Co-design of an Interactive 3D Objects Visualization Application: A User-Centered Approach for the Visually Impaired

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***Abstract*—This article presents the co-design of an interactive application to assist with the visualization of 3D objects, adapted for visually impaired individuals. It offers 2D renderings of 3D objects enhanced by image processing on a standard, general-purpose computer screen. This alternative to 3D or immersive glasses, which are challenging for visually impaired users to operate, leverages the richness of information inherent in 3D objects without relying on semantic segmentation or voice transcription. The 2D interface of the application is customizable and adapts to the user's visual needs. The evaluation of the application confirms the usefulness of the prototype for this population and its ease of use. These results validate our proof of concept and motivate us to develop a dedicated software that will consider the user's profile to provide tailored visualization assistance features**.

Keywords—Adaptive user application; Co-design methods; Interface co-design with visual impaired people; Usability testing and evaluation.

I. INTRODUCTION

This article is an extended version of the research works presented at the Seventeenth International Conference on Advances in Computer-Human Interactions (ACHI) 2024 [1]. It presents the co-design of an interactive 3D objects visualization application specifically tailored for individuals with visual impairments. This application is named: IRENE *(AssIstance foR 3D objEct visualizatioN to visual ImpairmEnt)* application.

Visual impairment is defined by the World Health Organization when visual acuity is less than 3/10 after optical correction and/or when the visual field is less than 10° [2].

In this article, we define a "visually impaired" person as someone with moderate to severe visual impairment (also known as low vision), but not reaching the stage of profound impairment (blindness) [3]. A visually impaired person therefore has binocular vision described as unique and residual [4]. Despite this residual vision, sight remains the dominant sense for visually impaired [5].

The aim of IRENE application is to leverage this residual vision to improve 3D object recognition. This alternative to VR headsets or 3D glasses, which are difficult for visually impaired to use [6] is based on the use of an ordinary 2D screen, where the renderings of 3D objects are augmented by image processing, without semantic segmentation. To facilitate the recognition and exploration of 3D objects, the IRENE application offers visualization aids (outlines, zoom, lighting effects, etc.) and settings functions of the 2D interface (menu choices, fonts, backgrounds, etc.) for the visually impaired.

Section II presents the state of the art of existing visualization systems for visually impaired people. Section III describes the research context and Section IV highlights the challenges of co-designing with visually impaired. Section V details the co-design of our application and Section VI presents the IRENE application itself. Section VII describes its evaluation. We conclude with our research perspectives.

II. STATE OF THE ART

There are numerous tools to assist people facing visual difficulties in better perceiving their environment [7][8]. Efforts are primarily driven by the search for software and/or hardware solutions to enhance the quality of life for visually impaired individuals by helping them perform their daily tasks more effectively. The most common actions include mobility [9] identification of objects or their characteristics (color, texture, shape), and reading of content.

A. 2D Content Visualization Systems

Interactive 2D systems to help visualize 2D content (web pages, emails, text documents, graphics, images, etc.) allow people with visual disabilities to access all types of digital content most often through a computer screen, a tablet or even a smartphone.

The operating systems of these devices integrate native functionalities [10]. For example, Windows users have access to features like screen reading, contrast enhancement, and magnification.

Apple devices offer several accessibility features such as the Siri voice assistant, text enlargement options, zoom, color inversion, VoiceOver and voice selection [11]. There are also accessibility features on Android devices [12][13].

Screen magnifier applications such as “ZoomText” also make it possible to enlarge digital content such as documents, spreadsheets, web pages or even emails [14]. They also improve the rendering of the font (for example by offering bolding), the color contrast as well as the highlighting of pointers associated with the mouse. This type of application allows people with impaired vision to continue accessing digital content.

Other applications such as screen readers help visually impaired and blind people access information presented on the screen, by describing it either orally or in Braille with a dedicated device. Among these applications, we find the “JAWS” screen reader, for “Job Access with Speech”, as well as “Windows Eyes” [14].

B. 3D Content Visualization Systems

Most 3D content visualization applications rely on the video feed from the smartphone camera. Depth information is lost when the scene is projected onto the camera's photosensitive matrix, so image processing techniques are then used to identify objects.

Applications like Microsoft's Seeing AI, Google's Lookout, and TapTapSee advanced image processing algorithms for image segmentation and object recognition based on convolutional neural networks [15][16]. Once objects are identified and segmented in a scene captured by the mobile device camera, these applications provide accurate and detailed vocal descriptions using text-to-speech modules. This system significantly enhances accessibility for visually impaired individuals by enabling seamless interaction with their environment. However, their effectiveness can be influenced by the quality of the internet connection required to access artificial intelligence models, as well as by lighting conditions and the complexity of the scenes captured. All these drawbacks can pose issues for individuals with visual impairments.

Other visual augmentation systems in augmented reality, such as the one proposed by [17] involving Google Glass, enhance contrast perception through edge detection. Google Glass has a minimal interface for setting edge detection and displaying edge type. This system has no interface, as its sole purpose is to enhance the depth perception of objects between them.

By using a depth camera, it is possible to access the distance of objects within its field of view. This information can then be processed and translated into appropriate visual signals. This is the focus of the research by Hicks et al. [18], who propose a device aimed at improving depth perception to avoid obstacles and assist with navigation in complex environments.

In virtual reality, depth information is known since each object in the scene has been modelled. Therefore, there is no need to measure or reconstruct it, unlike in real-world environments.

Applications in the field of virtual reality are on the rise but remain challenging for individuals with visual impairments. There is limited research in this domain. The “ForeSee” prototype allows users of virtual reality headsets to zoom in, enhance and invert contrasts in real-time [19]. This device lacks an interface for activating these features; users must verbally request them.

One of the most advanced projects is called “SeeingVR” [20]. It’s a framework that offers 14 features to enrich the visual experience in virtual reality video games with assistive functions such as magnification, edge detection, contrast enhancement, voice description of annotated objects or text to speech. Similar to “ForeSee”, the selection and adjustment of treatments are done through a voice input system, without an interface, which can lead to a poor gaming experience.

More recently, [21] developed a virtual reality platform named “VIRRAKE”. In the context of public transport infrastructure design, it allows importing all or part of a building plan and activating filters to simulate visual impairments to assess the impact of proposed installations on visually impaired individuals. Similar to accessibility tools in operating systems, [22] suggests integrating accessibility tools directly into virtual reality frameworks to standardize approaches and establish a standard to limit specific developments for each VR environment.

Using virtual reality headsets can pose challenges for individuals with visual impairments: difficulty in appreciating distances and scene depth, accessibility of content with a restricted field of view, latency, headset weight, difficulty in wearing glasses, and more [6][23]. Immersion also causes physical fatigue [24] as well as eye strain [25]. Brightness, repeated visual patterns, problems with contrast, color or the presence of elements to be read can also be sources of discomfort [26].

We propose an alternative to immersive visualization systems for viewing 3D objects on a simple 2D computer screen. The InteRactive for viEwiNg 3D objEcts (IRENE) application offers, on the one hand, a range of accessibility functions to meet the specific needs of the visually impaired. This addresses the lack of customization in existing applications and eliminates, among other things, the need to configure the native accessibility features of operating systems. On the other hand, our application provides visualization assistance functions that leverage the 3D geometry of the object to highlight its characteristic features. Since the goal is to enable visually impaired to independently identify everyday objects by offering features that help them explore these objects, we exclude semantic segmentation followed by voice transcription

Our ambition is to provide an enhanced visual experience while avoiding the drawbacks associated with existing immersive systems.

III. Research Context

The IRENE application is proposed as an alternative to immersive systems for visualizing 3D objects on a simple 2D computer screen. We consider this application more as a proof of concept (a prototype). Our goal was to validate the feasibility of this alternative idea and test it before proceeding with further development and large-scale implementation.

For the design of IRENE, we opted for a co-design approach rather than relying on the ISO 16355 standard [27], which is dedicated to quality management and product engineering methods, even though these standards focus on customer needs and expectations. However, we will discuss the standards and guidelines we used in Section VII, Evaluations.

