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FlexiSee: Flexible Configuration, Customization, and Control of Mediated and Augmented Vision for Users of Smart Eyewear Devices

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Abstract We present “FlexiSee,” an application for smart eyewear devices, such as see-through Augmented Reality glasses and Head-Mounted Mixed Reality Displays, that enables flexible configuration, customization, and control of augmented and mediated vision. By default, FlexiSee implements several types of vision assistance techniques, called "visual filters" in this work, including color correction, edge highlighting, contrast adjustment, and face detection that were informed by an analysis of prior work in assisting visual perception for people with visual impairments. FlexiSee is coupled with a web-based user interface where authorized users, other than the wearer of FlexiSee, can specify and apply custom visual filters that are automatically uploaded to FlexiSee users. To this end, FlexiSee introduces and works with the distinction between primary users and vision monitors and assistants that have various degrees of control, from their remote locations, over the augmented and mediated vision of the primary users. We also introduce “FlexiSee-DS,” a three-dimensional design space for FlexiSee-like applications, that includes mediation & augmentation, user categories, and control design dimensions.

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1 Introduction

Smart eyewear devices, in the form of Augmented Reality (AR) smartglasses and Head-Mounted Displays (HMD) for Mixed Reality (MR) and Extended Reality (XR) applications, represent a convenient category of wearable devices to implement vision assistance and vision rehabilitation for people with visual impairments. Examples of applications from the scientific literature include contrast enhancement, edge highlighting, magnification, and text and sign reading [26, 58, 61, 68, 69], while commercial eyewear devices, such as eSight [15] and OrCam [44] among others, implement a variety of *vision mediation* features to assist people with various visual disorders, including glaucoma, age-related macular degeneration, or people who are blind. Recently, the XRAccess initiative [64] has been consolidating a community of researchers and practitioners around the common goal of making Virtual, Augmented, and Mixed Reality (all referred under the term "XR" [35]) more accessible to people with various disabilities, including people with visual impairments [6, 62, 65, 66]. However, possible applications of smart eyewear devices go beyond vision rehabilitation and address users without visual impairments toward delivering more accurate visual perception in low ambient light conditions [42], increased field of view [17, 50], better peripheral vision [12], or new perceptions of phenomena occurring in other regions of the electromagnetic spectrum beyond visible light [1–3, 34]. Commercial AR and MR eyewear devices, such as Vuzix Blade [63], MagicLeap [32], or HoloLens [38], enable *vision augmentation* with computer-generated graphical content.

Research and development targeting assisted vision and vision rehabilitation have attracted a lot of interest and efforts from the scientific and practitioner community. However, existing systems are not always configurable or customizable and, where they are, customization is usually limited to just some features. For example, Zhao *et al.* [69] reported that the study participants trying out their "CueSee" system expressed interest in customizing the color used to highlight objects of interest, while the "ChromaGlasses" prototype of Langlotz *et al.* [29] enabled users to select a custom shift in the RGB space for compensating various types of color blindness. Other works discussed customization as a desirable feature of their systems or as a conclusion of their investigation that was left for future work [37, 59]. In the context of making AR, MR, and VR devices and applications more accessible and inclusive [64], enabling *flexibility in controlling mediated and augmented vision* becomes a relevant feature. In

Fig. 1 *Top:* Screen capture of the FlexiSee application for HoloLens presenting the user with a custom mediation of visual reality, represented in this example by color correction and highlighted edges. *Bottom:* this specific type of mediated vision is specified via a web user interface accessible from any web browser, such as web browsers running on smartphones (left) or smartwatches (middle), and can be controlled either by the primary user (top right) or by a vision assistant from a remote location (bottom right) on behalf of the primary user. FlexiSee features flexibility in terms of (i) configuration and customization of visual mediation and augmentation filters, (ii) user roles that are involved in specifying and controlling the visual filters, and (iii) input modalities, *e.g.*, using the eyewear or an external device.

this work, we address the aspect of flexibility in presenting mediated and augmented vision to smart eyewear users at several dimensions: flexibility in controlling augmentation and mediation, flexibility in terms of the categories of users involved in the mediation and augmentation process, and flexibility in terms of the input device and input modality to control augmented and mediated vision. Our practical contributions are as follows:

1. We introduce "FlexiSee-DS," a three-dimensional design space for flexible configuration, customization, and control of mediated and augmented vision for smart eyewear users, including users with visual impairments. We distinguish among primary users, vision monitors, and vision assistants as three distinct user roles for FlexiSee-like applica-

tions, and between various types of visual augmentation and mediation, such as predefined, customizable, adaptive, and configurable features.

2. To demonstrate the FlexiSee-DS design space, we present “FlexiSee,” a highly-customizable and configurable vision mediation and augmentation application designed for the Microsoft HoloLens HMD [38]; see Figure 1. We present the engineering details and technical implementation of FlexiSee and, in order to encourage further exploration of our concepts toward more development of assistive technology for users with visual impairments, we make the source code of our HoloLens FlexiSee application freely available in the research community.

