable of providing force feedback”) provided cues such as bumps at the boundaries of countries and states and constant vibrations on cities. The system was successfully tested with maps of Roman Britain and North Carolina.

6.2.3. *Mathematics and Visualization.* Graphs, bar charts and other visual representations of data sets and mathematical functions are commonly used by the sighted to assimilate large amounts of information quickly and to grasp trends or other features of the data. This information can be adapted to some extent for the blind by the use of tactile drawings. As discussed previously, however, these drawings are less accessible than their visual counterparts and do not provide as much information. Many researchers have thus attempted to use haptic technology to solve this problem.

Ebina et al. used a tactile display similar to a refreshable braille display to show stock quotes and other complex graphs [43]. Many other researchers opted instead for visualization in 3D space using 3 degrees of freedom (DOF) haptic devices such as the PHANTOM® [8]. Fritz and Barner proposed a set of methods for the haptic visualization of 1D, 2D, or 3D data sets [46]. Magnusson et al. [77] used the PHANTOM® and the Virtual Reality Modeling Language (VRML) to feel 3D surfaces.

Yu and Brewster investigated the use of a multimodal virtual reality environment to convey bar charts to the blind [103]. The haptic feedback was used for guidance rather than to convey the height of the bars. They also compared the effectiveness of the PHANTOM® and the much cheaper Logitech® WingMan® force feedback mouse [102]. They found that the PHANTOM® is better in the haptics only condition but that this advantage is lost when audio feedback is added. A similar setup was used to test the exploration of line graphs with the PHANTOM® [104].

6.2.4. *Virtual Reality.* More generally, the blind require access to virtual reality and virtual environment. This problem was of particular concern in recent years due to the expected increase in the use of VRML on the web. Although this has yet to materialize, the accessibility of 3D pictures and even more interestingly the use of 3D pictures for rehabilitation deserve attention. The use of virtual reality with the blind amounts to the study of virtual reality in the absence of visual input. Vision being generally believed to be dominant in multimodal environments, the removal of this stimulus may have a significant impact on the fidelity requirements of haptic simulations. Jansson, for example, used the PHANTOM® to investigate the perception of sandpaper texture without visual feedback and noticed differences between the intended and the perceived texture [67].

Many researchers investigated the use of haptic devices to explore VRML environments by the blind. Magnusson et al. tested blind subject's capacity to explore models of objects using the PHANTOM® and concluded that "the users could identify and understand fairly complex objects" [77]. Similarly, Hardwick et al. used the Impulse 3000 Engine to explore virtual environments described in VRML [18, 55]. Colwell et al. also observed that perceived properties of virtual objects (size, texture, etc.) do not necessarily correspond to the physical properties programmed in simulations [35, 36].

Sjöström experimented with virtual environments for the blind using the PHANTOM® and the Logitech WingMan Force Feedback Mouse [91, 93, 92]. Based on this, he proposes a set of guidelines for the design of haptic interfaces that compensate for the point-like interaction of most devices. For example, a search tool (such as a cross or a magnet) can be used to facilitate finding scattered objects. The importance of well defined, easy-to-find reference points is also insisted upon. The shape of objects also has an effect on the ease of use of the interface. A sharp edge, for example, is difficult to follow from the outside.

Many researchers have attempted to use non-visual virtual environments to provide spatial information to the blind and prepare them for independent travel. Schneider and Strothotte, for example, implemented an orientation method called constructive exploration in which users learn routes by physically constructing a model of them [89]. In a first version of the system, the users built the model by assembling physical objects onto a grid following audio feedback given by a computer. In a second version, the interaction was provided through a PHANTOM® haptic device with an engraved map and virtual objects. Similarly, Lahav and Mioduser used a virtual environment with force feedback provided by a Microsoft Force Feedback Joystick to train a blind subject in navigating and exploring a room [71]. After training the subject was able to build a model of the room and to navigate in the physical room. Magnusson et al. [77] implemented a virtual traffic environment with a PHANTOM®. Users were asked to navigate from house to house, finding the shortest path.