In this context, we also did not follow the "Six Sigma" quality management [28] and process improvement method, which aims to reduce defects and variations in processes to optimize quality. Our objective was not to produce a final product using methods such as Quality Function Deployment [29].

A. Co-design method

Co-design is a method that involves the end user in the product design and development process. This design is multidisciplinary, collective and collaborative [30]. Co-design stems from user-centered design [31]. It aims to gather user needs and convert them into design choices. The co-design cycle is divided into four phases [32].

1. The analysis phase identifies user's needs. The tools used are document studies, questionnaires, interviews and direct observation method.
2. The ideation phase allows collaboration, contribution and creativity. The tools used are brainstorming, brainwriting and focus groups.
3. The design phase defines the interface and future functionalities to be developed. This phase leads to the proposal of a (paper or digital) mock-up. In the case of digital mock-ups, either high-fidelity or low-fidelity prototypes are used. These prototypes are an interactive representation that simulates the final product. They are designed to reflect the user experience, as closely as possible. Unlike low-fidelity prototypes, which focus on basic structure and navigation, high-fidelity prototypes include detailed design elements such as colors, typography, icons and images, close to the final design specification. Once the mock-up (paper or digital) has been validated, development begins.
4. The evaluation phase assesses the final application and measures the user's satisfaction (usability and usefulness criteria). The user-centered, heuristic, and analytical evaluations can be employed [33][34][35].

When the co-design is dedicated to the design of products for a specific disability is named inclusive co-design [36].

B. Considerations for co-design with the visually impaired

For a sighted person, the field of view is very wide [37]. The processing of information perceived by sight is parallel. This is much more challenging, or even impossible, for visually impaired who compensate their deficiency through the sense of touch and/or hearing.

The problem is that the tactile perceptual field is less efficient than sight for Braille reading tasks, as it made up of successive and discontinuous elements [38]. For example, when visually impaired read documents, they have to rely mainly on memory and exert significant efforts to memorize. This is due to the fact that they do not have a global vision of the text's structure [39].

In contrast to the persistent nature of sight, auditory perception operates through a fleeting mode of analysis. Auditory memory in the visually impaired therefore entails a high cognitive load, as it is sequential in nature [40].

The co-design tools available for visually impaired individuals must take their sensory perception into account, as not all tools used in co-design are suitable.

Reference [41] recommends observation and oral interviews, specifying that anything involving paper must be excluded. Reference [42] emphasizes the careful use of brainstorming to avoid fatiguing visually impaired. Reference [43] recommends the use of high-fidelity software prototypes.

IV. Co-Design with visually impaired

To design the IRENE application, we selected co-design tools suitable for visually impaired.

A. Selection of suitable tools for Visually Impaired

We chose tools that depend on hearing but do not involve too much cognitive load, as recommended by [41].

We used interviews (semi-structured or open), which encourage interaction and discussion. Direct observation was employed to collect behavioral and verbal data (video capture and field diary). Brainstorming sessions aimed to generate ideas orally and relied on spontaneous creativity. User-centered evaluations and heuristic evaluations were used to inspect usability and utility.

B. The problem of (paper or digital) mock-ups for the visually impaired

During the design phase, paper mock-ups, which represent sketches and drawings in the form of storyboards, are difficult to use for visually impaired people. Visualizing display areas and their content remains complicated (poor perception, interpretation, problems of scale, layout, etc.). Moreover, interactions are often poorly defined, preventing them from imagining and interpreting them. They therefore prefer using a digital mock-up, particularly a high-fidelity prototype [43].

High-fidelity prototypes are realistic simulations of the final product's appearance and functionality. They allow for interactive exploration of different scenarios. Once the high-fidelity prototype has been validated, the development phase can begin. Once development is complete, the evaluation phase begins. However, if the final prototype does not meet user expectations, new ideas may need to be generated, necessitating the creation of a new digital mock-up.

This results in a back-and-forth between the ideation, the design and the evaluation phase. This process quickly becomes costly in terms of development and iteration time.

C. Adaptation of co-design phases to visually impaired people

The problem of using a high-fidelity prototype for the visually impaired has led us to adapt the design phase.

We propose to use software prototyping instead of a high-fidelity prototype. Software prototyping covers all the activities involved in creating software prototypes, i.e., incomplete versions during development. As a reminder, the IRENE application represents a finalized version of this software prototype, but not the complete version of a product ready for deployment.

For this development, we propose an iterative cycle spirals based on the spirals model [44]. In each spiral, the prototype is evaluated by design tests. The evaluators check whether the objectives have been achieved and decide if new objectives are necessary.

To maintain collaboration, contribution and creativity, we suggest combining the ideation and design phases. Thanks to the design tests, visually impaired users directly interact with the prototype at each spiral iteration and assess whether it meets their user experience expectations. If not, brainstorming sessions are held to come up with new proposals for the next spiral. The visually impaired can then interact directly with different versions of the final prototype, test the functionalities and evaluate whether the product meets their expectations.

We propose a co-design method for the visually impaired based on three phases: Analysis, Spiral prototyping and Evaluation.

1. Analysis phase begins with a study of the population (understanding visual impairments and pathologies) and a study of the existing situation. An interview grid is created based on this information. We recommend conducting semi-structured interviews, based on this interview grid. At the end of this phase, analysis of interviews is be used to produce an observation grid for the next phase.
2. Spiral prototyping phase begins with brainstorming. The aim is to encourage creativity and free verbal discussion. The interview then uses the observation grid from phase 1, asking open-ended questions.
   Data analysis enables the creation of an interface sketch and a list of the basic prototype functionalities. The spiral development cycle (version 1 of the final prototype) begins. At the end of the first spiral, we propose conducting design tests. Visually impaired people test the prototype directly. We can see if the version meets the user experience through direct observation. If not, brainstorming sessions are organized to formulate new proposals for the next spiral. The functionalities of the final prototype and its interface are thus completed and refined in the next cycle (spiral 2).
3. Evaluation phase measures end-user satisfaction (usability and utility). We propose to use direct observation and semi-structured interviews for this phase.

V. Co-Designing the IRENE Application

We started the co-design of the application with the analysis phase.

A. Analysis phase

We studied pathologies and various forms of visual impairment. We used “OpenVisSim” [45] to simulate their vision and better understand the visual perception of partially sighted. Our focus was on the main pathologies: retinitis pigmentosa (impaired peripheral vision), retinopathy (vision obstructed by spots), age-related macular degeneration (impaired central vision), cataracts (severe myopia).

Next, we conducted semi-structured interviews with 6 visually impaired to gather their needs and expectations. The interviews included questions divided into three themes: visual perception, expectations, needs related to viewing 3D objects. They lasted, on average, one hour. The analysis of these interviews highlighted that all participants use tools to assist them in daily tasks (mobility, object identification, reading content, etc.). They use (when they can) their residual vision. Additionally, when using digital tools, they express dissatisfaction with the lack of adaptation and personalization, admitting that in some cases, it doesn't really help them. Based on these insights, we created an observation grid for the brainstorming of the next phase, with open-ended questions about settings of the 2D interface and visualization aids.

B. Spiral prototyping phase

This phase began with a brainstorming session. During this session, we ensured that our participants were not cognitively overloaded: limited duration to a maximum of one and a half hours, in the morning, with regular breaks, in small groups, allowing time for speaking, reformulating, writing down ideas, and repeating them orally.

Three brainstorming sessions resulted in a list of 2D interface specifications: customizable fonts, menus, and object backgrounds.

- Five fonts were selected: Arial, Liberation, Luciole, Tiresias and OpenDys, to limit an overloaded selection menu.
- Four highly contrasted color themes were chosen for the menus: white (white background and elements, black fonts and outlines), light gray (light gray background, white elements, black fonts and outlines), dark gray (dark gray background, black elements, white fonts and outlines) and black (black background and elements, white fonts and outlines). Adjustments to the thickness of menu and button borders were also made to improve item detection.
- The ability to adjust the background scene contrast, to place the menu on the left or on the right side of the screen was preferred. The use of buttons, sliders and drop-down menus was also chosen.