2 Related Work

We discuss in this section prior work on Mediated, Augmented, and Mixed Reality applications for smart eyewear devices, and focus on prototypes designed for users with visual impairments. We start our discussion by highlighting the distinction between *mediated* and *augmented* vision, the two concepts that we address in the FlexiSee-DS design space and implement in our FlexiSee application. Throughout this paper, we use the term "smart eyewear" to refer to devices worn at eye-level, that incorporate a video camera, and feature see-through lenses and Wi-Fi connectivity.[1]

2.1 Mediated *vs.* Augmented Vision

Following previous work on Augmented, Mixed, and Mediated Reality [7–9, 33, 34, 39–41, 56], we distinguish between *augmented* and *mediated* vision. By augmented vision, we understand the use of AR and MR technology to render digital content on top of the visual reality for users of smart eyewear devices. For example, highlighting human faces in live video by means of a red rectangle and displaying next to each detected face the name and other information about the identified person represents a case of augmented vision. By mediated vision, we understand any modification of the visual reality by applying computer vision algorithms on the video frames captured by the video camera embedded in the smart eyewear device. For example, adjusting the contrast or highlighting the contours of the objects detected in the video delivered through HMDs represent

[1] By using this terminology, we follow Kress *et al.* [28] that provided an overview of commercial HMDs and distinguished between (1) connected glasses (featuring Bluetooth or Wi-Fi connectivity, digital imaging, and optional display), (2) smartglasses (incorporate displays, may include prescription lenses), (3) smart eyewear (that extend smartglasses by integrating the optical combiner into the prescription lenses, and have the look and feel of conventional eyeglasses), (4) VR HMDs, and (5) devices for niche markets, such as high-end professional AR devices and HMDs for the defense market.

instances of mediated vision. The distinction between augmented and mediated vision is important since augmented vision brings into the user's field of view *new* information, while mediated vision enhances the *existing* information already present in the visual reality. Moreover, mediated vision can be used to filter out unwanted selected information toward creating an antonymy with respect to AR, such as in the form of Diminished Reality. For example, according to Mann [33], *"Mediated Reality ... differs from virtual reality (or augmented reality) in the sense that it allows us to filter out things we do not wish to have thrust upon us against our will"* and, respectively, *"Mediated Reality goes a step further [with respect to VR/AR/MR] by mixing/blending and also modifying reality"* [34] (p. 1). Also, it is noteworthy mentioning that augmentation and mediation of the visual reality can occur independently and simultaneously, such as when over the contrast-enhanced video capture of the visual reality several visual effects are superimposed to highlight the presence and location of specific objects of interest to facilitate visual search tasks [69] while overall improving visual perception of the surrounding physical world [33, 68]. In this case, the result can be referred to as Augmented Mediated Reality or, for short, Augmediated Reality [27, 34, 55].

Other concepts from the scientific literature are equally relevant for our discussion regarding the mediation and augmentation of human vision using smart eyewear devices. For example, Zolyomi *et al.* [73] defined "multiplicities of vision" as technology-mediated sight that is a form of skilled vision, neither fully human nor fully digital, but rather *"continuously assembled through a combination of social and technical affordances"* (p. 220). Furthermore, Peli *et al.* [47] proposed "vision multiplexing" for people with visual impairments, representing superpositioning of contour images over the natural view of a scene *"to avoid or reduce [...] limitations [of other approaches] by combining both the wide field-of-view and the high-resolution capabilities in devices in ways that permit these functionalities to be both separable and useful"* (p. 366). Following the multiplicity perspective of Zolyomi *et al.* [73] and the multiplexing concept of Peli *et al.* [47], we discuss and implement in this work sets of visual filters that, when applied in a specified order, progressively mediate and augment the visual perception of users of smart eyewear devices.

2.2 Smart Eyewear Applications for Users with Visual Impairments

Prior work has proposed and evaluated a variety of applications for smart eyewear devices, such as video camera glasses, AR smartglasses, and MR HMDs. According to Coughlan and Miele [13], AR applications for users with visual impairments, abbreviated "AR4VI," can be divided in two categories: global applications that augment the physical world in the user's proximity, and local applications that augment physical objects that the user can touch and explore. In this section, we overview such applications and focus on the type of vision augmentation and mediation that they implement. But before, we briefly discuss studies that examined the needs of users with visual impairments for assistive technology.

An important preliminary stage in the process of designing assistive technology that is relevant and useful is represented by understanding challenges experienced by people with visual impairments in using technology in general as well as their needs for vision augmentation and mediation with AR, MR, and VR devices in particular. By adopting interviews as the methodology of choice to understand potential users' needs for vision augmentation via smartglasses, Sandnes [53] reported face and text recognition being the most important features that people with visual impairments, participants from their study, sought in smartglasses applications. Brady *et al.* [11] documented visual challenges experienced in everyday life by people who are blind by conducting a large-scale study with over 5,000 participants and 40,000 questions regarding the content of photographs captured by blind people. The authors created a taxonomy of questions and highlighted various categories, such as "what color is this shirt?" or "what does this say?," for which a social community (the VizWiz Social) could provide answers. Szpiro *et al.* [60] reported that the needs of people with low vision with regards to assistive technology are different from the needs of people who are blind, and highlighted the importance of designing technology for vision enhancement [59, 60, 68, 69]. Rusu *et al.* [51] reported results from a lead-in study with five participants with low vision, in which they correlated psychological well-being evaluations, self-perceived efficiency for performing daily activities, and reported needs for eyewear technology to assist and augment their visual abilities. The authors also suggested the use of models of human vision, *e.g.* from Marr *et al.* [36], to inform design of mediated and augmented vision.

Next, we discuss systems and applications that were designed to provide vision augmentation and mediation to users with visual impairments. We organize the rest of this section according to the specific features, *e.g.*, magnification, color correction, contour highlighting, etc., that these systems implement. We also report on the degree of customization of the vision augmentation and mediation functionality featured in prior work.