## 7. HUMAN-COMPUTER INTERACTION

Early computer interfaces afforded to the blind the same level of access as the sighted. The interface of the Microsoft disk operating system (DOS), for example, was largely sequential in nature and could easily be communicated through voice synthesis or refreshable Braille displays. In recent years, however, the Graphical User Interface (GUI) has become the dominant paradigm for computer interaction. While the GUI makes the computer more intuitive, and easier to use for non-technical computer users, its heavy reliance on visual metaphors and graphics makes it largely impossible to use by the blind. The sequential feedback given by Braille and voice synthesis cannot easily provide an overall picture of the desktop and of the spatial relationship between its objects. Similarly, a mouse is unusable without visual feedback. Far from going away, the GUI paradigm is likely to spread to other devices such as domestic appliances.

Estimates are that 196,000 Americans with severe visual limitations have access to the internet, and that 102,000 use a computer on a regular basis [9]. Blind computer users currently rely on screen readers such as JAWS® combined with either refreshable Braille displays or voice synthesis to gain access to visual environments such as Microsoft Windows [5]. Linux is also a viable alternative for the blind with many free screen readers available for various applications [88]. Although these solutions enable the blind to use the computer, the experience is less satisfying than for the sighted. Voice synthesis, for example, is not yet sufficiently advanced to correctly pronounce every word and to provide natural-sounding voices [48].

The problem of web browsing deserves special attention. The internet offers the blind access to a wealth of information that was previously inaccessible or that had to be adapted explicitly for their use. Although web accessibility guidelines exist, many web sites are difficult, frustrating and inefficient for the blind [48, 17]. Most web pages, for example, do not supply alternate text for images. Headers that are repeated by screen readers on every page can also become irritant. One of the main problems however is that blind surfers have difficulty getting an overall picture of the page and sifting through irrelevant information. The use of contextual voices and keyword extraction have been proposed as partial solutions for these problems [105].

The solutions proposed by researchers to provide better access to GUIs can be divided in two classes: reinterpretation of the desktop and custom interfaces. While the first category attempts to maintain the same experience as the one given to the sighted, the second category goes further and designs custom software and interfaces specifically for the blind. These two categories are explored next.

7.1. **Reinterpretation of the Desktop.** Many ambitious research projects endeavored to reinterpret the Microsoft Windows user interface through the use of synthesized voices, sounds and haptic feedback. From a survey of the literature, Christian [33] proposes, among others, the following rules for tactile feedback:

- Tactile feedback should be used to guide the movement of the cursor, not to control it.

- Fitt's law may not apply to tactile feedback. Fitt's law states that the time required for a user to hit a target decreases with the logarithm of the distance and increases with the logarithm of the size of the target.
- The non-visual feedback should convey the interface of the GUI, not the content of the screen.
- Blind computer users must be able to collaborate with their sighted coworkers. "[T]he interface should attempt to convey to the blind users a mental model of the system similar to that of sighted users."

O'Modhrain and Gillespie's work on haptic computer interfaces was originally motivated by the digital sound studio [51]. As computers were introduced in the sound studio, blind sound engineers found themselves excluded from this traditionally accessible environment. The problem is particularly interesting since audio feedback interferes with sound editing tasks. O'Modhrain and Gillespie thus designed a 2D planar haptic device called the Moose. The hope was to reintroduce the tactile and kinesthetic interaction with audio equipment to the benefit of both blind and sighted sound engineers. The Moose was combined with software that maps the widgets on the screen to tactile sensations, thus providing non-visual access to the Microsoft Windows desktop [80]. The edge of a window, for example, was represented as a groove. A check box was represented as an attracting spring or repelling block depending on its state. Objects could literally be dragged and dropped, with the weight of the object being felt through the device. The goal was to create a library of haptic effects necessary for the development of a haptic user interface (HUI).

Similarly, the PC-Access project proposed the use of multi-modal feedback [84]. The system used absolute position pointers to restore the position feedback; either a standard drawing tablet or a 2D haptic device called the Pantograph. The haptic stimuli was used to provide the spatial information of the desktop (distances, object sizes). Non-verbal sounds and textual feedback (speech or Braille) were used to provide the remaining information about the desktop. The haptic model included physical boxes for the size of objects and physical gutters for boundaries. Dynamic forces, such as rubber bands, were used to provide distance information when moving icons, resizing windows, etc.