Seven functions requiring minimal configuration by the user have been also chosen: digital zoom, navigation around the object and automatic framing, sharpness and contrast, brightness and saturation, contours, texture and lighting effects.

We then started the spirals development cycle with Unity. Unity is a cross-platform game engine used in virtual/augmented reality [46]. Its native features include the ability to create 2D/3D renderings, design user interfaces and customize them. Shaders can optimize the quality of visual rendering and application performance. They enhance the appearance of 3D scenes (real-time dynamic lighting) and enable the implementation of special effects such as post-processing without compromising performance (GPU usage).

Three spirals development cycles were carried out to produce the IRENE system.

At the end of the first spiral, design tests based on direct observation led to modifications in the interface parameters. We also conducted a brainstorming session (in the form of an interview) to gather new ideas. They lasted about an hour, always in the morning, with regular breaks. A final free-form interview concluded the session in order to gather verbal suggestions.

At the end of spiral 2, the interface parameters were approved and a second brainstorming session was conducted to add two functions: texture and lighting. Spiral 3 focused on validating the visualization functions. This allowed us to move on to the evaluation phase to measure end-user satisfaction.

C. *Evaluation phase*

For the evaluation of the IRENE prototype, we focused on usability and utility [34]. Regarding utility, the objective is to assess whether the functions contribute to a better perception of the 3D object. In terms of usability, the goal is to determine if the interface respects the ISO standard [47] and ergonomic criteria [33][35].

To measure user satisfaction, we conducted interviews based on an interview guide. This guide we created was customized by combining ergonomic criteria and standards suited to our target audience [48]. This guide is accessible for consultation [49]. The results of the evaluation are detailed in Section VII.

VI. The IRENE Application Description

The seven functions listed below allow configuring the interface.

A. *Settings functions*

They allow for the selection of three main elements based on the visual needs of the visually impaired: fonts, menus, and the background of the 3D scene.

Choice of font type. Visually impaired can choose from five font types: Arial, Liberation, Luciole, OpenDys and Tiresias. Arial and Liberation are frequently used fonts in the daily lives of visually impaired individuals. Luciole and Tiresias are recommended for all pathologies [50]. OpenDys is a font for dyslexic persons but also used by visually impaired. This font, like all sans-serif fonts is recommended for the visually impaired as it improves readability by making letters more distinct and less likely to blend [51].

Choice of font size. Increasing the font size zooms in on the text. According to [52], the font should be at least 16 pixels (equivalent to 12 points). We have set the minimum size at 25 pixels for the smallest elements. The size range varies from +1 to +10 pixels. The size indication for the visually impaired is relative, the indication on the screen indicates that they add between 1 and 10 pixels to the size.

Choice of font style. Using "regular" or "bold" fonts can help with reading [51]. Some visually impaired people need to see thicker fonts to better discern the outlines of letters.

Choice of menu theme. Visually impaired people can choose from four colors themes: white, light gray, dark gray and black. These menus allow different interface elements to be clearly discerned [53], reduce visual fatigue and make reading easier. Visually impaired people need strong contrasts. Depending on visual conditions, some visually impaired people (such as those suffering from night blindness) will need a clear display and black text, while others may need to minimize screen brightness.

Choice of menu border thickness (menu or button). The purpose of this feature is to create, if necessary, a strong demarcation between the interface elements to improve their perception by making it easier to identify the buttons and clearly distinguish the menu area from the viewing area. We have set the size of the borders to a minimum of 1 pixel, and the sample size ranges from 1 to 6 pixels. The size indication for the visually impaired is relative.

Choice of menu position. Some visually impaired users have a very restricted field of vision, with one eye unable to see. To accommodate this, the menu can be positioned to the left or right, reducing the need for constant head movement. Placing the menu near their dominant eye allows them to focus more effectively on the screen's content.

Choice of scene contrast (object background). This function adjusts the contrast between the background and the object. The 3D object is positioned in a scene with a solid background color. This color is a gradient between white and black, for the same reasons as the menu themes.

B. *Visualization of 2D Interface*

Figure 1 shows an example of customizing. Here, the selected font type is "OpenDys", the relative size is set to +8 pixels, and the text is in bold.

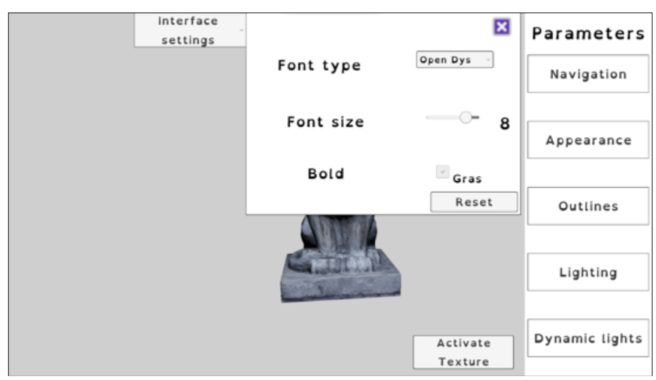

Figure 1. Screenshot, choice of font, size and style.

Figures 2 and 3 illustrate two scene contrast combinations of choice. On Figure 2, the menu theme is light grey, the border sizes are relative and are selected at 5 and 4 pixels, and the view settings menu is positioned on the left.

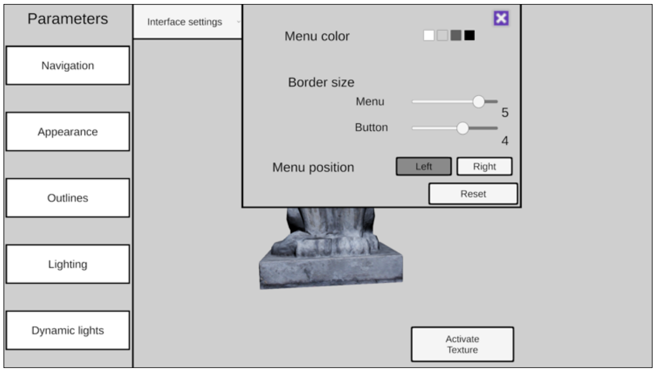

Figure 2. Screenshot, light grey theme and Arial black police.

On Figure 3, the menu theme is black, the border sizes are relative and are selected at 2 and 1 pixels, and the view settings menu is positioned on the right.

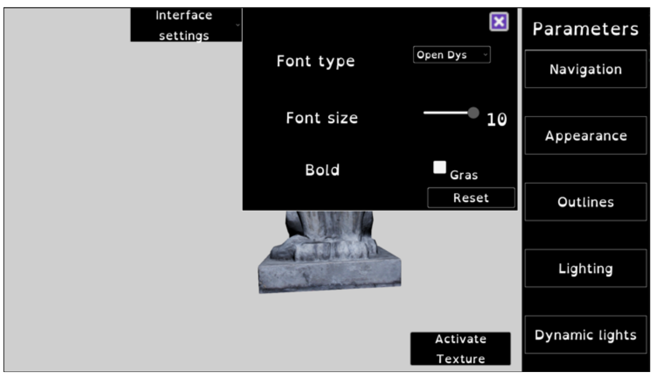

Figure 3. Screenshot, black theme and OpenDys white police.

Figure 4 shows a black background behind the object. It contrasts sharply with the menus (white).

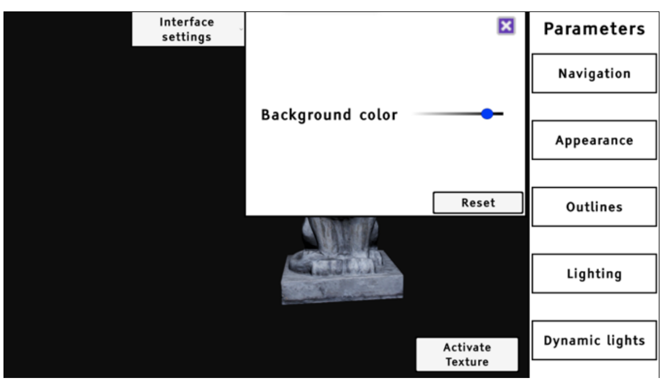

Figure 4. Screenshot, scene contrast, black.