2.2.1 Magnification, Reading Text and Signs

Harper *et al.* [21] discussed head-mounted video magnification devices for vision rehabilitation of people in need of assistance with reading, watching television, and independent travel. Huang *et al.* [24] proposed a sign-reading assistant implemented with the HoloLens HMD [38] that featured magnification and high-contrasting fonts. Their system allowed users to indicate to a nearby text sign, such as "Staff Only" or "Rooms 327-330," and the application displayed and read the text out loud. Reading was also addressed by Stearns *et al.* [57] that employed magnification to assist people in reading printed text by means of a finger-worn camera and results presented via the HoloLens HMD [38]. In a follow-up work, Stearns *et al.* [58] proposed an AR magnification tool in which the user captured a video frame with their smartphone, after which the image was magnified and displayed via HoloLens. The "VizLens" system of Guo *et al.* [19] is another example that relied on a mobile application to assist blind people in employing nearly any real-world interface via screen reading.

2.2.2 Independent Mobility and Wayfinding

Several systems and applications have been designed to assist with mobility and navigation. For example, Everingham *et al.* [16] proposed a system mobility aid consisting of a video camera and display unit that used a neural network classifier to identify objects in video. The video feed presented to the user was modified so that distinct colors would depict and highlight different objects. Hicks *et al.* [22] proposed a system to detect the distance to nearby objects by using brightness intensity values, *e.g.*, objects closer to the user were shown in brighter colors. Mobility was also addressed by Zhao *et al.* [67], who implemented AR visualizations delivered via the HoloLens HMD [38], to highlight stairs with color on the premise that stair navigation in unfamiliar environments can be challenging for people with low vision. Szpiro *et al.* [59] observed how their study participants with low vision performed wayfinding and shopping tasks in unfamiliar environments and reported that, although low vision aids were commercially available at the time of their study, participants mostly used their smartphones. However, while smartphones were found useful outdoors for wayfinding, they were also the source of frustrations during shopping tasks. The authors concluded with the need for assistive technology to enhance visual information for users with low vision, rather than converting that information into other output modalities, such as audio or tactile feedback [59].

2.2.3 Contours and Contrast Enhancement

Specific systems have been designed for specific vision conditions and disorders. For example, magnification and edge enhancement has been considered for the vision rehabilitation of people with peripheral or central vision loss [46, 47] to assist with visual search and collision detection tasks. For example, people with tunnel vision (*i.e.*, loss of peripheral vision with retention of central vision) experience collisions, may stumble, and encounter challenges in visual search tasks, for which edge enhancement represents an useful assistance tool [31]. Hwang and Peli [25] found that people with age-related macular degeneration, juvenile macular degeneration, glaucoma, and myopic degeneration preferred mild to moderate degrees of contour enhancement when watching TV or viewing images. Edge enhancement was also found to improve performance in visual search tasks performed on computer screens.

2.2.4 Color Correction

Color vision deficiency or color blindness has been addressed by changing colors in the live video feed delivered to users, *e.g.*, Melillo *et al.* [37] implemented changes in three color intervals corresponding to deuteranopia (red-green color blindness), protanopia (inability to perceived red light), and tritaniopia blue-yellow color blindness). Fuller and Sadovink [18] developed a Google Glass application that classified colors for people with color blindness, and Tanuwidjaja *et al.* [61] proposed "Chroma," a wearable Google Glass application that manipulated colors in AR to assist with color deficiencies. Experiments conducted by Zhao *et al.* [68] with "ForeSee," a customizable head-mounted vision enhancement system for people with low vision, reported that color red was challenging to distinguish by their study participants with low vision, while colors white and yellow performed the best. Moreover, most of the study participants reported that color blue attracted their attention more when looking at objects due to it having "more contrast," but they also found blue text difficult to read. "ChromaGlasses" [29] is another example of a system designed to replace "critical colors" in the video feed presented to colorblind users with more easily distinguished alternative colors.

2.2.5 Face Recognition

Another challenge experienced in everyday life by people with low vision is recognizing other people [71], which impacts negatively their involvement in social activities. To address this aspect, Zhao *et al.* [71] reported findings on the use of a face recognition application (the Accessibility Bot, a research prototype bot built on top of Facebook Messenger that helped identify friends from Facebook pictures) outside laboratory conditions. While the application was appreciated as helpful, user experience was negatively affected by the low perceived accuracy and difficulties while aiming the camera to capture the face of the nearby person.

2.2.6 Complex Smart Eyewear Applications Featuring Multiple Visual Enhancement Functions

A few applications have implemented several types of visual enhancements, which makes them more flexible to be employed in a variety of use case scenarios and for a variety of users. For example, Zhao *et al.*'s [68] "ForeSee" system implemented several image processing algorithms (referred to as visual filters in this work), such as contrast enhancement, text extraction, black/white reversal, edge enhancement, and magnification. "CueSee" [69] was designed to assist with recognizing specific products and delivering users with corresponding cues, such as flashes, spotlights, movements, or sunrays, to identify those products more easily. After a formative study to understand the challenges that people with low vision experience with VR technology, Zhao *et al.* [65] designed "SeeingVR," a set of low vision tools implementing several visual filters, such as magnification, brightness, contrast, edge enhancement, text augmentation, text-to-speech, depth measurement, object recognition, highlighting, and recoloring for VR applications addressing users with low vision.

Several recently available commercial eyewear devices implement many of the techniques discussed in this section for vision assistance. For instance, OrCam MyEye 2 [44] is a system designed for people who are blind or with visual impairments that implements computer vision algorithms for detecting, recognizing, and reading text, face recognition, general object recognition, such as banknotes, bar code reading, and color detection. Another example is eSight [15], an eyewear device designed to improve functional vision by means of contrast and brightness adjustment and magnification. During an investigation of eSight 2 with thirteen participants with visual impairments, Zolyomi *et al.* [73] documented the social and emotional impacts associated with assistive eyewear technology. Their results showed that assisted vision was not perceived as cure or replacement of fully functional sight, and also not appropriate for all situations, but rather *"a new type of sight that provided [participants] with an experience of the visual, if not the singular notion of "vision" that they might have held when they first heard about the device"* (p. 226).