7.2. **Custom Interfaces.** Researchers have also attempted to provide computer interfaces better adapted to the blind. Hampel et al. designed an Internet Relay Chat (IRC) client that corrects some problems found in traditional IRC clients when combined with a refreshable Braille display [54]. Instead of automatically switching to the latest message, for example, the client gave control to the user. Such seemingly small changes can make a significant difference in the accessibility of software.

Other researchers have designed custom multi-modal interfaces for specific applications. Petrie et al. used a touchtablet covered with a tactile overlay to provide a user interface for navigating through hypermedia applications [82]. Voice synthesis was used to provide user-requested information. Similarly, Bellik and Burger designed an accessible text editor using voice recognition, speech synthesis and a Braille terminal [27].

Sjöström experimented with haptic computer interfaces and haptic games for the blind [91, 93, 92]. He introduced the idea of radial haptic menus that are easier to use with the FEELit Mouse than conventional menus. He also experimented with search tools (such as a cross or a magnet) that can facilitate finding scattered objects, such as desktop icons. He also designed haptic games involving the exploration of virtual environments with a PHANTOM®. In the "Memory House", the player had to explore a 3D environment and match pairs of buttons. "Submarines" was a haptic version of the battleship boardgame in which the manipulandum became an helicopter dropping bombs on submarines. The state of squares of the board was represented by intuitive tactile sensations such as waves.

Although these custom interfaces and applications are likely to be more usable by the blind than a simple reinterpretation of the graphical user interface, they are less flexible, require more work for their implementation and may not be accepted by the users who often wish not only access to the computer, but also access to the GUIs of the sighted.

## 8. VISION SUBSTITUTION AND RESTITUTION

Restoring sight in the blind has long been a dream of researchers. In this section we will see how medical interventions and experimental implants can partially or fully restore sight in some blind people. We will then look at the sensory substitution research that has long tried to provide the blind with information equivalent to that obtained by vision through their unimpaired senses.

8.1. **Vision Restitution.** Medical interventions are sometimes able to restore sight in the blind. As briefly mentioned in Section 3.1, the results are highly dependent on the age of onset of blindness. For example, while the functional sight of the late blind can be restored almost completely when removing cataracts, the early blind show "some improvement of their vision with the passage of time, and the gaining of visual experience, but in most cases they never [develop] anything approaching normal vision" [61]. Despite having apparently good vision, patients are incapable to recognize shapes or faces, or making much functional use of their vision. Abrams even reports that about a third revert to blindness, preferring dark rooms and walking with their eyes shut [19].

Much past and ongoing research also attempted to create electronic devices that can be implanted in the brain or on the retina of blind patients to trigger visual sensations from external stimulus, such as images recorded from a camera embedded in a glass eye. Electrical stimulation of the visual cortex has been shown to produce the perception of light spots, or phosphenes [61, 40]. Low-resolution implants have been successfully tested. Given sufficient resolution, these implants may eventually provide sufficient usable vision to travel independently or to recognize faces and objects. As for the cataract surgery however, restoring sight in the early blind may not necessarily translate into functional vision. See [31] for more information on this topic.

8.2. **Vision Substitution.** A sensory substitution system converts information normally acquired by one sense to a modality suitable for another sense. In the case of vision substitution systems, the information acquired from optical cameras or other spatial sensors is converted to audio or tactile signals. The hope is, as Bach-y-Rita puts it, that "[w]e see with the brain, not the eyes" ([22, 23]). After extensive training, it is hoped that the blind can develop perceptual abilities similar to those provided by vision. It may be possible, for example, not only to locate an obstacle but also to identify it. These devices have achieved considerable success in the lab but are not widely used by the blind community.

Many systems convert spacial or visual information to sound. The SonicGuide, introduced in Section 5.1, may be viewed not only as an ETA but also as a vision substitution system. More recently, a similar system called the vOICe was created by Meijer [11]. The vOICe sweeps through video images and creates a corresponding 3D audio signal. As Meijer explains, "[m]astering it all will require lots of effort and practice, perhaps comparable to learning a foreign language" [15].

The most extensive study on vision substitution through touch is the Tactile-Video Substitution System (TVSS) by Bach-y-Rita which has been in progress since 1963 [22]. Bach-y-Rita experimented with the conversion of video images to tactile simulation in the form of vibrations or direct electrical stimulation. The stimulation was applied to the abdomen, the back or the thigh with arrays of 100 to 1032 points. Bach-y-Rita and his colleagues' latest efforts involve direct electrical stimulation of the tongue [22]. The TVSS is commercialized as VideoTact and costs in the order of $40,000 [14].