Figures below summarize various combinations of choice. On Figure 5, the menu is on the left, the background is grey, the menu theme is light grey and the font type is "Luciole". On Figure 6, the menu is on the right, with a black background, white theme and "OpenDys" font type.

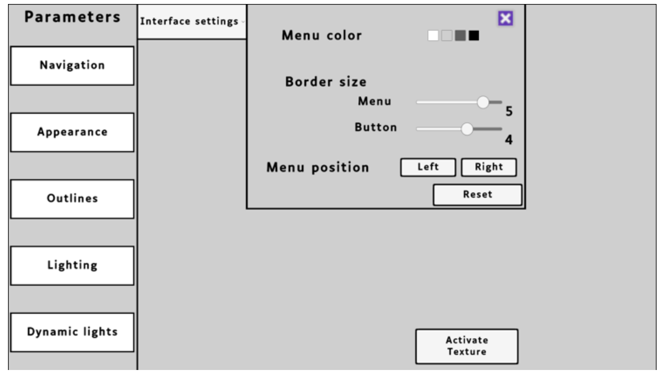

Figure 5. Screenshot, left menu position, light grey theme, light grey scene and font choice.

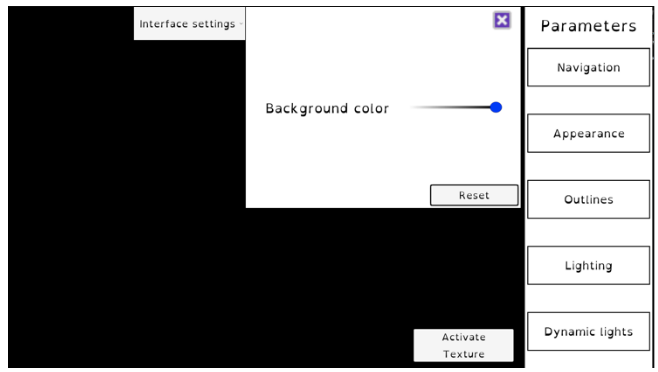

Figure 6. Screenshot, right menu position, white theme, black scene and font choice.

The digital treatments presented in the following section use, geometric data from the 3D models or brightness information obtained after 2D rendering.

C. *Visualization functions*

The seven functions below require a minimum of parameterization on the part of the visually impaired user to simplify their use.

Digital zoom. This is the simplest function to implement and also the most intuitive, as it is present in all tools. It magnifies elements of the scene, making them more perceptible. For the visually impaired, the impact of blurred vision is lessened, but at the cost of a diminished field of view.

Digital zoom enlarges the image through digital processing. The limitations of this tool are linked to the quality of the 3D model (geometric and surface data). For example, if the resolution of the texture file is insufficient, digital zoom will create new pixels by oversampling, with the possible consequences of loss of sharpness and noise amplification.

Navigation around the object and automatic framing. These functions enable selecting the optimal viewpoint for individuals with visual impairments. It is coupled with other functionalities, allowing, for example, zooming based on the chosen angle. We ensured that it is impossible to pass through the object with the virtual camera. At any moment, it is possible to return to the initial camera viewpoint with the object at the center of the image (automatic framing).

Sharpness and contrast. These functions are crucial in the perception of an image. Sharpness measures the precision of details and outlines in an image, while contrast quantifies the difference in brightness between the light and dark parts of the image. The benefit of a sharp and contrasted image is immense for individuals with visual impairments. It facilitates understanding the overall structure of the scene.

Numerous digital tools exist to enhance sharpness. One of the most commonly used methods to emphasize outlines is called “unsharp masking”. In its basic version, it involves subtracting a blurred version of the original image from the image itself to reveal the outlines present in the original image. Finally, this result is added back to the original image. This has the effect of accentuating the outlines by enhancing the pixel values that differ between the original and blurred images.

Brightness and saturation. This function provides the ability to adjust the overall brightness of the scene. It is widely used by individuals with visual impairments as it helps minimize visual discomfort, such as limiting glare. There are numerous methods to adjust brightness, but the simplest involves transitioning into the HSV (Hue Saturation Value) color space, known to be one of the closest to human perception. By modifying the “saturation”, we influence the color purity, transitioning from a dull color to a vibrant one without altering the hue. Adjusting the third parameter modifies the brightness of the pixels, making them darker or lighter.

Outlines. This function corresponds to rapid changes in the properties of the digital image generated by the presence of important structural elements in the scene. These changes can be related to depth discontinuities, surface orientation or color. The system detects and displays (with a customizable color/width) three types of edges computed respectively from depth gradient (*EDG*), normal gradient (*ENG,* Figure 8) and color gradient (*ECG*) thus highlighting the silhouette, geometric features and texture of the object. The process involves several steps: 1/ sampling the main texture around each pixel 2/ retrieve depth (I_d: depth buffer), color (I_c: r,g,b channels), and normal (I_n: x,y,z directions) information from sampled pixels 3/ compute gradients by convolving the depth, color, and normal data with the two Sobel kernels 4/ thresholding the gradients norms 5/ modifying the color of the point whose norm is greater than a threshold.

For example, to detect depth edges the system first calculates the horizontal and vertical gradients EDG_x and EDG_y by convolving the I_d image with $Sobel_x$ and $Sobel_y$ kernels respectively (edge detection in horizontal and vertical directions). The magnitude of the depth gradient *EDG* is computed as the norm of (EDG_x, EDG_y) vector.

In the case of color and normal gradients (*ECG, ENG*), the system only considers the largest magnitude among the 3 color/direction channels for thresholding.

Texture. The two main elements of a 3D model are its geometric data and its texture. Texture is made up of two-dimensional images applied to the surface of the model to add realism (color, roughness, reflection, etc.). For the visually impaired, this information overload generated by an object with too little or too much texture can hinder identification. The object's native texture is replaced with a solid color or a stripe pattern (high-contrast alternating white/black stripes) to simplify understanding (surface state and depth).

Play of lights. The system allows simulation of fixed or dynamic lighting effects. The idea is to exploit, among other things, projected shadows to enhance understanding of the scene. The temperature of lighting is adjustable. A higher value makes the light appear cooler (or bluer), while a lower value makes the light appear warmer (or yellower). The benefits for individuals with visual impairments are manifold: improving depth perception, creating visual contrast between the illuminated area and the rest to make identification easier.

D. *Rendering visualization functions*

Figure 7 shows a treatment applied to a 3D object: a cactus. The screenshot on the left shows the 3D object without pathology. The right screenshot shows the object as seen by a visually impaired person suffering from myopia and tunnel vision.

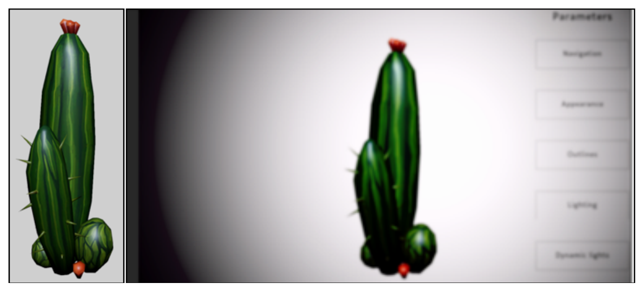

Figure 7. Screenshot, the 3D model of a cactus seen by a sighted person (on the left) and by a visually impaired (on the right).

Figures below illustrate various combinations of treatments applied to three 3D objects: a cactus, a torch and a soup plate. Figure 8 shows the cactus in profile. The screenshot on the left presents the 3D object seen without pathology. The screenshot on the right shows the 3D object with edge computed from normal gradient to delineate and identify the other small cactus.

Figures 9 and 10 below display the details of a 3D object, which are visible through “play of lights” function.