2.3 Video Camera Glasses, LifeLogging, and Abstracting Life

Some smart eyewear devices were not designed to deliver augmentation or mediation of vision in real time, but rather to record and collect visual data that users could consult at a later time as retrospective memory aids [4, 23, 30, 72]. These systems fall into the category of lifelogging applications [20]. For example, Aiordachioae [5] proposed a system to share first-person video, captured using smartglasses with embedded video cameras, with remote viewers. For such systems, there is no vision mediation or augmentation, but only video streaming to third parties, who can thus experience the visual perspective of the smartglasses user. Another example is Life-Tags [4], a smartglasses-based system and application for

Reference / System	Feature	Description / Quote
Everingham *et al.* (1998) [16]	Color	"The form of output is easy to customise to a particular user's requirements; in this case we have used a predefined set of high saturation colours, but these colours may be customised by a user to improve visibility according to his or her particular visual impairement." (p. 3)
Harper *et al.* (1999) [21]	Magnification, contrast	"These image enhancement strategies relate to the observer, and could be customised to the requirements of an individual patient, changing as the pathology progressed." (p. 498)
Zhao *et al.* (2015) [68] / ForeSee	Magnification, contrast, edges, color, text	"ForeSee enables users to customize their visual experience by selecting, adjusting and combining different engancement methods and display modes in real times." (p. 239)
Szpiro *et al.* (2016) [59]	n/a†	"Critically, mobile systems designed for low vision should take into account the variety of visual conditions and preferences of low vision users and allow for customization of visual enhancement." (p. 70)
Zhao *et al.* (2016) [69] / CueSee	Color	"Participants had differing opinions about Guideline's color. [...] Participants all expressed interest in customizing the color by themselves." (p. 79)
Zhao *et al.* (2017) [66]	Color, text	"We described how participants with different visual impairments customized the enhancements to optimize their visual experience for viewing near- and far- distance materials, showing that participants had unique preferences for vision enhancements." (p. 4171)
Stearns *et al.* (2017) [57]	Magnification, text, other	"For each of our interface designs, the user should be able to customize the magnification level, position, text processing and other settings." (p. 362)
Melillo *et al.* (2017) [37]	n/a†	"from the technical point of view, a future development could be tuning of the correction matrix in order to be customized for the specific alteration of each subject." (p. 6)
Stearns *et al.* (2018) [58]	Magnification, position, size	"Because voice commands proved too limiting for the variety of customization options we wanted to support, we used the gesture recognition capabilities provided by the HoloLens to allow users to adjust the display's position, size and zoom level." (p. 32)
Langlotz *et al.* (2018) [29] / ChromaGlasses	Color	"we also integrated the option to select a custom shift in RGB space(RGBShift Adjusted) that can be interactively controlled by the user." (p. 369)
Zhao *et al.* (2019) [65] / SeeingVR‡	Magnification, brightness, contrast, edges, text, color	"After starting the app, the user can now select and adjust various tools of SeeingVR in real time" (p. 6)

† These references do not describe a customizable system or prototype, but they highlight the need of personalization or customization of assistive systems.
‡ System exclusively addressing VR, but we include it because of its many customizable features.

Table 1 Types of customization for mediated and augmented vision identified in the scientific literature. *Note:* references are listed in chronological order.

abstracting life in the form of clouds of tags and concepts, automatically extracted from video.

2.4 Customization of Mediated and Augmented Vision

In this paper, we are interested in ways to provide users with flexible configuration, customization, and control over the mediation and augmentation of visual reality delivered by see-through eyewear devices. In the next section, we formalize various dimensions of flexibility for augmented and mediated vision in the form of a design space, FlexiSee-DS, that can be used to characterize the features of existing prototypes and applications as well as to inform future developments. In Table 1, we re-discuss the systems overviewed in the previous subsections from the perspective of how much customization and flexibility they allow to their users for controlling mediated and augmented vision. For each paper that presented a functional prototype, we identified and extracted the features that users could control and to what extent. Table 1 lists our findings and highlights system features, *e.g.*, color correction, edge enhancement, or magnification, with corresponding quotes from each evaluated system.

3 The FlexiSee-DS Design Space and FlexiSee Application

We describe in this section the design principles, software architecture, and technical implementation of our FlexiSee application. We also introduce the FlexiSee-DS design space that enumerates possible design options for a variety of FlexiSee-like applications.

3.1 Visual Filters for Mediated and Augmented Vision

We start by defining the notion of a "visual filter" employed by FlexiSee. A visual filter is any software-based modification of the video frames captured by the built-in video camera of the smart eyewear device that are rendered on the see-through lenses and aligned with the physical world; see Figure 1, top from Section 1 for an example of a visual filter illustrating edge enhancement.[2] Visual filters can implement either mediation (*e.g.*, contrast adjustment or edge enhancement) or augmentation (*e.g.*, detected faces are highlighted with a flashing rectangle around them); or, they can implement both mediation and augmentation for Augmediated Reality [34]. Using C++ language formalism and OpenCV [43] data structures,[3] a visual filter is any implementation of a function that takes as input a video frame and outputs a modified version of it, as follows:

[2] Mann [33] also employs the concept of "visual filters," but his definition is different from ours, *i.e.*, a visual filter *"allows the wearer to create a visual attention access control system"* and *"by wearing special sunglasses in which a visual filter is implemented [...], it is possible to filter out offensive advertising"* [33].