Impressive results were obtained with these devices. Although extensive training was required, it was shown that subjects could "learn to make perceptual judgments using visual means of analysis, such as perspective, parallax, looming and zooming, and depth judgments" [22]. Moreover, subjects eventually "exteriorized" the sensations and no longer felt them as being applied to the skin [62, 32]. In fact, "[s]ubjects learned size constancy to the extent that they involuntarily ducked their heads when the tactile image was suddenly magnified by a turn of the zoom lever on the camera" [34]. These perceptual abilities, however, only arise when the user is given control of a movable sensor. This leads Lenay et al. to propose the use of "sensori-motor coupling device" as a more adequate term for such devices [32]. It's also interesting to note that subjects can easily adapt to a displacement of the stimulators from one region of the body to another [32]. Despite these results, the concept was found to be of limited practical value. Testing in complex, outdoor scenes proved the stimulus to be impossible to interpret [34]. Moreover, "the amount of user concentration necessary is too great to be sustained for long periods of time, let alone allow the user to perform other tasks at the same time" [34].

The question of user expectations is also interesting. Despite the name, a vision substitution system does not allow the blind to experience or recover sight, often leading to disappointment [73, 32]. The new perceptions also do not carry subjective value. Bach-y-Rita mentions, for example, that the 'sight' of a loved one does not give rise to emotions. Similar observations have been made about the recovery of sight by congenitally blind persons (see Section 8.1). Bach-y-Rita notes however that "a blind infant using a vision substitution system smiles when he recognizes a toy and reaches for it" [22].

Using a more intuitive tactile mapping, Di Stefano et al. created a portable system that converts "stereo vision images into virtual 'bas-relief' surfaces" [39]. The surface was explored with a haptic device employing actuated wires.

## 9. DISCUSSION

This section analyzes the survey of the literature provided in the previous sections to extract information useful for future research projects aimed at the blind, particularly with the use of haptic technology. This is followed by an examination of current trends in technology and their significance for the future of assistive technology. Finally, the section closes on an overview of opportunities for haptics in the design of technological aids for the blind.

9.1. **Adaptive Technologies Market.** Although technology is pervasive in the life of many blind people, most of the more advanced aids have met with very limited commercial success. This is particularly true of ETAs, none of which "has achieved any significant degree of penetration of the potential market" [30]. It was estimated that only approximately 3000 to 3500 ETAs had been sold by 1985 [16].

It is thus important to ask whether assistive devices are filling a need. It is generally agreed, for example, that "many blind people achieve a high degree of mobility without electronic aids" [16]. Moreover, it is conceivable that many blind people "choose caregiver assistance if they have a choice between doing necessary tasks with an assistive device or having a caregiver do such tasks for them" [86]. Finally, Brabyn considers that the "development of electronic travel aids for the blind has largely preceded our understanding of the needs of the mobile blind pedestrian" [30].

Although there is clearly a demand for assistive devices by part of the blind population, it is important to remember that the blind are not desperate for them and that they will not embrace these devices at all costs. This is particularly true of sensory substitution devices. Congenitally blind people "do not 'miss' sight; they know that the faculty exists, that life in a world where most people can see would be more convenient if they could too, but they do not long to see the sunset" [64]. Similarly, the late blind may miss their sight but "the visual world is recalled less and less vividly with the passage of time" [64].

Developers of assistive technologies should not to be unduly encouraged by the statistics listed in Section 2. The potential market for assistive devices is far from reaching the 40 million blind people in the world, most of which live in the third world and cannot afford them. The remaining blindness community varies in buying capability (depending on the level of governmental or insurance support for example) and in receptiveness to new technologies. The elderly, which composes a large proportion of the blind, cannot generally be expected to learn how to use a demanding device such as the SonicGuide. Even in the remaining minority of blind persons who are interested in assistive devices, there may be significant differences in their ability to use them [42]. The users who succeed at learning and making effective use of complex aids may be the exception rather than the norm.