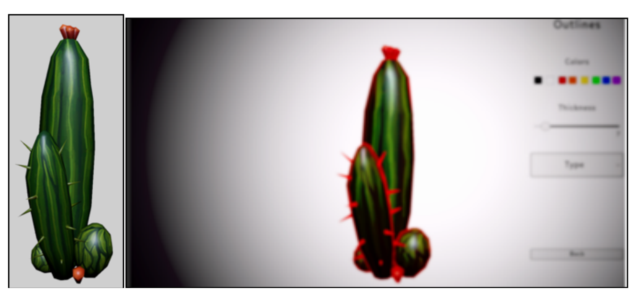

Figure 8. Screenshot, the cactus without processing (on the left) and with treatments (on the right): edge computed from normal gradient.

Figure 9 shows the details of a torch, in particular the two red buttons, which appear thanks to dynamic lighting effects.

Figure 9. Screenshot, the torch with treatments: navigation, zoom and dynamic lighting, seen with tunnel vision and myopia.

Figure 10 shows the outlines of the torch, which are emphasized using contour lines, with static lighting effects.

Figure 10. Screenshot, the torch with treatments: navigation, zoom, high static light and edge computed from depth gradient.

Figure 11 shows how the use of texture substitution on a 3D object helps to better understand its depth.

Figure 11. Screenshot, the soup plate with treatments: navigation, zoom and texture substitution.

VII. The IRENE Application Evaluation

Evaluating with visually impaired individuals is considered a "challenge" [54], as gathering a sufficient number of participants is difficult.

A. *Final evaluators*

According to [55], the recommended number of participants ranges between 3 and 10. Thus, we found four visually impaired through the “Departmental House for Disabled Persons”. They participated in the evaluation phase as end users. None of these participants had taken part in the co-design process.

Table I summarizes their visual disabilities and provides the left eye and right eye vision scores for each of them. One person perceives spots in the intermediate field of vision (U1), another has impaired vision over the entire field of view (U2), the third has tunnel vision (U3), and the last person has severe myopia (U4). We can thus notice that these handicaps are very important and we will see that the results of the experiment depend on this fact.

The participants have different visual impairments, but some similarities can still be observed: U1 and U3 have retinitis pigmentosa, while U1 and U2 have only half of their visual field.

TABLE I. THE VISUAL DISABILITIES OF THE PARTICIPANTS

	User 1 (U1)	**User 2 (U2)**	**User 3 (U3)**	**User 4 (U4)**
Left eye/10	0	0	4	1
Right eye/10	1	1	1	1
Vision	Vision with spots in the intermediate field of view	Impaired vision over the entire field on view	Tunnel vision	Severe blurred vision
Pathology	Scotoma with pigmentary retinopathy	Meningioma (optic nerve atrophy)	Usher syndrome with pigmentary retinopathy	Nystagmus with severe myopia
Color perception	Need contrast	Need contrast	Need contrast	Good
Light sensitivity	Yes	Yes	Yes	Yes

These participants took part in both the usability evaluation and the utility evaluation. With this number of participants, we are aware that the evaluation cannot focus on quantitative metrics but rather on qualitative insights. This is why our evaluation is considered more of a "pilot study," as recommended by [55].

B. *Protocol and evaluation*

We selected seven 3D models representing everyday objects (see Figure 12). These include a soup plate, a can, a statue of a lion, a grapefruit, a sweet potato, a torch and a basket. Some of these 3D models are intentionally ambiguous to test the effectiveness of the visualization assistance functions by introducing potential confusion with other objects. None of the models are annotated.

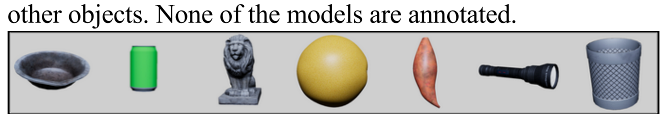

Figure 12. The seven 3D models used to test the 3D visualization tool.

The prototype evaluation took the form of four semi-structured interviews, each lasting approximately an hour and a half. The focus was on prioritizing verbal interaction to avoid cognitive overload. Each interview was conducted using an evaluation grid comprising questions categorized into two themes: utility and usability.

To develop the usability evaluation grid, we based our approach on the list of recommendations [56] dedicated to co-design with visually impaired, ergonomic guidelines [33][35], heuristics, and the ISO 9241-125 standard [47] for the visual presentation of information.

We created a consultable evaluation grid [57]. This grid includes the following five criteria: 1- Ease of use (20 questions: Is the interface elements easy to manipulate?), 2- Interface minimalism (21 questions: Do the presented information not cause visual overload?), 3- Reactivity (3 questions: Does the interface provide immediate feedback?), 4- Standards and clear designation (8 questions: Does the interface respect standards?), 5- Flexibility (18 questions: Does the interface adapt to the users' visual preferences and technological habits?). For the utility evaluation grid, each assistance function corresponded to an evaluation criterion (Does the function help better perceive the 3D object?). Thus, we established 14 criteria in total.

The visually impaired participants were positioned in front of a computer screen. Initially, they had the opportunity to customize their interface according to their preferences, including options such as font choice, size, menu position, menu background color, borders, etc. The questions were posed progressively as the customization options were presented. Participants could respond with "Yes," "No," or "Not really," and were encouraged to share their impressions and comments throughout the evaluation.

After selecting their preferences, the 3D objects were presented in the following sequence: soup plate, can, torch, basket, lion statue, grapefruit, sweet potato. The visually impaired participant then selected the useful functions according to their needs to recognize the 3D object optimally, interpret its volumes, surface aspects, color, and texture. Questions regarding the features were posed after each treatment. For example: "Is the sharpness function helpful, in the sense of aiding better vision?" or "Which types of outlines are most useful for you?".

When a person believes he/she has identified the 3D object, he/she gives its identity and can move on to the next one.

C. Results and analysis for the usability criterion

Given the small number (4) of participants, statistical methods could not be used. We only have 320 responses. For each criterion, we calculated the percentage of responses (yes, no, not really). Figure 13 shows the response rate of participants per evaluation criterion.

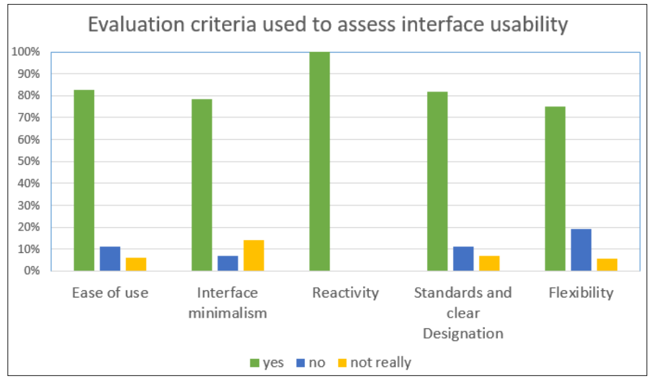

Figure 13. The response rate of participants per evaluation criterion.

More than 75% of the participants validate the usability of the application (for all 5 criteria). For each of the five criteria, the analysis is as follows:

1. **Ease of use.** The difficulties encountered stem from the participants' visual impairments (severely reduced and blurry vision, difficulty in perceiving colors and their variations, sensitivity to light). They have difficulty seeing the mouse cursor (too small), the font size (too small, even at maximum), and the dropdown menu (information too small). The "checkbox" is the most difficult element to use for 3 participants, regardless of their visual condition (too small, and the difference between checked and unchecked is not visible).
2. **Interface Minimalism.** The difficulties also arise from the visual impairment. The interface elements are small, and participants struggle to position the mouse pointer on these elements. Participants with retinitis pigmentosa prefer the harmonization of interface elements.
3. **Reactivity.** 100% of participants found the interface "reactive" and felt that it responded immediately to their actions.
4. **Standards and clear designation.** 82% of participants used the interface independently. For the remaining 18%, the issue was primarily with the terminology used in the menus, such as the "Parameters" menu for visual assistance functions, which was confused with settings. The term "saturation" was not understood. The term "reset" in the "appearance" menu was confused with "resetting" the interface settings.
5. **Flexibility.** Table II below summarizes the interface customization based on individual needs.