[3] In this work, we use the Open Computer Vision Library (OpenCV) to implement the FlexiSee application. In order to create a smooth transition to the next, more technical subsections of this paper, we provide here a definition of visual filters using the OpenCV C++ formalism. Note that other work in assistive technology for vision augmentation or vision rehabilitation has also employed OpenCV [19, 37, 61].

```cpp
cv::Mat& visualFilter(cv::Mat& videoFrame, int filterType, int number, ...) {
   cv::Mat& processedFrame = videoFrame.clone();
   switch(filterType) {
       // process the video frame
       // according to the filter type
       // and parameters from the list denoted by ...
   }
   return processedFrame;
}
```

where `cv::Mat` is the OpenCV class for implementing n-dimensional dense arrays,[4] which in our case are video frames represented by matrixes of RGB pixels; `filterType` specifies the type of processing that is to be applied to the video frame (*e.g.*, contrast adjustment); and `...` indicates a number of optional parameters and the parameters that may follow (*e.g.*, the amount by which the contrast is adjusted).

By defining a visual filter as a function that takes input and returns data of the same type (`cv::Mat`), applying multiple visual filters in a sequence becomes an easy task both conceptually and from a practical perspective. For example, a contrast adjustment visual filter can be followed by an edge enhancement filter, after which face detection results can be rendered on the contrast- and edge-enhanced video frame. Moreover, such a sequence of visual filters and their corresponding parameters can be specified using standard data representation and data-interchange formats, easy to understand and edit by users. In the next subsections, we present our technical implementation for sequences of visual filters, which are specified in the FlexiSee application in the form of JSON representations.

3.2 FlexiSee-DS, a Design Space for FlexiSee-type Applications

Before presenting our FlexiSee application, we introduce the FlexiSee-DS design space and describe the steps that led us to the identification of the three design dimensions of FlexiSee-DS. In a first stage, we formulated design principles for the operation of the FlexiSee application in the form of three quality properties (Q_1 to Q_3, presented below) regarding the flexibility envisaged for customizing visual perception (*i.e.*, the degree in which augmented and mediated vision is customizable), flexibility in terms of user categories and roles (*i.e.*, who controls the visual filters?), and flexibility regarding the control modalities allowed by FlexiSee (*i.e.*, how are visual filters specified, activated, and deactivated?), as follows:

- Q_1. *Specification of visual filters.* FlexiSee should enable easy specification of visual filters and of their corresponding parameters to address a wide range of usage scenarios and user categories, such as users with low vision.

[4] `https://docs.opencv.org/3.4/d3/d63/classcv_1_1Mat.html#details`.

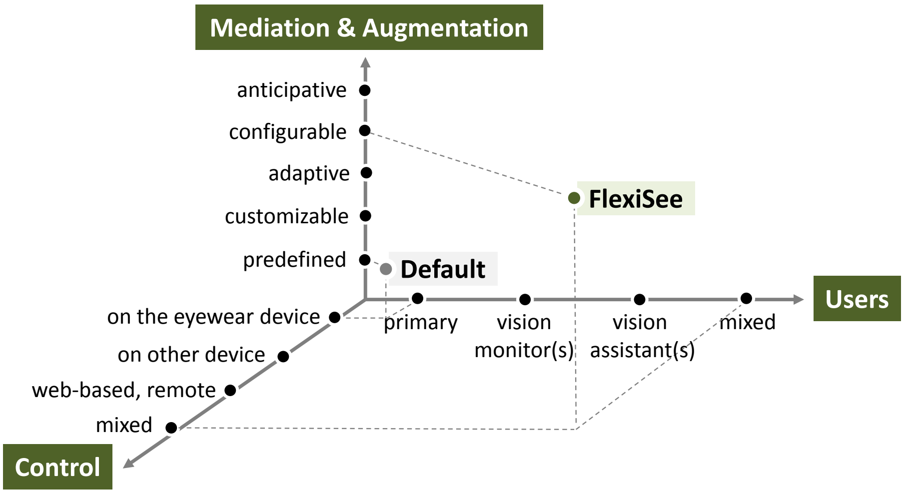

Fig. 2 The FlexiSee-DS design space, highlighting the three quality dimensions regarding flexible mediation and augmentation, user roles, and control modalities in the form of three independent axis with various design options. *Notes:* the origin specifies no augmentation, no control, and no user, *e.g.*, regular eye glasses when they are not used. The "default" point near the origin of the FlexiSee-DS space specifies a system with predefined augmentations that can be controlled by the primary user and via the system exclusively. The most flexible instantiation of a visual perception enhancement system in this space would be anticipative augmediation with mixed control performed by a mixed category of users.

Q_2. *Control of visual filters.* FlexiSee should enable both local and remote control of visual filters by both the wearer (primary user) and assistants (secondary users).

Q_3. *Integration with other personal smart devices.* FlexiSee should easily integrate with other smart devices, such as smartphones and smartwatches, and with applications and services available on the web via standard web-based protocols.

In the second stage, we extended these quality properties into design dimensions for prototyping FlexiSee-like applications with various functionalities and for various contexts of use by identifying design options for each property. The result is represented by the FlexiSee-DS design space with the following three dimensions (see Figure 2 for a visual illustration):

1. The *Mediation & Augmentation* axis specifies possible ways in which users' visual perception is enhanced by FlexiSee-like applications implementing visual filters on smart eyewear devices. For this dimension, we identify five categories or design options:
   (a) *Predefined* mediation and augmentation visual filters that are built-in in the hardware/software of the smart eyewear device.