Considering the efforts required to learn the use of some of these devices, it is also important to consider whether the blind community does or should believe the claims made by researchers and manufacturers of assistive device. Baldwin writes that "[t]here is great scepticism in the blindness community, and well meaning inventors have not always been welcomed with open arms" [25]. Similarly, Lauer [72] says:

> "High hopes and exaggerated claims in the 1970s had left a backlash of people who were disappointed at the long training needed to use the Optacon, the difficulty of learning to use it, and the price. The blind public grew disillusioned and all but forgot how useful the instrument had become to several thousand of them."

In the absence of performance measures for ETAs [16], the blind must fall back on information provided by manufacturers and word-of-mouth. The marketing of devices often exaggerates their benefits, raising expectations and leading ultimately to disappointment in the buyers. The mainstream media is also quick to accept and disseminate these claims, touting each new technology as a revolutionary step forward. In such a context, it is easy to understand why the blindness community is weary of embracing new technologies, and sometimes even cynical.

Another serious issue is the stability of manufacturers and product lines [42]. Many devices, particularly travel aids, have been discontinued by their manufacturers because they were not commercially viable. This causes significant problems for those who have invested time, money and efforts into mastering these devices, sometimes becoming dependent on them. When the Optacon was pulled from the marked in 1996, many of its devoted users were extremely disappointed and now fear being deprived of their device if it breaks [95]. Considering the history of electronic travel aid commercialization, it is hard to convince a potential buyer that the latest device will be supported and serviced years from now.

9.2. **Recommendations.** Many recommendations and guidelines have been put forward to help designers meet the requirements of the blindness community. This is particularly true of portable devices, such as ETAs. A portable device "must be comfortable, ergonomically sound and convenient to use and to 'park' when not in use" [42]. Lenay et al. state the list of requirements: autonomous, light, robust, visible (in order to inform others of the person's condition if necessary), but also discrete (so as to allow the person to blend in), inexpensive, and removable (can be easily worn or removed) [73]. A travel aid should ideally not interfere with the normal use of the senses, such as requiring the user to wear gloves. Some users, however, contend that this may be acceptable. Downie, for example, mentions that masking environmental sounds is accepted for some tasks if the SonicGuide provides more appropriate information [42].

The importance of social factors is also often underestimated by device designers. As with any other consumer product, there is an emotional component attached to the purchase and use of an assistive device. The goal of greater mobility, for example, may conflict with the goal of integration in society. Most of the blind will not accept to wear devices that marginalize them, even if they prove very useful. This is understandable considering that the sighted often show an involuntary change in attitude when interacting with the blind [64].

Finally, collaboration between the blind, rehabilitation and research communities is crucial. A collaborative design process is the best hope for assistive devices of practical use. Designers of innovative devices must be ready to face a natural opposition to changes that go against conventional wisdom. Although input from the blind and rehabilitation communities is very important, going against accepted ideas may lead to interesting and valuable results. The Institute for Innovative Blind Navigation mentions humorously that Louis Braille would undoubtedly be turned down if he proposed Braille today [24]. As a matter of fact, Braille's acceptance at the time was controversial and did not occur overnight.

Moreover, it must be remembered that no blind person can speak for the entire community. The opinions and needs vary between individuals. One must also not assume that the blind, like any other consumer, is aware precisely and completely of all his needs and of the best way to meet them.

9.3. **Trends and Future Developments.** The current trends in technology allow us to speculate on the future of technological aids for the blind. One area that is likely to gain grounds in the future is the field of neural and retinal implants (see Section 8.1). While these implants currently offer only low resolution vision, improvements to the technology could soon provide much higher resolution and give blind people a limited degree of functional vision. It must be remembered however that restoring sight does not necessarily restore the perceptual visual capabilities of the early blind (see Section 8.1).

Computers are expected to be more pervasive and more tightly networked then ever in the future. This technology will likely benefit the blind. Advances in smart homes, for example, could facilitate the control of appliances or provide information in a manner that is intuitive both for the sighted and the blind. Such a system could, for example, respond to verbal commands and reply with synthesized speech. Similarly, the Radio Frequency Identification (RFID) tags now being tested for stores could allow the blind to identify and locate items by their radio signature. Finally, computers are becoming more and more portable, now being even embedded in clothing. This computational power can be harnessed for the blind for many purposes such as navigational assistance. Systems using GPS and other positioning methods are likely to proliferate in the future. The beauty of these advances is that they largely rely on generic technology, and thus benefit from economies of scale.