TABLE II. INTERFACE SETTINGS CHOSEN BY EACH PARTICIPANT

Elements		U1	U2	U3	U4
Font	Type	Luciole	Luciole	Luciole	Luciole
	Size	10 (max)	10 (max)	10 (max)	4
	Bold	Yes	Yes	No	No
Menu	Theme	Black	White	Black	White
	borders	5 (max)	5 (max)	2	5 (max)
	Button borders	5 (max)	5 (max)	1 (min)	5 (max)
	Position	Left	Right	Left	Left

3D model background	Black	White	Dark gray	White
Vision	Vision with spots in the intermediate field of view	Impaired vision over the entire field on view	Tunnel vision	Severe blurred vision
Pathology	Scotoma with pigmentary retinopathy	Meningioma (optic nerve atrophy)	Usher syndrome with pigmentary retinopathy	Nystagmus with severe myopia

Similarities in the choice of settings were observed, particularly among participants with similar visual disabilities. Participants suffering from retinal disorders (U1 and U3) preferred a "black theme" interface with a dark background for the 3D objects. Participants with significantly reduced vision in both eyes (U1 and U2) preferred bold text because reading was difficult for them.

D. Results and analysis for the utility criterion

The results for the utility criterion are synthetized in Figure 14, where for each user, one can see if the functions help to recognize the 3D objects.

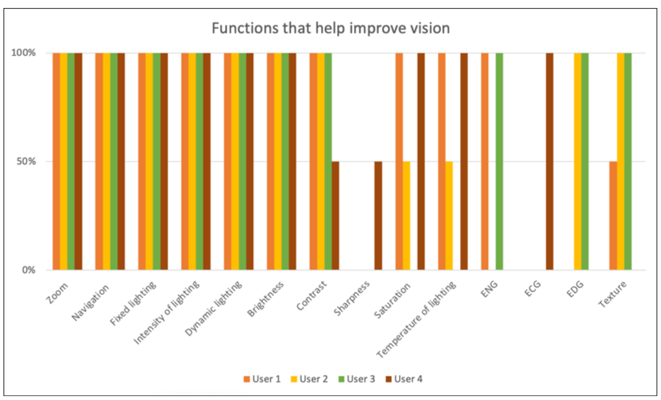

Figure 14. Usefulness of functions according to users.

The responses to the questions on the usefulness of the functionalities show that there is unanimous agreement on the value of zoom and navigation. These two basic functions, which rely essentially on movement, are fundamental, whatever the visual disability, as they stimulate perception and help to remove ambiguities. Moreover, they permit checking the symmetry, whether it is mirror, translational or rotational, which is fundamental to access to the shapes *veridically* [58].

There was also unanimous agreement on the benefits of lighting (all three modes), brightness and contrast.

Sharpness may be considered unnecessary for these four users. The interest in the other functions is specific to the users: the functionalities are called upon depending on the pathology. For example, U3 does not use temperature of lighting and saturation because he doesn't perceive colors.

These results also show that processing using gradients is clearly useful and can visibly compensate for certain visual impairments, even though they are rarely, if at all, present in the usual visualisation tools. But for the rest, and as pointed in [58] about the human perception of 3D shapes "The role of depth cues is secondary, at best".

Figure 15 shows the results of the recognition of the 7 objects for each user with a recall of their vision score.

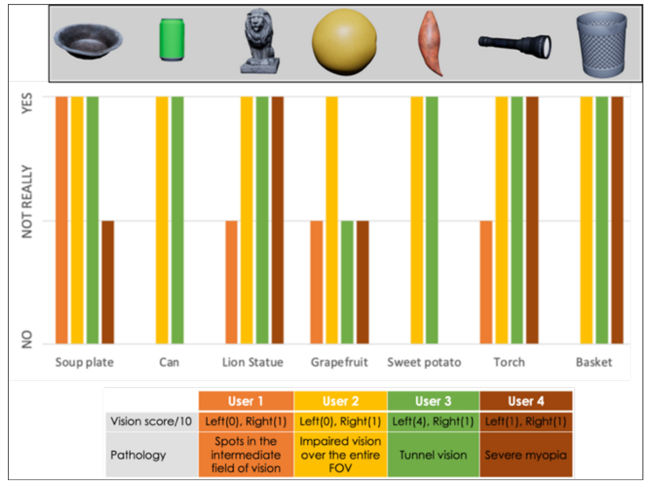

Figure 15. Results of object recognition according to each user.

These results show that four objects were recognized by at least three users. The Gradient feature was used by U3 to recognize six out of seven objects, confirming its value.

The recognition score for grapefruit is mixed for several reasons. Firstly, this fruit is primarily characterized by its size, color and texture. However, size is challenging to perceive in 3D, as observed in this experiment. The other two characteristics are evidently limiting for the visually impaired. Nevertheless, when we analyze the users' responses in detail, we note that two users identified it as a citrus fruit, which can be considered the correct response in this context.

Similarly, for sweet potato, two users responded with "bean pod", a hypothesis that could have been invalidated if the users had access to the size information.

VIII. Conclusion and Future Work

This article presented the co-design of the IRENE application: an interactive prototype designed to assist with the visualization of 3D objects, adapted for visually impaired individuals. The 2D renderings of 3D objects are enhanced through image processing on a standard 2D computer screen. This alternative to immersive systems, which are challenging for visually impaired users, leverages the richness of information inherent in 3D objects without relying on semantic segmentation or voice transcription.

The originality of this contribution lies in the fact that it offers, within a single application, interface customization functions and visualization assistance features (such as contour enhancement, zoom, contrast, sharpness, brightness, saturation, light effects, and textures).

For the co-design of IRENE, we opted for an inclusive co-design approach rather than following the ISO 16355 standard [27], which is dedicated to quality management and product engineering methods, even though these are centered on customer needs and expectations. As Newell and Gregor point out, gathering a representative sample from a heterogeneous user group, especially one including individuals with disabilities, can be challenging [59], as is the case with our target population. Therefore, we adapted to the context and specificities of our target group [60] to test our proof of concept. We successfully reached out to 12 visually impaired individuals through associations in the Hauts-de-France region: 6 participated in the "needs analysis" phase, 2 in the co-design process, and 4 in the final evaluation.

The results regarding the usability of the interface are promising, with over 75% of participants responding positively. Future improvements to the 2D interface of the final product include enlarging the mouse cursor size, increasing font size, improving dropdown menus, enhancing checkboxes, and modifying menu terminology. We also plane to integrate a user profile with a pre-configuration of the interface based on the user's specific visual impairment. The results related to the utility of the 3D visualization aid functions are also promising. They demonstrate that gradient-based post-processing is clearly useful and can significantly compensate for certain visual impairments, even though such features are rarely found in standard visualization tools.

We can now build upon these results to design the IRENE product. In this context, we will be able to implement the Voice of the Customer (VoC) [61] approach, a product development method that plays a key role in customer-centric methodologies such as Six Sigma [28] and Quality Function Deployment (QFD) [29].

We will also consider the ISO 16355 series of standards, particularly ISO 16355-2 (Customer Needs Analysis), which provides guidelines for collecting, analysing, and prioritizing customer needs, and ISO 16355-3 (Characteristics Analysis), which helps translate customer expectations into technical specifications.

References

[1] A. Ambles, D. Groux-Leclet, and A. Potelle, “Co-Design of an Adaptive User Interface for the Visually Impaired People,” The Seventeenth International Conference on Advances in Computer-Human Interactions - ACHI 2024, IARIA, May 2024, pp. 168- 173, ISSN: 2308-4138, ISBN: 978-1-68558-163-3 [retrieved: 11, 2024].

[2] World Health Organization, “World report on vision”. 2019. [retrieved: 11, 2024]. [Online]. Available from: https://www.who.int/publications/i/item/9789241516570

[3] M. Torossian, “Definitions and classifications of visual impairment,” in French orthoptic journal, vol. 11, issue 1, pp. 26-28, 2018. doi: https://doi.org/10.1016/j.rfo.2018.02.002 (in French) [retrieved: 11, 2024].