(b) *Customizable* visual filters, for which users can tune parameters, *e.g.*, the level of contrast for a contrast enhancing filter or the colors that are shifted by a color changing or correction filter.
(c) *Adaptive* visual filters tune their parameters automatically based on data collected by sensing and understanding the context of use, *e.g.*, a contrast adjustment filter that adapts to low ambient lighting conditions according to the measurements provided by a light sensor embedded in the eyewear device would fall into this category.
(d) *Configurable* visual filters, for which users can define new functionality, *e.g.*, by combining multiple filters that, when applied in a specific order, can generate new types of augmediated vision. For example, a color correction filter followed by an edge enhancement filter may lead to a different result compared to the case when the application of two filters is reversed. Sequences of visual filters that users can specify by themselves achieve the property of configurability, which subsumes customizability.
(e) *Anticipative* visual filters, where built-in Artificial Intelligence models and algorithms use data (*e.g.*, user's settings and preferences, user profile, logs and usage history of the device and application, etc.) to anticipate needs and to perform corresponding adjustments of the visual filters, including recommendations provided to users.

Note the increasing level of complexity of the way in which mediated and augmented vision can be specified, from *predefined* filters that can be modified solely via software or hardware updates to an *anticipative* behavior of the smart eyewear device, reflective of the characteristics of systems and applications pertaining to Ambient Intelligence [14, 52] and semantic Ambient Media [48, 49] use case scenarios. As we showed in Section 2, customization of augmented and mediate vision has been implemented to a limited extent by the systems introduced in prior work (see Table 1), but we could not find any cases of adaptivity (*i.e.*, automatic customization) or configurability (*i.e.*, repurposing existing application features to define new functionality), let alone anticipatory behavior.

2. The *Users* axis identifies the *primary user* wearing the smart eyewear device that has direct access to the augmented and mediated vision, *vision monitors*, *vision assistants*, and the *mixed* category, where control is shared by several categories of users, *e.g.*, primary and assistants, or primary, monitors, and assistants alike. We distinguish between vision monitors that only have access to the live stream of the augmediated video and vision assistants that have

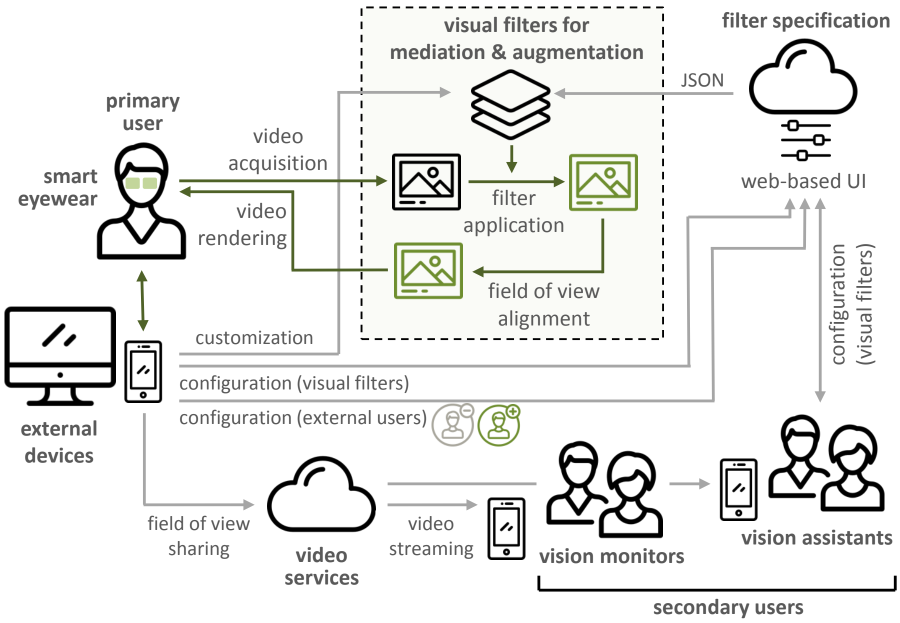

Fig. 3 Architecture of the FlexiSee application highlighting visual mediation and augmentation filters, control devices and web-based user interface, user categories, and data flows.

some degree of control over the visual filters applied by the FlexiSee application for the primary user.

3. The *Control* axis characterizes the ways in which control of the visual filters (*e.g.*, specification, activation, deactivation, etc.) is implemented. We distinguish four categories of control and corresponding design options: *on-the-eyewear* operated by the primary user; *on-other-device*, such as the primary user's smartphone or smartwatch; *remote* via a web-based user interface, to which secondary users, such as vision vision assistants have access; and *mixed*, including combinations of the previous categories.

3.3 Software Architecture of the FlexiSee application

Figure 3 illustrates the software architecture of FlexiSee. Video frames are acquired from the video camera embedded in the smart eyewear device, processed by applying visual filters according to the current configuration, and rescaled to align as best as possible with the user's field of view. Customization and configuration of visual filters are implemented by the primary user via an external device, such as a smartphone or smartwatch, that runs a web browser. Vision assistants have access to the same web-based user interface. Both vision assistants and vision monitors can watch a live video stream of the primary user's mediated and augmented field of view, as delivered by FlexiSee. Unlike vision monitors who only have access to the live video stream, vision assistants can specify visual filters and apply those filters for the primary users of the FlexiSee application.

3.4 Technical Details of the Implementation of FlexiSee

We implemented FlexiSee using a 1st gen. Microsoft HoloLens HMD [38] featuring 32-bit Intel architecture, 64 GB Flash and 2 GB RAM memory, and running Windows 10. We used Visual Studio 2017 and the Windows Software Development Kit (SDK) for the Windows 10 operating system and the C++ programming language to implement a Universal Windows Platform (UWP) application. We also used Boost [10] (the boost-system, boost-date-time, and boost-regex components) and RapidJSON,[5] a header-only fast JSON library.