While many of the trends described so far benefit the blind, others could prevent the blind access to some of the advances made for the sighted. One such problem is the increasing use of GUIs and visual metaphors in computing. As computers become more powerful, they will likely attempt to engage the user in more intuitive ways. Vision playing a large role in the sighted's perception, there is a risk of leaving the blind behind. This is particularly problematic since many of the traditionally accessible appliances and commodity items are now switching to visual interfaces.

Promising efforts are currently under way to address these issues to the benefit of all consumers, with or without disabilities. Standards are being developed to provide an Alternative Interface Access Protocol (AIAP) to a variety of consumer electronic devices [106, 78]. The aim is to allow these devices to be operated through Universal Remote Consoles (URCs). A URC will be able to discover a device's functionalities and provide an appropriate bi-directional user interface with both controls and feedback. This would allow the blind to use an adapted URC relying on audition or touch without requiring any customization by the target device's manufacturer.

To read further on the future of technological aids for the blind, see [24, 50].

9.4. **Opportunities for Haptic Technologies.** As we have seen in previous sections, many rehabilitation devices rely on the haptic sense to provide information to the user. Among those, we have seen the use of simple vibrotactile stimulation (MiniGuide), the use of multiple vibrating buttons (UltraCane) and the use of complex 2D arrays of tactile stimulators (TVSS). Many research projects also use haptic devices such as the PHANTOM®, the Pantograph or cheaper consumer-grade force feedback mice, joysticks and trackballs. The use of haptics seems to have been well received by the blind despite the many practical advantages of voice synthesis and audio solutions. In this context, it is interesting to look at the opportunities still available for haptic research with a potential benefit for the blind.

Targeting the blind as a potential user of haptic technology means in essence using haptics in absence of visual feedback. Much of the research is thus applicable to the blind. Care must be taken, however, not to rely on vision to support haptics and to be aware of the changes this may cause to the sensation delivered with a haptic device. Some practical considerations must also go in the design of the finished haptic interface. A blind user, for example, must be able to easily find the manipulandum of a device.

One of the promising research orientation is the use of tactile displays. The absence of affordable, reliable and robust tactile display technology on the market is often cited as a problem for the presentation of dynamic graphical material such as maps. While the demand for maps and tactile drawings may be limited, static versions are currently used with some degree of success.

There are also opportunities to augment existing assistive devices with simple, low cost haptic mechanisms providing intuitive feedback to their user. Haptic knobs such as those proposed by Immersion Corp. could be ideal for the blind [53]. Other simple devices such as those shown in [94] could also be useful.

## 10. CONCLUSION

This literature review began with an overview of blindness and its consequences. It was noted that the blind form a heterogeneous group. A survey of the psychology literature showed that there are important differences between the early and late blind, particularly with respect to spatial abilities. It was also seen that the blind are better at attending and making functional use of their remaining senses.

The following sections continued with a broad survey of technological aids for the blind, both at the research and commercial levels. The survey began with simple but remarkably useful daily living aids. Followed the rich field of orientation and mobility, in which it was concluded that, despite valiant efforts to introduce high technology, simple aids such as the guide dog and the white cane remain the dominant aids. Aids for access to textual and graphical information were then introduced. The accessibility issues for human-computer interfaces, and particularly GUI-based computer interaction, were then discussed. Finally, we examined the most recent developments in vision substitution and restitution.

The literature review concluded with a discussion of the findings of the survey. The discussion began with an attempt at gaining a better understanding of the requirements for successful aids and of the reasons for the failure of many more advanced devices. It then took a forward view at the expected technological developments of the near future and at their impact on the life of the blind. Finally, it discussed the topic of haptics for the blind and explored the research opportunities that may be available in that field.

This survey made clear that the complexity of applying technological solutions to the problems encountered by the blind is a challenge. It showed that there are great opportunities for many technologies, including haptics, to make a difference in the quality of life of the blind. It also showed, however, that the blind are not desperate for technology and that they will reject devices that are not designed properly. This fact should be accepted as a challenge by the well informed researchers rather than a rejection of their efforts.

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