[4] J. Fraser and C. Gutwin, “A framework of assistive pointers for low vision users,” in Proceedings of the fourth international ACM conference on Assistive technologies – Assets ‘00, Arlington, Virginia, USA, Nov. 2000. Association for Computing Machinery, New York, NY, USA, pp. 9–16. doi: https://doi.org/10.1145/354324.354329 [retrieved: 11, 2024].

[5] R. M. A. van Nispen et al., “Low vision rehabilitation for better quality of life in visually impaired adults,” in Cochrane Database of Systematic Reviews 2020, issue 1, no. CD006543 Jan. 2020. doi: https://doi.org/10.1002/14651858.CD006543.pub2 [retrieved: 11, 2024].

[6] M. Mott et al., “Accessible by Design: An Opportunity for Virtual Reality,” in 2019 IEEE International Symposium On Mixed And Augmented Reality Adjunct - ISMAR-Adjunct, Beijing, China, IEEE, Oct. 2019, pp. 541-545. doi:10.1109/ismar-adjunct.2019.00122 [retrieved: 11, 2024].

[7] R. Ani, E. Maria, J. J. Joyce, V. Sakkaravarthy and M. A. Raja, “Smart Specs: Voice assisted text reading system for visually impaired persons using TTS method” in Proceedings of the International Conference on Innovations in Green Energy and Healthcare Technologies – ICIGEHT ’17, Coimbatore, India, IEEE, Mar. 2017, pp. 1-6. [retrieved: 11, 2024].

[8] N. Parikh, I. Shah, and S. Vahora, “Android Smartphone Based Visual Object Recognition for Visually Impaired Using Deep Learning” in 2018 international conference on communication and signal processing – ICCSP, Chennai, India, IEEE, Apr. 2018, pp. 420-425. doi: 10.1109/ICCSP.2018.8524493 [retrieved: 11, 2024].

[9] K. Bineeth, S. Raju, and E.S. Frode, “Tools and Technologies for Blind and Visually Impaired Navigation Support: A Review,” in IETE Technical Review, Taylor & Francis, vol. 39, issue 1, pp. 3-18, 2022. doi: 10.1080/02564602.2020.1819893 [retrieved: 11, 2024].

[10] K. Akif and K. Shah, “An insight into smartphone-based assistive solutions for visually impaired and blind people: issues, challenges and opportunities,” in Universal Access in the Information Society, Springer, vol. 20, no. 2, pp. 265–298, 2021. [retrieved: 11, 2024].

[11] V. Braimah, J. Robinson, R. Chun, and W. M. Jay, “Usage of accessibility options for the iPhone/iPad in a visually impaired population,” in Seminars in Ophthalmology, informa Healthcare USA, Inc, 1–9, 2015. DOI: 10.3109/08820538.2015.1045151 [retrieved: 11, 2024].

[12] S. Chiti and B. Leporini, “Accessibility of android-based mobile devices: A prototype to investigate interaction with blind users” in Proceedings of the 13th International Conference on Computers Helping People with Special Needs – ICCHP ‘12, Linz, Austria, Springer, July 2012, part II 13, pp. 607–614, Berlin, Heidelberg. [retrieved: 11, 2024].

[13] A. Shera et al., “Blind and visually impaired user interface to solve accessibility problems,” in Intelligent Automation and Soft Computing, vol. 30, issue 1, pp. 285-301, 2021. doi: 10.32604/iasc.2021.018009 [retrieved: 11, 2024].

[14] R. Samout, “Access to information in situations of disability: the case of visually impaired students,” Information and communication sciences. Thesis presented at the University of Lille, 2019. (in French) [retrieved: 11, 2024].

[15] R. Girshick, J. Donahue, T. Darrell, and J. Malik, “Rich feature hierarchies for accurate object detection and semantic segmentation,” in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition - CVPR, Columbus, OH, USA, 2014, pp. 580-587. [retrieved: 11, 2024].

[16] L. Chen, G. Papandreou, I. Kokkinos, K. Murphy, and A. L. Yuille, “DeepLab: Semantic Image Segmentation with Deep Convolutional Nets, Atrous Convolution, and Fully Connected CRFs,” in IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 40, issue 4, pp. 834-848, April 2018. doi: 10.1109/TPAMI.2017.2699184 [retrieved: 11, 2024].

[17] A. D. Hwang and E. Peli, “An Augmented-Reality Edge Enhancement Application for Google Glass” Optometry and Vision Science, vol. 91, issue 8, pp. 1021-1030, Aug. 2014. doi: 10.1097/OPX.0000000000000326 [retrieved: 11, 2024].

[18] S. L. Hicks et al., "A Depth-Based Head-Mounted Visual Display to Aid Navigation in Partially Sighted Individuals," PLoS ONE, vol. 8, no. 7, pp. 1-8, Jul. 2013. doi: https://doi.org/10.1371/journal.pone.0067695 [retrieved: 11, 2024].

[19] Y. Zhao, S. Szpiro, and S. Azenkot, "Foresee: A Customizable Head-Mounted Vision Enhancement System for People with Low Vision", in Proceedings of the 17th international ACM SIGACCESS Conference on Computers & Accessibility – ASSETS '15, ACM, Oct. 2015, pp. 239-249. doi: https://doi.org/10.1145/2700648.2809865 [retrieved: 11, 2024].

[20] Y. Zhao et al., "SeeingVR: A Set of Tools to Make Virtual Reality More Accessible to People with Low Vision," in Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems – CHI '19, ACM, May 2019, pp. 1-14. doi: https://doi.org/10.1145/3290605.3300341 [retrieved: 11, 2024].

[21] A. Burova et al., "Virtual Reality as a tool for designing accessible public transportation services," in Transportation Research Procedia, Elsevier, vol. 72, pp. 2760-2767,2023. doi: https://doi.org/10.1016/j.trpro.2023.11.818 [retrieved: 11, 2024].

[22] F.J. Thiel and A. Steed, "A Way to a Universal VR Accessibility Toolkit," in Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems – CHI '21, ACM, June 2021, pp. 1–5. doi: https://doi.org/10.48550/arXiv.2106.00321 [retrieved: 11, 2024].

[23] M. Morel, B. Bideau, J. Lardy, and R. Kulpa, "Advantages and limitations of virtual reality for balance assessment and rehabilitation", Clinical Neurophysiology, Elsevier, vol. 45, issues 4–5, pp. 315-326, Nov. 2015. ISSN 0987-7053. doi: https://doi.org/10.1016/j.neucli.2015.09.007 [retrieved: 11, 2024].

[24] C. Creed, M. Al-Kalbani, A. Theil, S. Sarcar, and I. Williams, "Inclusive AR/VR: accessibility barriers for immersive technologies," Universal Access in the Information Society, Springer, vol. 23, no. 1, pp. 59-73, 2024. [retrieved: 11, 2024].

[25] N.M. D'Cunha et al., "A mini-review of virtual reality-based interventions to promote well-being for people living with dementia and mild cognitive impairment," Gerontology, vol. 65, issue 4, pp. 430–440, 2019. doi: https://doi.org/10.1159/000500040 [retrieved: 11, 2024].

[26] A. Wong, H. Gillis, and B. Peck, "VR accessibility: Survey for people with disabilities," Disability Visibility Project. Technical report, 2017.

[27] ISO 16355-1:2021, "Application of statistical and related methods to new technology and product development process, Part 1: General principles and perspectives of quality function deployment (QFD)," Edition 2, 2021. [retrieved: 11, 2024] [Online]. Available from: https://www.iso.org/standard/74103.html

[28] M. Harry and R. Schroeder, "Six sigma: the breakthrough management strategy revolutionizing the world's top corporations" in Crown Currency, 2006.

[29] Y. Akao, "Quality function deployment: integrating customer requirements into product design," in CRC Press, 1990.

[30] S. Bφdker, K. Grφnbæk, and M. Kyng, "Cooperative design: techniques and experiences from the Scandinavian scene" in Readings in human-computer interaction, Morgan Kaufmann Publishers, pp. 215-224, 1995. doi: https://doi.org/10.1016/B978-0-08-051574-8.50025-X. [retrieved: 11, 2024].