Listing 3 illustrates a section of `C++` code implementing the visual filters that FlexiSee provides by default. These filters are configured and their parameters customized either by the primary user or by the vision assistants via the web-based user interface and uploaded to FlexiSee using the JSON data-interchange format; see Figure 3. The procedure from Listing 3 iterates over all the JSON members to identify relevant keywords, such as "contrast", "edge", "replace," or "color" that match the default visual filters. The `applyVisualFilters(..)` method calls the prototype function `visualFilter(..)` presented Subsection 3.1. Listing 1 shows an example of a JSON that customizes a single visual filter, face detection enabled for the "HoloLens-1" user, while Listing 2 presents a more complex JSON configuration file specifying a sequence of visual filters and their corresponding custom parameter values, *e.g.*, contrast is increased by 60% and edges are highlighting against the background of the visual reality, among other visual filters.

Listing 1 Example of a JSON customized file activating face detection in FlexiSee.

```
{
  "Users":"Hololens-1",
  "Face-detection": "true"
}
```

Listing 2 Example of a complex JSON configuration file specifying a sequence of visual filters and corresponding custom parameter values.

```
{
  "Users":"Hololens-1",
  "Contrast": "1.6",
  "Brigthness": "35",
```

[5] https://rapidjson.org/

```
  "Face-detection": "true",
  "Edge-enhancement": "Highlight Background Over Edges",
  "Color-modification": {
    "From": {
      "R": 171,
      "G": 61,
      "B": 194
     },
    "To": {
      "R": 241,
      "G": 241,
      "B": 14
     }
   }
}
```

Listing 3 C++ sequence of code implementing several visual filters in FlexiSee.

```cpp
using namespace rapidjson;
void AppMain::applyVisualFilters(cv::Mat& videoFrame) {
  if (document.HasParseError()) {
    rapidjson::ParseErrorCode error = document.GetParseError();
    return;
  }
  for (Value::ConstMemberIterator iter =
    document.MemberBegin(); iter < document.MemberEnd(); ++iter) {
      std::string name = iter->name.GetString();
      if (name.find("Contrast") != std::string::npos) { // adjust contrast
          std::string con = document[name.c_str()].GetString();
          double contrast = atof(con.c_str());
          videoFrame = visualFilter(videoFrame, ADJUST_CONTRAST, 1, contrast);
      }
      else
      if (name.find("Brightness") != std::string::npos) { // adjust brightness
          std::string con = document[name.c_str()].GetString();
          con.erase(remove_if(con.begin(), con.end(), isspace), con.end());
          double brightness = atof(con.c_str());
          videoFrame = visualFilter(videoFrame, ADJUST_BRIGHTNESS, 1, brightness);
      }
      else if (name.find("Edge") != std::string::npos) {    // highlight edges
              std::string type = document[name.c_str()].GetString();
              videoFrame = visualFilter(videoFrame, DETECT_EDGES, 1, type);
    }
      else if (name.find("Color") != std::string::npos) {
              // (R,G,B) values of the color to be replaced
              rapidjson::Value& val = document[name.c_str()];
              int oldR = getColorComponent(val, "From", "R");
              int oldG = getColorComponent(val, "From", "G");
              int oldB = getColorComponent(val, "From", "B");
              // (R,G,B) values of the replacing color
              int newR = getColorComponent(val, "To", "R");
              int newG = getColorComponent(val, "To", "G");
              int newB = getColorComponent(val, "To", "B");
              // replace colors based on a similarity tolerance
              videoFrame = visualFilter(videoFrame, CHANGE_COLOR, 6,
```

```
                            oldR, oldG, oldB, newR, newG, newB);
    }
    else if (name.find("detection") != std::string::npos ||
                name.find("Face") != std::string::npos)
                    videoFrame = visualFilter(videoFrame, DETECT_FACES, 0);
  }
}
```

The following visual filters are implemented by default in FlexiSee using the OpenCV library [43]:

1. *Contrast adjustment.* Figure 4, first row demonstrates contrast adjustment by 30%, 60%, and 90%, respectively. The corresponding OpenCV function is `convertTo(..)`:[6] To increase contrast by 30%, the `beta` parameter of the function is set to `1.3`. When `beta` is less than 1, contrast is decreased by the specified amount. We decided to implement contrast adjustment in FlexiSee since previous systems from the literature demonstrated its effectiveness for vision mediation; see Harper *et al.* [21], Peli [45], eSight [15], Zhao *et al.* [65, 69], Tanuwidjaja *et al.* [61], Hwang *et al.* [25], and Satgunam *et al.* [54].
2. *Brightness adjustment.* This visual filter was equally implemented with the OpenCV `convertTo(..)` function. This time, the argument is added to each pixel value. Figure 4 illustrates brightness adjustment implemented in FlexiSee with parameters 15, 35, and 55, respectively. When the specified value is negative, brightness is decreased. Prior work [15, 22, 65] inspired us to implement this visual filter in FlexiSee.
3. *Edge enhancement.* We implemented the Canny filter to detect edges and present them with a distinct color (Figure 4, third row, second image) and with coloring effects for the background (Figure 4, third row, third and fourth images). We implemented this filter since previous work found it useful for vision rehabilitation; see Peli *et al.* [47], Hwang and Peli [25], Langlotz *et al.* [29], and Zhao *et al.* [65, 68, 70].
4. *Color replacement.* This visual filter is implemented by creating masks for the lower and upper values of the color that will be replaced. Figure 4, fourth row illustrates the color replacement visual filter customized for three different types of color blindness: deuteranopia, tritanopia, and protanopia. We implemented color replacement in FlexiSee due to a large number of previous work demonstrating its utility for vision rehabilitation; see Zhao *et al.* [65,66,69], Fuller and Sadovnik [18], Langlotz *et al.* [29], Melillo *et al.* [37], and Tanuwidjaja *et al.* [61].
5. *Face detection.* In order to implement this visual filter, we used the `detectMultiScale(..)` function[7] from OpenCV with a classifier trained

[6] https://docs.opencv.org/2.4/modules/core/doc/basic_structures.html#mat-convertto

[7] https://docs.opencv.org/2.4/modules/objdetect/doc/cascade_classification.html#cascadeclassifier-detectmultiscale

Fig. 4 Output examples for visual filters implemented by FlexiSee with custom parameter values. From top to bottom: contrast adjustment, brightness adjustment, edge enhancement, color replacement, and a sequence of visual filters (contrast enhancement, color correction, and face detection). *Notes:* the images shown in the first column are not processed; the other columns show the effects of the respective visual filters with custom parameter values.

with the `frontalface` model. Figure 4, last row and column shows the result of applying the filter. The implementation decision was informed by the results of prior systems and studies [44, 53, 66], *e.g.*, Sandnes [53] reported face and text recognition being the most important features that people with visual impairments, participants from their study, sought in smartglasses applications.

While the first four rows of Figure 4 demonstrate customizability, the last row illustrates configurability, *i.e.*, the application of a sequence of visual filters in a row, as follows: contrast enhancement (second image), contrast enhancement and replacing red with yellow (third image), and face detection (fourth image).

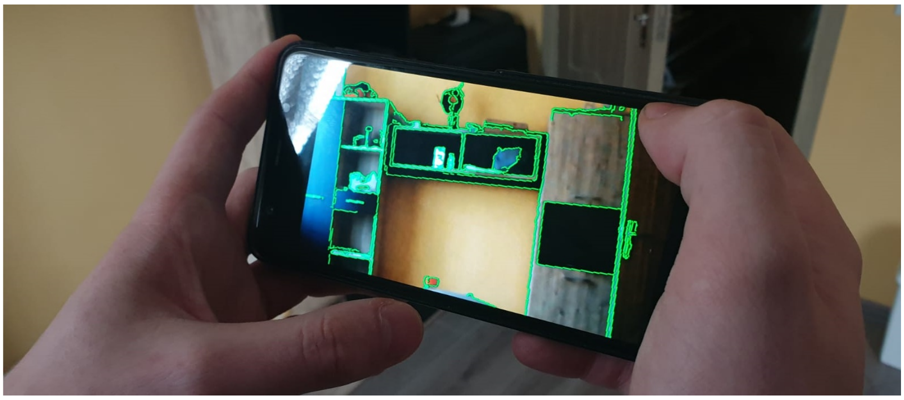

Fig. 5 A vision monitor has access to the primary user's mediated and augmented vision via live video streaming on their smartphone. Also see Figure 1, bottom for illustrations of the web-based user interface for vision assistants.

Vision monitor and vision assistant roles are implemented in FlexiSee via a web-based user interface and a video streaming service over the web. The web user interface is illustrated in Figure 1 from Section 1 and was implemented using standard HTML5 and CSS technology. We decided for a web-based implementation since it can be accessed easily from any web browser and any device and operating system featuring a web browser, including mobile and wearable devices, such as smartphones and smartwatches for the primary user and desktop PCs for vision assistants and monitors; see Figure 1. For the implementation of vision monitoring, we opted for live video streaming over the web. The HoloLens HMD allows streaming live video, referred to as Mixed Reality Capture (MRC).[8] When the HoloLens HMD is connected to a WiFi network, MRC can be visualised via an internal IP address[9]. We used Open Broadcaster[10] in order to distribute the MRC video stream to a dedicated YouTube channel, which can be accessed via any web browser from any device; see Figure 5. In this implementation, both vision monitors and assistants have easy access to the primary user's video stream of augmented and mediated vision.

4 Open Source Code for FlexiSee

To foster more research and development regarding vision augmentation and mediation, we are releasing the source code of the FlexiSee application in the open source domain. The source code, representing a Visual

[8] https://docs.microsoft.com/en-us/hololens/holographic-photos-and-videos
[9] https://blog.kloud.com.au/2016/09/01/streaming-hololens-video-to-your-web-browser/
[10] https://obsproject.com/

Studio project and application written in C++, can be freely downloaded from `https://github.com/cpamparau0/HoloLensForCV`.

5 Conclusion and Future Work

We presented in this work FlexiSee, an application for smart eyewear devices that demonstrates flexibility in terms of configuring, customizing, and controlling augmented and mediated vision. FlexiSee comes to address a gap in the scientific literature, where previous systems for vision augmentation and/or vision rehabilitation were designed with little flexibility in terms of customizing their features and functionality. Together with FlexiSee, we introduced the FlexiSee-DS design space to inform future developments of FlexiSee-like systems that meet various application and user needs. The source code of FlexiSee is equally available to the scientific and practitioner community to foster more research and development in this direction. Future work will look at implementing various FlexiSee-like applications, according to the design possibilities enumerated by the FlexiSee-DS space, including anticipative behaviour and recommendation systems for custom visual filters, and also to evaluating the performance of FlexiSee for specific use case scenarios and categories of users. We also plan to integrate FlexiSee with concept recognition applications and systems, such as Life-Tags [4], toward augmediated applications for lifelogging enthusiasts. We hope that our contributions will lead to better, more flexible designs of assistive technology for vision augmentation and vision rehabilitation that can better adapt to meet their users' needs.

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