[31] M.R. Dekker and A.D. Williams, "The use of user-centered participatory design in serious games for anxiety and depression," Games for health journal, vol. 6, no. 6, pp. 327-333, Dec. 2017. doi: https://doi.org/10.1089/g4h.2017.0058 [retrieved: 11, 2024].

[32] D. Schuler and A. Namioka, "Participatory design: principles and practices," in CRC Press, 1993.

[33] J. Nielsen, "Heuristic evaluation", in J. Nielsen et R.L. Mack (Eds.), Usability inspection methods, New York, John Wiley & Sons, ACM, Chapter 2, pp. 25-62, June 1994.

[34] M. Grislin and C. Kolski, "Evaluation of human-machine interfaces during interactive system development ", Journal of Information Sciences and Technologies - TSI Series: Computer Techniques and Science, vol. 15, no. 3, pp. 265-296, 1996. (in French) [retrieved: 11, 2024].

[35] C. Bastien and D. Scapin, "Ergonomic criteria for the evaluation of human-computer interfaces", Doctoral dissertation, Inria, RT-0156, INRIA. 1993, pp. 79. [retrieved: 11, 2024].

[36] B. Nanchen et al., "Designing with and for people with disabilities: towards an integrated and transdisciplinary approach to inclusive design" in Vulnerabilities and emerging risks: thinking and acting together for sustainable transformation: Proceedings of the 56th SELF Congress, Genève, Suisse, Jul. 2022, pp. 371-377. (in French) [retrieved: 11, 2024].

[37] J. J. Gibson, "The ecological approach to visual perception: classic edition", Psychology Press, First edition, 2014. ISBN : 978-0898599596.

[38] I. Verjat, "The functional cerebral asymmetry in manual tactilo-kinesthetic modality", The Psychological Year, vol. 88, no. 1, pp. 83-109, 1988. (in French) [retrieved: 11, 2024].

[39] A. Dufresne, O. Martial, and C. Ramstein, "Multimodal user interface system for blind and "visually occupied" users: Ergonomic evaluation of the haptic and auditive dimensions" in Proceeding of Human-Computer Interaction - Inteact'95, Lillehammer, Norway, 1995, pp. 163-168 [retrieved: 11, 2024].

[40] Y. Hatwell, "Images and non-visual spatial representations in the blind", in Colloquium French National Institute of Health and Medical Research - INSERM, John Libbey Eurotext Ltd, vol. 228, pp. 13-35, 1993.

[41] J. Albouys-Perrois, J. Laviole, C. Briant, and A. M. Brock, "Towards a multisensory augmented reality map for blind and low vision people: A participatory design approach", in Proceedings of the Conference on human factors in computing systems - CHI '18, Montreal, QC, Canada: ACM, Apr. 2018, pp. 1-14. doi: https://doi.org/10.1145/3173574.3174203 [retrieved: 11, 2024].

[42] A. Brock et al., "Methods and tools for participatory design with blind users" in Proceedings of the 22nd Conference on Human-Computer Interaction – IHM '10, Luxembourg, Luxembourg: ACM, Sept. 2010, pp. 65-72. doi: https://doi.org/10.1145/1941007.1941017 (in French) [retrieved: 11, 2024].

[43] R. Sefelin, M. Tscheligi, and V. Giller, "Paper prototyping-what is it good for? A comparison of paper-and computer-based low-fidelity prototyping", in Proceedings of CHI'03 extended abstracts on Human factors in computing systems - CHI '03, Lauderdale, Florida, USA, ACM, Apr. 2003, pp. 778-779. doi: https://doi.org/10.1145/765891.765986. [retrieved: 11, 2024].

[44] B. W. Boehm, "A spiral model of software development and enhancement", Computer, IEEE, vol. 21, no. 5, pp. 61-72, May 1988. doi: 10.1109/2.59. [retrieved: 11, 2024].

[45] P.R. Jones, T. Somoskeöy, H. Chow-Wing-Bom, and D.P. Crabb, "Seeing other perspectives: evaluating the use of virtual and augmented reality to simulate visual impairments (OpenVisSim)" in NPJ digital medicine, Nature Publishing Group, vol. 3, issue 1, pp. 32, 2020. [retrieved: 11, 2024].

[46] Unity. [retrieved: 07, 2024]. [Online]. Available from: https://unity.com/fr

[47] ISO 9241-125:2017, "Ergonomics of human-system interaction - Part 125: guidance on visual presentation of information", 2017. [retrieved: 11, 2024]. [Online]. Available from: https://www.boutique.afnor.org/en-gb/standard/nf-en-iso-9241125/ergonomics-of-humansystem-interaction-part-125-guidance-on-visual-presentat/fa184266/79938

[48] M. Maguire, "Methods to support human-centred design", in International journal of human-computer studies, Elsevier, vol. 55, issue 4, pp. 587-634, 2001. doi: https://doi.org/10.1006/ijhc.2001.0503 [retrieved: 11, 2024].

[49] The table of the "Criteria Composition" : https://extra.u-picardie.fr/nextcloud/index.php/s/AyrQzfsMgrDtJ7y

[50] F. Navamuel, "Three fonts designed for the visually impaired", in ICT Tools, Apr. 2023. [retrieved: 11, 2024]. [Online]. Available from: https://outilstice.com/2020/02/3-polices-de-caracteres-concues-pour-les-malvoyants/ (in French).

[51] E. Russell-Minda et al., "The legibility of typefaces for readers with low vision: A research review" in Journal of Visual Impairment & Blindness, vol. 101, issue 7, pp. 402-415, Jul. 2007. doi: https://doi.org/10.1177/0145482X0710100703. [retrieved: 11, 2024].

[52] E. Lassfolk, "User Experience App Design for Visually Impaired Elderly", 2023. [retrieved: 11, 2024].

[53] J. Nielsen, "Let users control font size", in Nielsen Norman Group, August 2002. [retrieved: 11, 2024]. [Online]. Available from: https://www.nngroup.com/articles/let-users-control-font-size/

[54] A. Budrionis, D. Plikynas, P. Daniušis, and A. Indrulionis, "Smartphone-based computer vision travelling aids for blind and visually impaired individuals: A systematic review," in Assistive Technology, vol. 34, issue 2, pp. 178-194, Apr. 2022. doi: https://doi.org/10.1080/10400435.2020.1743381. [retrieved: 11, 2024].

[55] J. Lazar, J. H. Feng, and H. Hochheiser, "Research methods in human-computer interaction," in Morgan Kaufmann, Second Edition, 2017. [retrieved: 11, 2024].

[56] C. Magnusson, P. O. Hedvall, and H. Caltenco, "Co-designing together with Persons with Visual Impairments," in Mobility of visually impaired people: fundamentals and ICT Assistive Technologies. Springer, Cham, 22 August 2017, pp. 411-434. ISBN : 978-3-319-54446-5. [retrieved: 11, 2024].

[57] The interface evaluation grids: https://extra.u-picardie.fr/nextcloud/index.php/s/AyrQzfsMgrDtJ7y

[58] Z. Pizlo, "Human Perception of 3D Shapes," in Kropatsch, W.G., Kampel, M., Hanbury, A. (eds), International Conference on Computer Analysis of Images and Patterns – CAIP 2007, Springer, vol. 4673, pp. 1-12. doi: https://doi.org/10.1007/978-3-540-74272-2_1 [retrieved: 11, 2024].

[59] A. F. Newell and P. Gregor, "User sensitive inclusive design - in search of a new paradigm," in Proceedings on the 2000 conference on Universal Usability – CUU '00, Arlington, Virginia, USA, Nov. 2000, pp. 39-44. doi: https://doi.org/10.1145/355460.355470

[60] V. Lespinet-Najib, A. Roche, and Q. Chibaudel, "Health and disability: from user-centered design to universal design," in Mines Industrial Realities Journal, Eds Institut Mines Télécom, n.2, pp. 25-27, 2017. (in French).

[61] A. Griffin and J. R. Hauser, J. R. "The voice of the customer," in Marketing science, vol. 12, no. 1, pp. 1-27, Feb. 1993. doi: https://doi.org/10.1287/mksc.12.1.1